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Superfund '89

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The Hazardous Materials Control Research Institute

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U.S. Department of Energy
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PREFACE

The rigorous control and management of hazardous materials and wastes is an urgent necessity for safeguarding the public health, our environment and natural resources, while at the same time, fostering the continued economic growth of the nation. Since 1980, the Hazardous Materials Control Research Institute has organized an annual conference and exhibition to review, update, and exchange information on the latest research and technical findings from the laboratory, industry, and the field concerning hazardous materials and hazardous waste management. With the cooperation of our affiliates, this annual Superfund Conference and Exhibition has become the most comprehensive gathering and information exchange available on the complex of technical and policy issues that flow from the Superfund program. These proceedings include the most up-to-date technical developments, the impact of federal and state policies as well as the legal, health, and economic issues that emanate from the Superfund program.

CERCLA (The Comprehensive Environmental Response Compensation and Liability Act) or "Superfund," as it is now commonly known, was first passed in 1980. This Trust Fund, administered by the U.S. Environmental Protection Agency (EPA), was created to help pay for cleanup of hazardous waste sites that threatened the public health or environment.

Under CERCLA, EPA developed a strategy composed of three major elements. The first called for assessing the uncontrolled hazardous waste sites in the Agency's current inventory. Second, those sites which presented an imminent threat to public health or the environment were to be stabilized. Third, using the National Contingency Plan (NCP) for guidance, the NPL sites were ranked to receive priority attention for remedial cleanup action.

The "Superfund" extension, the Superfund Amendments and

Reauthorization Act (SARA), signed into law in October 1986, was funded at a level of 9 billion dollars. The extension represented a much increased funding level over the previous five-year period, 1980-1985. A significant portion of these resources will be devoted to remedial construction projects at existing and additionally listed NPL sites.

SARA is designed to achieve greater effectiveness by intensifying all activities under CERCLA and adding more facets to the scope of Superfund activities. Within the total program, SARA states will be placed in the implementing role and greater responsibilities will be delegated to the EPA Regional Administrators. Through the implementation of SARA, new sites will be identified and new technologies will be developed and employed. There are now approximately 981 sites on the National Priorities List (NPL) plus other sites administered directly by the affected states.

In addition to EPA's program responsibilities, there is now an even larger involvement of other federal agencies concerned with hazardous materials control or cleanup at federal facilities. Chief among them are the Departments of Defense and Energy. To gauge the extent of their involvement, EPA is slated to spend \$9 billion through 1990, while DOD and DOE have admitted to requiring \$120 and \$170 billion respectively over the next 30 years.

This year's *Proceedings* include 125 papers and lecture outlines that emphasize the latest developments and cumulative experiences gained from the spectrum of Superfund activities. This knowledge and experience can serve as an immediate technology transfer for solutions to your areas of concern.

Hal Bernard
Executive Director
HMCRI

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- U.S. Agency for Toxic Substances and Disease Registry
- American Society of Civil Engineers
- Association of Engineering Geologists
- National Environmental Health Association
- National Solid Waste Management Association

The Program Review Committee reviewed an unprecedented number of abstracts to develop this informative and interesting program. The Committee was composed of:

- Hal Bernard, Hazardous Materials Control Research Institute
- Hal Snyder, U.S. EPA, Chief, Site Assessment Branch
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Hal Bernard
Executive Director-HMCRI
Program Chairman, SUPERFUND '89

GLOSSARY OF FREQUENTLY USED ACRONYMS & ABBREVIATIONS

ACS	American Chemical Society
AICE	American Institute of Chemical Engineers
API	American Petroleum Institute
AQCR	Air quality control region
ARAR	Applicable or Relevant and Appropriate Requirement
ATSDR	Agency for Toxic Substances and Disease Registry
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CMA	Chemical Manufacturers Association
COE	U.S. Army Corps of Engineers
CWA	Clean Water Act
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
DOT	U.S. Department of Transportation
EDF	Environmental Defense Fund
EMSL	U.S. EPA Environmental Monitoring Systems Laboratory
EPA	U.S. Environmental Protection Agency
FEMA	U.S. Federal Emergency Management Agency
HMCRI	Hazardous Materials Control Research Institute
HMTA	Hazardous Materials Transportation Act
HRS	Hazardous Ranking System
HSWA	Hazardous and Solid Waste Amendments
HWERL	U.S. EPA Hazardous Waste Engineering Research Laboratory
HWTC	Hazardous Waste Treatment Council
LOIS	Loss of Interim Status
LUST	Leaking Underground Storage Tanks
MCL	Maximum contamination level
NCP	National Contingency Plan
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanographic and Atmospheric Administration
NPL	National Priorities List
NRDC	National Resources Defense Council
NSWMA	National Solid Waste Management Association
NWA	National Water Alliance
OERR	Office of Emergency and Remedial Response
ORD	Office of Research and Development
OSW	U.S. EPA Office of Solid Waste
OSWER	Office of Solid Waste and Emergency Response
OTA	Office of Technology Assessment
PCB	Polychlorinated biphenyl
PRP	Potentially Responsible Party
RCRA	Resource Conservation and Recovery Act (RCRA)
RI/FS	Remediation Investigation/Feasibility Study
ROD	Record of Decision
SARA	Superfund Amendments and Reauthorization Act of 1986 (SARA)
SITE	Superfund Innovative Technology Evaluation program
TSCA	Toxic Substances Control Act
TSDF	Treatment, Storage, Disposal Facility
TTU	Transportable Treatment Unit
UST	Underground Storage Tank
USWAG	Utility Solid Waste Activities Group

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CERCLA: Current Judicial, Regulatory and Legislative Developments

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ABSTRACT

This seminar will include: (1) a review and analysis of cases significant to CERCLA since the Superfund '88 Conference, with particular emphasis on judicial interpretations of the "innocent owner" provisions, the requirement that private response actions be consistent with the NCP, and the scope of CERCLA liability; (2) a status report on major regulatory developments in 1989, focusing on upcoming revisions to the NCP, the hazard ranking system, release reporting requirements, and U.S. EPA settlement policy and (3) a brief update on proposed legislation related to CERCLA. Because of the topical nature of the seminar, a final determination of all of the matters to be covered and the issues that will be highlighted will not be made until just prior to the conference.

I. JUDICIAL DEVELOPMENTS

A. Consistency with NCP

City of Philadelphia v. Stepan Chemical Co., Civ. No. 81-0851 (E.D. Pa. Apr. 11, 1989. 18 CWLR 565.

U.S. EPA approval of a second cleanup phase and use of CERCLA funds for such cleanup did not entitle the City to a presumption of consistency with the NCP.

Cooper v. Armstrong Rubber Co., Civ. No. J88-0464(L) (S.D. Miss. Feb. 3, 1989).

The court inferred that the plaintiff's assertion of entitlement to recovery of response costs included an implied assertion that the response costs were consistent with the NCP, since only those costs consistent with the NCP are recoverable.

Amland Properties Corp. v. Aluminum Co. of America, 711 F. Supp. 784 (D.N.J. Apr. 18, 1989) 18 CWLR 113.

Substantial compliance with NCP is not sufficient for recovering costs in a §107 private party action; specific compliance with the NCP is necessary. Initial monitoring costs, however, are recoverable, detailed NCP provisions governing other response actions cannot reasonably be applied to preliminary monitoring and evaluation of a release of hazardous substances.

General Electric Co. v. Litton Business Systems, Inc., No. 87-3333-CV-S-4 (W.D. Mo. June 20, 1989).

Consistency with the NCP does not necessitate strict compliance with its provisions. The NCP is not intended to provide complex and detailed site-specific decision-making criteria, but rather presents the federal government's general plan or framework for responding to hazardous substance releases. Public hearings are not mandated in the NCP when compliance with state requirements provides a substantial equivalent. The NCP specifically provides that no federal approval of any kind is

a prerequisite to cost recovery under §107. A response action may be consistent with the NCP in either of two ways: as a removal or remedial action.

Jersey City Redevelopment Authority v. PPG Industries, Inc., No. 88-5184, 88-5185, 88-5520 (3d Cir. Dec. 28, 1988) 17 CWLR 626.

The response costs for off-site disposal of contaminated soil were consistent with the NCP, despite lack of formal comparative cost assessment of remedies, because the party conducting the cleanup hired a highly qualified and competent consultant, whose testimony indicated that the alternatives were carefully considered and that the removal was both necessary and cost-effective.

Retirement Community Developers, Inc. v. Merine, Civ. No. PN-87-2464 (D.C. Md. May 18, 1989 (29 ERC 1625).

Building owner cannot sue former owner under §107 for cost of removing asbestos from building because such a response cost is inconsistent with the NCP.

B. Liability of Owners & Operators

Louisiana-Pacific Corp. v. Asarco, Inc., CIV. No. C-88-217TB (W.D. Wash. Feb. 9, 1989) 29 ERC 1450.

The purchaser of assets of a copper smelting company is not liable for response costs under §107 because the purchaser received explicit CERCLA indemnification from the seller, the sale was not a merger or consolidation constituting continuation of the original enterprise, the purchaser was not a mere continuation of the seller and the sale was not made to fraudulently avoid liabilities. State law of successor liability is controlling on issue of liability of third-party defendant corporation.

Kelley v. Arco Industries, Inc., CIV. No. K87-372-CA4 (W.D. Mich. Feb. 9, 1989) 17 CWLR 1114.

A claim against individual defendants (the Chairman of the Board/controlling shareholder and President/shareholder) was adequate where plaintiffs plead that the Chairman and President were owners and operators of co-defendant Arco, that individual defendants improperly stored, handled or disposed of hazardous materials and that Chairman had overall responsibility for operation and maintenance of site and President directly supervised operation and maintenance of site.

Edward Hines Lumber Co. v. Vulcan Materials Co., 19 ELR 20187 (7th Cir. Nov. 7, 1988).

In a contribution action under CERCLA §113(f), a supplier of wood preserving chemicals is not an owner or operator under §107(a)(2).

U.S. v. Nicolet, CIV. No. 85-3060 (E.D. Pa. May 10, 1989) 18 CWLR 341.

Allegations that the corporate parent was directly liable as a former owner and operator because it was the sole shareholder of the subsidiary, actively participated in its management, was familiar with the subsidiary's waste management practices and benefitted from those practices, adequately supported a cause of action.

Polger v. Republic National Bank, 19 ELR 20938 (D. Colo. Mar. 2, 1989).

The owner of a hazardous waste site may sue a bank that had foreclosed on a tenant's contaminated equipment for contribution under CERCLA §107.

C. Innocent Landowner Defense

In re Sterling Steel Treating, Inc. Civ. No. 86-02999-R (E.D. Mich. Dec. 30, 1988) 17 CWLR 900.

The purchasers of contaminated property are not entitled to the innocent landowner defense (despite lack of knowledge of presence of hazardous substances) because they had done business with the seller and were aware of the uses of the property, and the property was open for inspection before the sale.

South Florida Water Management District v. Montalvo, Civ. No. 88-8038-CIV (S.D. Fla. Feb. 14, 1989).

The present owner and lessor of the contaminated site is not entitled to the innocent landowner defense because the owner purchased the property with full knowledge of the lessee/defendant's activities on the land. The owner/lessor is jointly and severally liable with the lessee and generator of the hazardous contamination, even though the owner/lessor was not the source of any of the contamination.

Jersey City Redevelopment Authority v. PPG Industries, Inc., Nos. 88-5184, 88-5185, 88-5220 (3d Cir. Dec. 28, 1988) 17 CWLR 626.

The appropriate inquiry under the innocent landowner defense is whether the landowner knew at the time of sale that the substance existed on the property, not whether he knew specifically that it was hazardous. The innocent landowner defense is not available to a defendant who "caused or contributed" to the release or threatened release, so that a buyer of chromium-contaminated property who sold the contaminated soil as fill material was not entitled to invoke the defense.

U.S. v. Fleet Factors Corp., Civ. No. CV687-070 (S.D. Ga. Dec. 22, 1988) 17 CWLR 657.

The owners of a facility containing 700 drums of toxic chemicals, as well as large amounts of asbestos, invoked the innocent landowner defense claiming that Fleet Factors, the secured creditor who arranged for the foreclosure auction and who allegedly forbade the owners from disposing of the drums because of their potential value as assets, caused the release. The court, in examining the parties' cross motions for summary judgment, rejected this argument, finding that the owners were not entitled to the third-party defense because the secured creditor was not solely responsible for the release. The court also found that Fleet Factors, the holder of a security interest in a bankrupt, non-operating facility, was not an "owner or operator" of a facility where hazardous substances were disposed because of the security interest exclusion in §101 (20)(A).

U.S. v. Pacific Hide & Fur Depot, Inc., Civ. No. 83-4052 (D. Idaho Mar. 13, 1989) 18 CWLR 147.

Shareholders of a closely-held corporation who received their shares through familial gifts or inheritances were innocent landowners because the release was caused solely by act of a third party, they had no reason to suspect hazardous substances were on the property, they had no specialized knowledge or experience concerning PCBs or hazardous wastes, etc. The legislative history of SARA establishes a three-tier system: commercial transactions are held to the strictest standard; private transactions are given a little more leniency; and inheritances and bequests are treated most leniently.

U.S. v. Parsons, Civ. No. 4:88-cv-75-HLM (D.Ga. May 30, 1989) 18 CWLR 573.

The officer of a company arranging for disposal of waste and the

company which agreed to take care of the wastes could not assert the third-party defense under CERCLA, since the relationship was contractual and the officer failed to exercise due care. Summary judgment granted as to liability against the owner of property at which hazardous substances were disposed, despite contention that owner was in Jamaica at time of disposal, had no knowledge of disposal, and had not given permission to his grandmother to consent to disposal.

International Clinical Laboratories, Inc. v. Stevens, Civ. No. CV87-3472 (E.D.N.Y. Apr. 12, 1989) 17 CWLR 1105.

The lessor of contaminated property is not entitled to the "third-party" defense, because the CERCLA §101(35) definition of "contractual relationship" clearly includes lease agreements. An "as is" clause in a contract for the sale of property under New York law bars only actions based upon breaches of warranty; it does not bar an action against the seller of the property under CERCLA.

D. Other Defenses

Channel Master Satellite Systems, Inc. v. JFD Electronics Corp., No. 88 605-CIV-5 (E.D.N.C. Dec. 29, 1988) 29 ERC 1172.

In a §107 cost recovery action, the court rejected the defendant seller's contention that an indemnity clause in the sales agreement relating to state law shifted CERCLA liability to the plaintiff because a violation of federal law was also a violation of state law. A buyer of land may recover response costs from the seller under §107 despite provisions in the sales contract dealing with warranties, the "as is" condition of the land, and indemnification. The thrust of §107(e) is that although one may not deny liability for response costs by virtue of an indemnity agreement, such an agreement is not eliminated by the strict liability provisions of CERCLA.

Browning-Ferris Industries South Jersey, Inc. v. Muszynski, No. 89-CIV 1929-LLS (S.D.N.Y. May 10, 1989)

A prior RCRA §7003 consent order addressing the same site and general circumstances does not prevent the subsequent issuance of a CERCLA §106 order requiring more substantial and specific actions, where the RCRA consent order was entered into after CERCLA's enactment and made no provisions for subsequent CERCLA orders. The U.S. EPA's breach of the prior RCRA order, however, can be asserted as a defense to the subsequent CERCLA enforcement.

Colorado v. Iadarado Mining Co., No. 83-C-2385 (D.Colo. Feb. 22, 1989) 29 ERC 1348.

The court found that the defenses to liability under CERCLA were limited to those set forth in §107(b), and denied the availability of laches, estoppel, failure to mitigate damages and the State's alleged encouragement of mining which gave rise to disposal as defenses. The court also found that none of these additional defenses was sustained by the evidence, including the de minimis party defense, and held that defendants were liable for cleanup even as de minimis polluters. Habitat mitigation activities, including the stocking of streams and rivers with fish, are necessary, and the court required that such actions be taken as part of a general remediation program.

U.S. v. Farber, CIV. No. 86-3736 (D.N.J. Mar. 3, 1989) 17 CWLR 873.

A genuine issue of material fact existed as to whether the sale of the assets of an entire company that included hazardous substances was an "arrangement" for the treatment or disposal of hazardous substances under §107(a)(3) of CERCLA.

E. Citizen Suits

McCormick v. Anschutz Mining Corp., CIV. No. S88-97C(5) (E.D. Mo. Jan. 30, 1989) 29 ERC 1707.

Plaintiff failed to satisfy the injury requirement for standing in a §303 citizen suit through a claim that he could be subject to future liability. The possibility of future injury is not enough.

Neighborhood Toxic Cleanup Emergency v. Reilly, CIV. No. 89-2578 (SSB) (D.N.J. July 5, 1989) 18 CWLR 553.

The court interpreted §113(h) to allow judicial review of EPA's selection

of a remedy only after the first phase of the remedy is complete.

Lutz v. Chromatex, Inc., CIV. No. 88-1764 (M.D. Pa. June 9, 1989).
A citizen suit under §310 may not be based on wholly past violations.

Sauers v. Pfiffner, CIV. No. 4-88-457 (D. Minn. Mar. 23, 1989) 29 ERC 1716.

The court dismissed an action brought under RCRA and CERCLA citizen suit provisions because of improper venue (and refused to transfer the case to proper venue). The suit was brought in the district of plaintiff's residence, and venue is proper in the district in which the alleged violation occurred.

Schalk v. EPA, CIV. No. IP-88-344-C (S.D. Ind. Dec. 6, 1988) 28 ERC 1655.

Plaintiffs cannot bring suit under §310 to compel the U.S. EPA to provide an EIS, because §310 permits citizens to challenge only failures to perform non-discretionary duties.

F. Hazardous Substances

U.S. v. Sharon Steel Corp., CIV. No. 86-C-0924J (D.Utah May 17, 1989).

Raw ore sold to steel manufacturer is not a hazardous substance. Raw materials which do not pose an immediate threat without further treatment are not hazardous substances.

G. Response Costs

Regan v. Cherry Corp., 706 F.Supp. 145 (D.R.I. Feb. 10, 1989).
"Necessary costs of response" under §107 does not include punitive damages.

Coburn v. Sun Chemical Corp., 19 ELR 20256 (E.D. Pa. Nov. 9, 1988).

Costs of medical screening and future medical monitoring are not response costs under CERCLA & plaintiffs cannot maintain a citizen suit under RCRA §7002(a)(1)(A) against two former owners of a hazardous waste site]. [but see *Williams v. Allied Automotive* 19 ELR 20689 (N.D. Oh. Aug. 3, 1988). Future medical monitoring costs may be recoverable under CERCLA §107 if they are necessary and consistent with the NCP.]

Ascon Properties, Inc. v. Mobil Oil Co., 866 F.2d 1149 (9th Cir. Jan. 31, 1989) 17 CWLR 821.

CERCLA does not require a property owner to allege the particular manner in which a release or threatened release has occurred in order to make out a prima facie claim under §107(a). In order to state a cognizable prima facie claim, a property owner must allege at least one type of "response costs" recoverable under CERCLA.

H. Natural Resource Damages

Acushnet River & New Bedford Harbor: Proceedings re: Alleged PCB Pollution, No. 83-3882-Y

Recoverable damages under §107(f) are of three types: (1) divisible damages occurring on or after Dec. 11, 1980 (such as daily losses to lobstermen); (2) indivisible damages which began prior to Dec. 11, 1980 and continued thereafter (including possible indivisible aesthetic injury damages) and (3) latent damages which will occur at some as yet undetermined time. In an action for natural resource damages, the defendant bears the burden of proof as to the exclusion of recovery of those damages under §107(f).

I. Criminal Liability

U.S. v. Greer, 28 ERC 1254; 19 ER 971 (11th Cir. 1988).

Eleventh Circuit reinstated guilty verdict against Greer, finding that he knowingly disposed of, or knowingly caused others to dispose of, hazardous wastes when he told an employee to "handle" the waste despite knowing that his firm had no storage capacity. Greer was ordered to serve 13 mo in prison.

J. Liability of States

State of New York v. Johnstown, 701 F.Supp. 33 (N.D.N.Y. Dec. 31,

1988).

Waste generators counterclaimed against the state seeking indemnity and contribution in connection with landfills where the state directed deposits of hazardous substances in an attempt to control environmental damage, but failed to issue permits for the site. The court found that where the state is a plaintiff in a CERCLA action, it waives its sovereign immunity as to compulsory counterclaims, but the court dismissed the counterclaim, noting that absent a special duty owed to the defendant, no liability should be imposed upon a state for its alleged failure to enforce its regulations.

Pennsylvania v. Union Gas Co., No. 87-1241, (57 U.S.L.W. 4662 June 15, 1989).

Language of CERCLA shows that Congress clearly intended that states may be held liable along with everybody else for the costs of cleaning up hazardous waste sites.

K. Recovery from Fund

Wagner Seed Co. v. U.S., CIV. No. 88-1922 (D.D.C. Apr. 4, 1989) 29 ERC 1453.

The court sustained the U.S. EPA's determination that the plaintiff company, which had nearly completed response actions ordered under §106(b)(2) as part of SARA, was not entitled to assert a claim under that provision for reimbursement of its costs. The statute was ambiguous, and the U.S. EPA's interpretation of it was not unreasonable.

L. Insurance Coverage

Hazen Paper Co. v. United States Fidelity & Guaranty Co., 19 ELR 20364 (Mass. Super. Ct. Jan. 10, 1989).

A comprehensive general liability insurance policy covers liability for response costs under CERCLA (as well as the Massachusetts Oil and Hazardous Materials Release, Prevention and Response Act).

M. Pending Cases

Joslyn Manufacturing Co. v. T. L. James & Co. (on appeal to 5th Circuit)

U.S. v. Carr

II. REGULATORY DEVELOPMENTS

- A. Status of proposed revisions to NCP.
- B. Revised Hazard Ranking System—results of field tests report (54 Fed. Reg. 37949, Sept. 14, 1989).
- C. Scope of Federally Permitted Release Exemption (54 Fed. Reg. 29306, July 11, 1989).
- D. Definition of Release—placement into unenclosed containment structures (54 Fed. Reg. 22524, May 24, 1989).
- E. Arbitration Procedures for small cost recovery claims (54 Fed. Reg. 23174, May 30, 1989).
- F. Proposed response claims procedures for claims asserted against the fund (54 Fed. Reg. 37892, Sept. 13, 1989).
- G. Applications of policy on the placement of RCRA sites on the NPL (54 Fed. Reg. 41004, Oct. 4, 1989).
- H. Guidance on landowner liability under §107 (a)(1) of CERCLA, *de minimis* settlements under §122(g)(1)(B) of CERCLA, and settlements with prospective purchasers of contaminated property (Juen 6, 1989).
- I. Evolution of Municipal Settlement Policy.

III. LEGISLATIVE DEVELOPMENTS

- A. HRC 2085 (LaFalce)—would exclude commercial lending institutions acquiring facilities through foreclosure or similar means and corporate fiduciaries administering estates or trusts from definition of owner or operator under CERCLA §101(20).
- B. HR 2087 (Weldon)—attempts to define "all appropriate inquiry" (i.e., Phase I Environmental Audit) for purposes of qualifying for the "innocent landowner" defense under CERCLA §101(35).
- C. Potential effect on CERCLA of pending Clean Air Act and RCRA amendments.

Cover Design and Other Closure Considerations For a Low-Level Radioactive Waste Site

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ABSTRACT

Closure requirements and cover designs were evaluated for a low-level radioactive waste site on the Hanford Reservation in the State of Washington. Consideration was given to the impact of wind erosion and subsidence on the performance of cover systems. Two cover designs were evaluated; a thick sand cover and a multiple layer design cover. Recommendations were given to the State of Washington to dynamically compact the waste and close the site with a multiple layer cover. The multiple layer design included biotic, capillary and hydraulic barriers in addition to a gravel top dressing and vegetated surface.

INTRODUCTION

A study was commissioned by the State of Washington to develop a closure plan for the commercial low-level radioactive waste disposal facility (LLRWDF) on the Hanford Reservation¹. Objectives for closure of the LLRWDF included the following:

- To stabilize the waste and close the facility in a manner that would minimize the need for both environmental monitoring and cover maintenance
- To construct a cover which would minimize drainage through the waste and prevent biotic intrusion into the facility for 1,000 yr
- To reduce gamma radiation from buried waste to background at the site boundary
- To prevent run-on from episodic climatic events
- To minimize wind and water erosion of the final cover
- To minimize or accommodate long-term waste settling and cover subsidence

The most demanding objective was to minimize drainage through the waste over a 1,000-yr time-frame. If this one objective could be met, nearly all other objectives also would be met. For instance, both wind erosion and biotic intrusion would have to be minimized if drainage through the waste was to be kept to a minimum. Similarly, subsidence of the cover would have to be minimized in order to minimize drainage through the waste. Wind erosion and subsidence are discussed below, followed by a brief description of two cover systems evaluated for the site.

WIND EROSION

Wind erosion has long been recognized as having the potential to degrade the performance of a cover system for the LLRWDF². One practice used to reduce wind erosion has been to place a gravel layer as a topdressing on the cover. While this approach effectively minimize wind erosion, it also may impact both infiltration and the kind and amount of vegetation.

Little information could be found in the literature delineating the optimal layer thickness and particle size distribution for a gravel topdressing. Consequently, on-site test plots were recommended to develop

a better understanding of this layer. The importance of these studies can be seen by the fact that the wrong gravel layer design may have the dual effect of increasing infiltration while reducing evapotranspiration (by inhibiting plant growth).

It has been observed that gravel topdressings may be buried through the natural deposition of fines. Studies were recommended to evaluate the influence of a buried gravel layer on the overall water balance of a cover.

SUBSIDENCE

No multiple layer cover system can be effective if steps are not taken to minimize or accommodate long-term waste settlement or cover subsidence. This is an especially difficult problem where waste has not been densified prior to or during placement. At the site under study, waste was placed in a low density form and stacked greater than 24 ft deep in many places. Assuming 25% voids in the waste, an eventual 6 ft of subsidence would be possible due solely to consolidation of waste solids. One third of the waste was assumed to be biodegradable organic materials. Consequently, another 6 ft of subsidence could occur, giving a total subsidence of 12 ft. Anywhere near this amount of subsidence would result in complete failure of a multiple lift cover system.

Arid conditions at the site assured that both biodegradation of organic materials and consolidation of the waste could take place over as much as several hundred years. This long period of change makes the real difficulty in the situation clear; much of the subsidence would occur after the end of institutional control.

Excavation and Proper Redisposal

In hindsight, it can be seen that it was a mistake to place the waste in a low density form. This one management approach has made long-term containment of the waste an extremely difficult problem. If it is easiest to dispose of the material properly in the first instance, many would suggest that the next easiest solution would be to do it right the second time. This corrective process would involve excavating all the waste, destroying the organic materials through biodegradation or incineration, compacting the residual inorganic materials to 95% of modified Proctor density and redispersing this dense material.

While the above solution may be the most effective way to minimize long-term cover subsidence, it also has significant disadvantages. There was little doubt that many of the waste containers already were partially degraded or crushed. This degradation would have released radioactive materials into the immediate vicinity of the broken containers. This situation would both greatly complicate any attempt to safely excavate the material and substantially increase the volume of material to be handled.

Another disadvantage of this solution to the low density waste problem would be the potential for air release of radioactivity during excava-

tion, treatment, compaction and redispersion of the waste. This proposal corrective solution might actually result in greater releases of radioactivity than no action at all. Very intensive safety procedures and equipment would be needed to safely implement this solution. Considering also the scale and sophistication of the treatment operation, this solution could easily cost several hundred million dollars. While this expense is comparable to that encountered with some of the largest Superfund sites, it would be rejected on the grounds of cost and the potential for both air releases and direct exposure of cleanup personnel.

Dynamic Compaction

Another solution which would densify the waste while minimizing air releases, worker exposure and cost, was dynamic compaction. This process would involve a very large weight (such as a 40-ton hammer) repeatedly dropped from a substantial height (such as 45 ft) until there was no further consolidation of the waste. This type of operation has been considered elsewhere on the Hanford Reservation, West Valley, Maxey Flats, and had actually been implemented at the Savannah River Facility.

There are, however, disadvantages to this solution. For example, the compaction process would likely result in the breaking open and crushing of underlying containers. One could argue that most of these containers do not represent secure long-term containment of the waste anyway. Consequently, the argument that the existing containers at the site provide containment would only be partially true in a short-term sense and completely invalid in a long-term sense.

To argue that these containers should not be crushed has to be viewed in the following context:

- Many containers never provided containment (cardboard boxes and wooden crates)
- Many barrels were probably crushed as a result of the existing overburden pressure
- Steel barrels rust and corrode in soil environments
- If the containers were not dynamically compacted, there would be so much eventual settling in the waste that the cover would subside and fail
- If the cover failed, moisture would quickly move into the facility through the waste, pick up contaminants and migrate to the groundwater
- If the containers were crushed via dynamic compaction and a long-term effective cover was placed over the waste, the amount of radioactivity reaching the groundwater would be much less than if the cover failed

Consider for a moment what would happen if all containers were broken. Radioactivity likely would be released to the immediate vicinity of the containers. This release in itself, would not result in any migration of radioactivity out of the facility. For radioactivity to migrate any appreciable distance, there would have to be movement of moisture through the waste. The only effective means to prevent moisture movement through the waste is construction and long-term maintenance of an effective cover system. It clearly followed that if subsidence was not prevented, the cover would fail. If the waste is not compacted, subsidence due to waste consolidation will occur. Consequently, if the waste is not densified or some other solution is not found to resist the forces of subsidence, the cover will fail. The ultimate solution would be to require all waste to be disposed in a form that would minimize subsidence.

There are two major causes for waste settlement; (1) consolidation of solids and (2) degradation of organic materials. Dynamic compaction only reduces consolidation of solids. If organic materials biodegradation proceeds, then cover subsidence still occurs. It could be argued that this could be significantly slowed by keeping the waste dry. The best way to keep the waste dry would be to maintain cover effectiveness by minimizing subsidence.

It would be difficult to provide an accurate evaluation of the expected rate of subsidence with or without dynamic compaction. In hindsight, it can be seen that an accurate assessment of subsidence under current conditions could have been obtained through simple and inexpensive

studies conducted at the site over the last 20 yr of operation. This is another area where policy action is needed now to require the kind of studies which will facilitate long-term effective closure.

Arch Ribbed One-Way Slab Concrete Cover

Another approach to accommodate long-term waste settlement is to construct a structure over the waste. The structure would have to have sufficient strength to resist subsidence due to both settlement of the underlying waste and the overburden pressure of the overlying cover. One structure which may be able to provide the required support would be an Arch Ribbed One-Way Slab (AROWS) concrete cover.

An example design of an AROWS, 160 ft wide and 880 ft long, is shown in Figure 1. Arch ribs, spanning 160 ft, are 1.5 ft to 2 ft wide and 5 ft deep (Fig. 2). The rise for the ribs is 10 ft. Ribs not only would be reinforced conventionally for bending and temperature stresses, but also would be post-tensioned/pre-stressed to minimize tension stresses and cracking. The slab would be 8 to 10 in. thick.

Forty-four slabs, 20 ft wide and 160 ft long, would be required for a typical trench at the site. A 75 lb/ft² superimposed load was used for this AROWS. This loading would allow only 1 ft of cover soil.

If a multi-layer cover system were deemed necessary to go over the AROWS, the cost would rise according to the thickness of the cover system. Based on the stated assumptions, the preliminary cost for the AROWS would be approximately \$20/ft². When this added cost is included with the probability of also needing a multiple layer cover, the total cost becomes prohibitive.

Another solution to the problem of subsidence would be to simply rebuild the cover periodically. How long a period would be allowed between rebuilding and the total number of rebuilds would be very hard to define in the absence of information on the rate and total expected amount of subsidence. If it were assumed that the cover was to be rebuilt, then the requirements for a cover that would last 1,000 yr could be relaxed. At the same time, however, the dollars set aside for long-term maintenance would need to be greatly increased.

As with the other solutions to the subsidence issue, the assumptions incorporated in this solution outnumber the hard facts. The solution that involves periodically readdressing the problem would have inherent advantages and reduced technical risks. By planning to rebuild the cover in 50 or 100 yr, advantage could be taken of new developments in materials and cover designs. It is important, however, to avoid placing emphasis on capital-intensive activities beyond 100 or 200 yr because it is impossible to determine if there would be effective institutional control that far into the future. It is likely that institutional control would not end suddenly. Control probably would begin to fade long before it actually ended. Consequently, if the presumed end of control were set at 300 yr, the final date for capital-intensive activities should be set well before this time.

Uncertainty about the way or time in which institutional control will end is in itself a very strong argument to develop a permanent solution as soon as possible following closure. The fact that so many areas of uncertainty remain about how to construct a permanent cover is a strong argument for greatly accelerated research now to develop the information needed to build very long lasting cover systems.

It may be that, considering all the uncertainties, the best solution to the subsidence problem would be a hybrid closure. This scenario would incorporate both an initial temporary cover and implementation of a final permanent cover as soon as research can be completed which would improve confidence in the ability to build such a cover.

COVER DESIGN ALTERNATIVES

Two specific cover design alternatives are discussed in this section. Cover design alternatives examined included a thick layer of sand and a multi-layer design.

Thick Sand Cover

The operator of the commercial LLRWDF proposed a design consisting of 10 ft of sand over a 6-in. layer of gravel. The gravel was designed to be a barrier to wind erosion while the thickness of the sand layer was to minimize bio-intrusion into the waste.

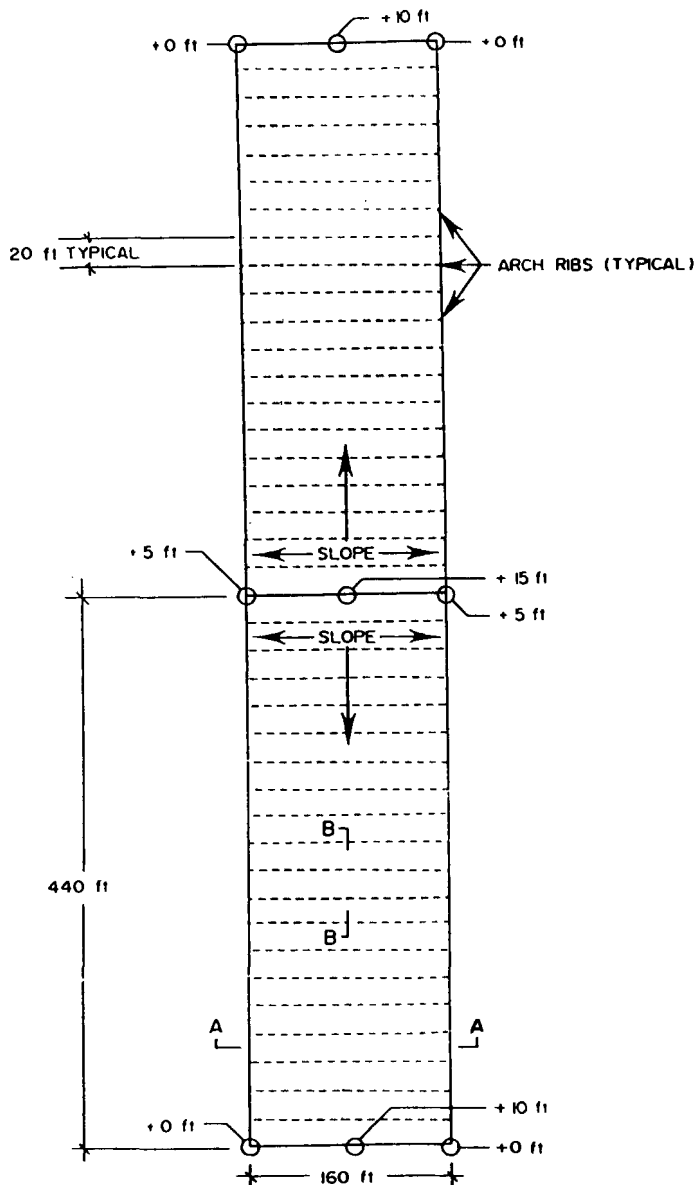


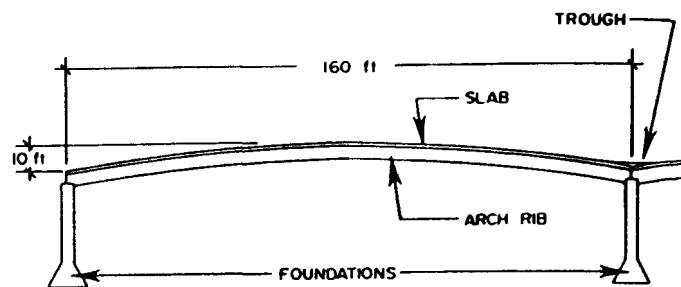
Figure 1
Plan View of an Arch Ribbed One-Way Slab

The cover lacks any hydraulic or capillary barrier which would divert the deep percolation of water. The presumption was that the recharge rate would be so minimal (0.2 in./yr) that the travel time to the aquifer would be sufficiently long (1420 yr) so that there would be no danger of contaminating the groundwater¹.

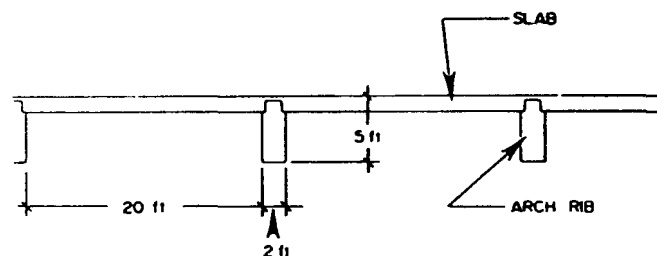
Deep percolation rates in the Hanford area in recent years have been reported as high as 2.4 in./yr². If one assumes that the relationship between deep percolation and transit time to groundwater is roughly linear, then the values postulated by Bergeron, et al.,³ can be used to estimate different transit times. For instance, the 2.4 in./yr value on the Hanford site would be 12 times that of the 0.2 in./yr estimate by Bergeron, et al.,³. Dividing the 1,420-year transit time by 12 yields a transit time estimate of 118 yr for a deep percolation rate of 2.4 in./yr. Climatic changes are possible over the long post-closure period. If a long-term trend develops toward a moderately wetter climate, then the transit time would be significantly less than 118 yr. Any cover design which uses the extreme low estimate of postulated current deep percolation rates will fail to protect the groundwater under all but the driest of possible conditions.

The design recommended by the operator adequately addresses wind erosion. In addition, it is difficult to envision how subsidence could

significantly degrade the performance of a sand pile. The design does not, however, provide for minimization of deep percolation during either the relatively wet conditions optimal for performance of a hydraulic barrier or the relatively dry conditions optimal for performance of a capillary barrier.



SECTION A



SECTION B

Figure 2
Cross-Sections of the Arch Ribbed One-Way Slab
Periodic Replacement of the Cover

Multiple Layer Design

A multiple layer cover design was developed which would meet all RCRA and NRC requirements. In addition, the cover met the most recent U.S. EPA technical guidance for final cover systems⁴. The design was developed to provide both a long service life and the operational flexibility to minimize deep percolation under both relatively dry and relatively wet climatic periods. In addition, the design would minimize erosion, bio-intrusion and long-term maintenance. Any multiple layer cover system is susceptible to performance degradation as a result of subsidence. Consequently, specific actions, such as dynamic compaction, would need to be undertaken in association with this cover design to minimize subsidence.

Each layer in a multiple layer cover design should serve specific functions, meet designated performance standards and be subjected to construction quality assurance procedures which verify that the performance standards are met. In addition, each layer in the cover should be compatible with the adjacent layers and support the overall objectives set out for the cover system. Discussions in the following sections include cover component integration and descriptions of all layers in the multiple layer cover system.

Any cover system should be developed with careful consideration of the context within which it must function. Two of the most important contextual aspects for this cover are the long lifespan and the range of potential climatic conditions. Consideration of the long half-life for

many of the radionuclides disposed in the facility suggests that the cover should be designed to function for 1,000 yr. Such a long time-frame emphasizes the need to design the cover for a range of climatic conditions.

There are two barrier systems which have been shown to reduce deep percolation¹. Each barrier system has an optimal efficiency at different water flow rates. At relatively high flow rates, the optimal system is a hydraulic barrier composed of a high permeability lateral drainage layer over layers of low permeability material (Fig. 3). At relatively low flow rates, the optimal system is a capillary barrier composed of a medium permeability layer, such as a loam, over a high permeability layer, such as a coarse sand or gravel (Fig. 4).

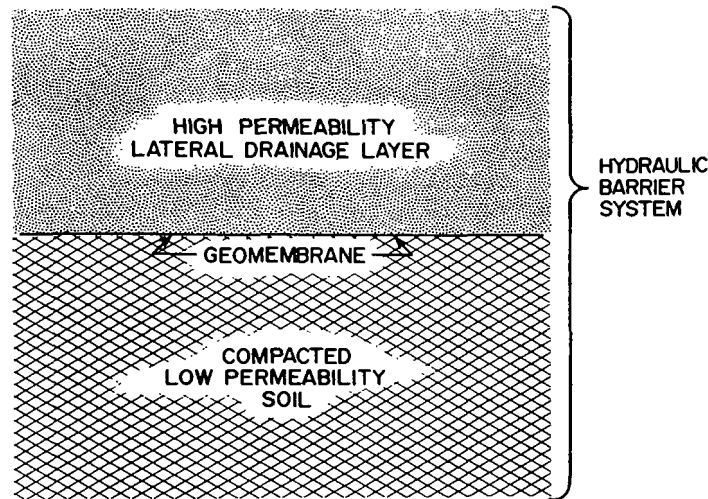


Figure 3
Barrier System for Optimal Reduction of Deep Percolation
Under Relatively High Flow Rates.

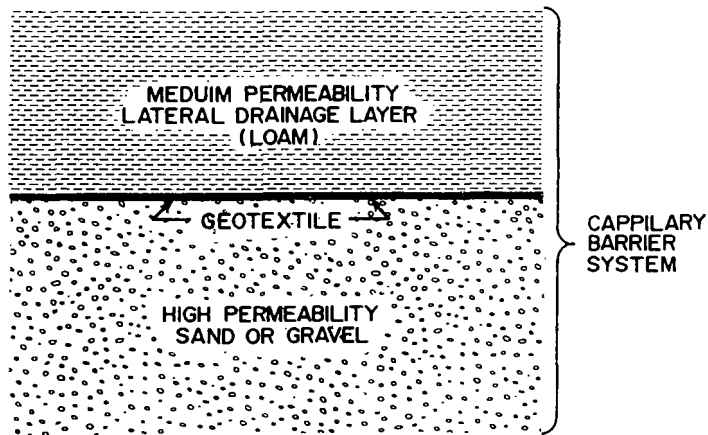


Figure 4
Barrier System for Optimal Reduction of Deep Percolation
Under Relatively Low Flow Rates.

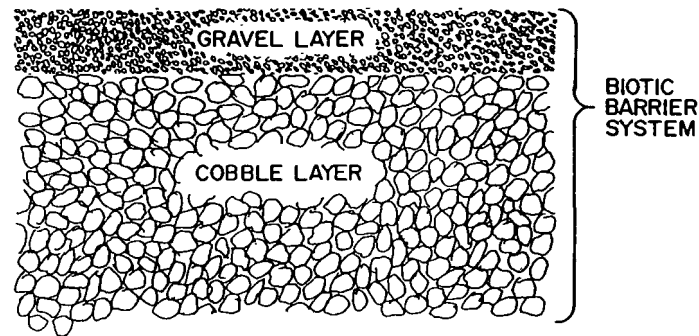


Figure 5
A Biotic Barrier System for Placement Above the Hydraulic Barrier
and Below the Capillary Barrier

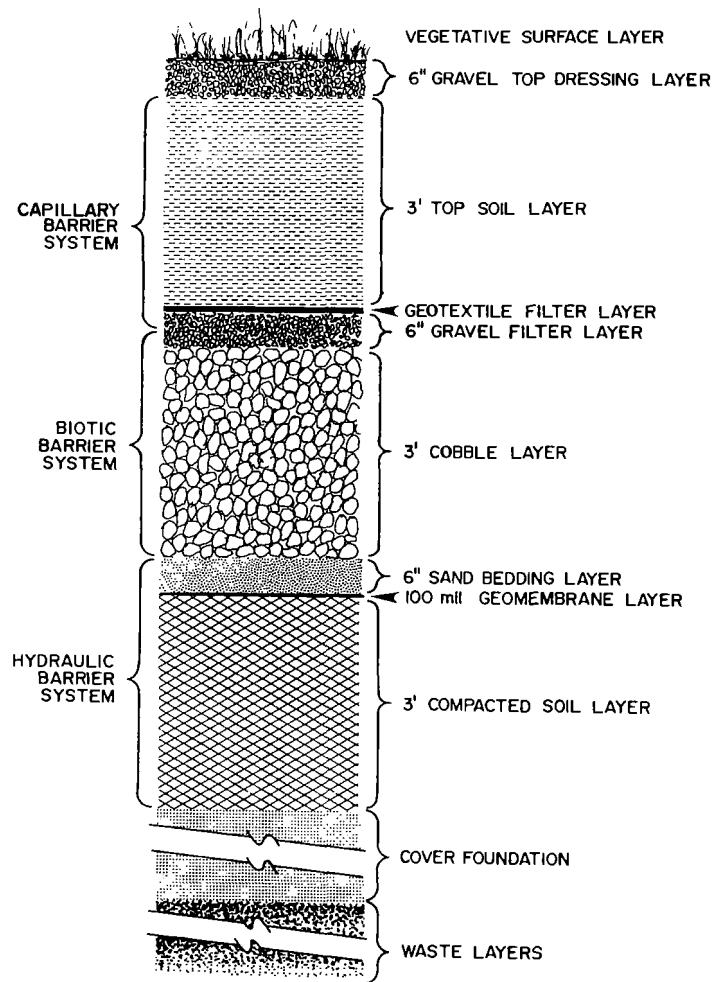


Figure 6
Multiple Layer Cover Design

A cover design that incorporates both a capillary barrier and a hydraulic barrier should have the ability to minimize deep percolation over a range of water flow rates. Schulz, et al.,⁵ noted that placing the hydraulic barrier over a capillary barrier would result in a very effective barrier system. This combination would be even more effective for the site under study, however, if the hydraulic barrier were placed under the capillary barrier. This is because of the need to protect the compacted soil component of the hydraulic barrier from both shrinkage cracks and biotic intrusion. When a compacted soil is placed near the surface in a cover system, it is susceptible to shrinkage cracking due to water loss from both evaporation and extraction by plant roots. In addition, near surface hydraulic barriers can be damaged by burrowing animals and holes left by penetrating plant roots.

If a biotic barrier system (Fig. 5) were placed over the hydraulic barrier, biotic intrusion could be prevented. By placing the capillary barrier over the biotic barrier, additional distance is placed between the hydraulic barrier and the disruptive near-surface factors discussed above. The biotic barrier also serves as both an excellent lower component to the capillary barrier system and an efficient lateral drainage component to the hydraulic barrier system. An illustration of the integrated hydraulic, biotic and capillary barrier systems is shown in Figure 6.

CONCLUSIONS

Recommendations were made to the State of Washington to subject the waste to dynamic compaction. In addition, a multiple layer cover was recommended that would minimize drainage through the waste to the maximum extent feasible with available cover technology. The cover included a vegetated surface, gravel top dressing, and biotic, capillary, and hydraulic barriers.

REFERENCES

1. Anderson, D.C. and Hana, S.L., "Results of Washington's Phase Two Study on Closure Requirements for the Hanford Commercial Low-Level Waste Facility: Design Objectives and Cover Alternatives," Proc. of the Symposium on Waste Management Tucson, AZ, pp. 173-178, 1989.
2. A. T. Kearney, Inc., Closure and Perpetual Care and Maintenance of the Commercial Radioactive Waste Disposal Facility on the Hanford Reservation, Prepared for Washington DOE, Olympia, WA, 104 p., 1986.
3. Bergeron, M.P., Napier, B.A., Reisenauer, A.E. and Sherwood, D.R., Environmental Pathways Analysis of the U.S. Ecology Low-level Waste Disposal Facility, Richland, Washington, Prepared for U.S. Ecology, Inc. Louisville, KY, 46 p., 1987.
4. U.S. EPA, Final Covers on Hazardous Waste Landfills and Surface Impoundments, EPA/530-SW-89-047, Washington, DC, 39 p., 1989.
5. Schulz, R.K., Ridkey, R.W. and O'Donnell, E. Control of Water Infiltration Into Near Surface LLW Disposal Units, NUREG/CR-4918, Vol. 2, 24 p., 1988.

Industrial Property Transfer Environmental Assessment Case Histories

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ABSTRACT

Environmental assessments have become an integral part of industrial property closures and transfers. Federal laws such as CERCLA, SARA and the State of New Jersey's Environmental Cleanup Responsibility Act (ECRA) have focused attention on such property transfers. The liabilities may be substantial for parties who had, have or will have interests in the ownership, operation or transfer of ownership of properties which may be contaminated by hazardous materials. This paper presents an approach for conducting environmental assessments for industrial property transfers and summarizes case histories for environmental assessments conducted at former industrial properties.

INTRODUCTION

This paper focuses on environmental assessments conducted for the current owner or seller of industrial property. Knowledge of potential environmental concerns allows the owner to identify the extent of possible liabilities associated with a particular piece of property and assess potential impacts on the property's value.

Industrial property environmental assessments may be performed to accomplish the following objectives:

- Provide a "snapshot" of existing site environmental conditions. This "snapshot" not only provides information relative to property values and impacts related to transfer of ownership, but it also provides a benchmark against which future site conditions may be compared. The information may, for example, show that contamination detected on the site at some future date was not caused by the previous owner.
- Identify site conditions which may be incompatible with proposed uses for the property. A former manufacturing site would likely require less remediation for future use in a similar manner than for future use as a site for an elementary school or shopping mall. Remediation requirements may make it impractical to reduce risk of contaminant exposure to levels required for such "high" levels of land use.
- Estimate the impact of site environmental conditions on the property's value. Develop a firm estimate for remediation costs. Understanding the costs of remediation will provide the seller with information required to negotiate the sale of the property. The seller may elect to perform site remediation prior to offering the property for sale or he may elect to offer to reduce the selling price or establish an escrow account to cover estimated remediation costs.

This paper suggests specific steps for planning and implementing industrial property environmental assessments. Steps include establishing objectives, assessment planning, historical review of facility operations, field data acquisition and data interpretation and presentation. The site history, combined with information from the field investigation, provides specific information regarding potential environmental

concerns at the site. This information then can be used by the owner to evaluate the potential impact of environmental conditions on the property transfer.

The case histories presented in this paper discuss applications of these techniques for environmental assessment programs at two closed industrial facilities. The paper summarizes steps taken at each facility including: identification of suspected contaminated areas; field investigation methods and findings; and development of remediation alternatives for areas of concern.

ENVIRONMENTAL ASSESSMENT APPROACH

Industrial property environmental assessments may be conducted at active or inactive industrial facilities, at property located within industrial parks or at sites where industrial or manufacturing activities are known or thought to have occurred. This paper and the case histories presented herein specifically address the performance of environmental assessments at inactive industrial sites where the recent history of site operations is reasonably well defined.

The following steps are recommended for conducting industrial property transfer environmental assessments:

- Develop a history of the site
- Develop a detailed site investigation plan
- Implement the site investigation
- Evaluate and present the data
- Develop remediation alternatives and estimate associated costs

Each step is discussed in greater detail in the following subsections.

Develop Site History

Sites with long histories of industrial use require that particular attention be paid to past operations on the site. Attitudes, regulations and generally accepted environmental management practices have changed dramatically, even in the past 15 to 20 yr. These changes can have a significant impact on a property's environmental condition. The development of a site history is important, therefore, to assist in evaluating where to look and what to look for regarding site environmental conditions. The following important factors may be considered in developing a site history:

- General site description and history
- Identification of key physical features of the site including buildings, storage areas, topography, geology, operational areas, processing facilities, underground storage tank locations, etc.
- Identification of groundwater use in the area that may impact or be impacted by site activities
- Identification of adjacent properties and activities that may impact or be impacted by site activities
- Site environmental management history

Information for developing the site history may be obtained from the following public and private sources:

- City, county, state and federal records
- Client records including site and utility plans (present and past); previous site investigations and reports; NPDES, RCRA or other permits; aerial photographs; waste manifests; material safety data sheets; spill prevention control and countermeasure (SPCC) plans; and records of spills or other accidental releases of hazardous materials
- Site personnel interviews focusing on general site history, operations and site environmental practices

Develop Site Investigation Plan

The site history and a detailed visual survey of the site provide the basis for developing a site-specific field investigation plan. The site investigation plan provides the following key information:

- Proposed sampling locations and their basis for selection
- Contaminants of concern at each proposed sampling location
- Specific detailed procedures for selected field investigation techniques such as soil borings, soil gas surveys, groundwater monitoring well construction and sampling, electromagnetic surveys, etc.
- Laboratory analytical methods
- Quality assurance/quality control procedures
- Health and safety procedures for conducting site operations

The site investigation plan is a working document written for use by the field investigation team. The procedures and techniques discussed therein should be clearly and concisely presented to provide clear direction for field operations. The site investigation plan is an important document that will define the type and extent of data to be obtained during the field investigation.

Implement The Site Investigation

Implementation of the site investigation involves implementation of the techniques and procedures outlined in the detailed site investigation plan. The site investigation may be carried out in two distinct phases; the premobilization site visit and the site investigation. The premobilization site visit provides the opportunity for key members of the field team to become familiar with the site and increase the efficiency of the full site investigation team. Suggested key objectives for the premobilization site visit include identifying and personally contacting existing and former key facility personnel; locating and staking proposed sampling locations; obtaining clearance from facility personnel for utility conflicts at selected sampling locations; establishing a schedule for coordination with existing facility operations; and identifying areas for establishing decontamination and command post areas at the site.

After completing the premobilization site visit, the full field investigation team may be mobilized and the detailed site investigation plan can be implemented.

Evaluate and Present Data

Data review, evaluation and presentation is the cornerstone for evaluating site environmental conditions and establishing a plan of action or negotiating stance to address environmental concerns. Acceptable environmental standards must be established to compare against site data. Suggested evaluation criteria include:

- Are contaminants present at levels in excess of local, state or federal regulatory limits?
- Are contaminants present at levels significantly in excess of background levels?
- Are contaminants present at levels which exhibit risks to human health or the environment?

Develop Remediation Alternatives

A significant portion of an industrial property environmental assessment may be the development of remedial action alternatives and associated estimated costs. Development and evaluation of remedial alternatives may include efforts ranging from the evaluation of a few simple alternatives to the detailed evaluation of numerous alternative technologies and combinations of technologies. Presentation of the

team's findings may be limited to a simple project memorandum or it may require a substantial written report including hundreds of pages, not unlike a Superfund feasibility study. The level of effort, cost, degree of confidence and amount of required detail generally will be determined by the owner's need for information. Information needs and corresponding degree of confidence likely will be less for an owner's preliminary budget-level assessment than for an assessment to be used for negotiating property value impacts.

Elements of the preceding approach were used to plan and conduct environmental assessments at two inactive heavy industrial facilities. Both studies represent cases in which industrial activities were conducted on the properties for many years. In the first case, the site had been an active World War II-era industrial site for more than 40 yr, first as an aircraft manufacturing facility and then as an automobile assembly facility. The second case history describes an industrial site which was active as a railroad maintenance facility for more than 100 yr.

CASE STUDY ONE

Case Study One involved the investigation and assessment of an inactive automobile assembly facility. The facility operated for approximately 45 yr with production discontinued in May, 1987. Prior to its use for the assembly of automobiles, the facility was used for the production of military aircraft. The Case Study One site is shown in Figure 1.

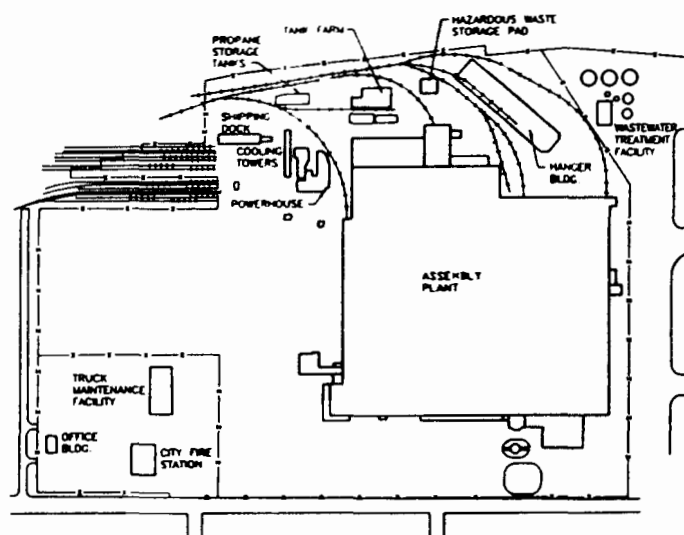


Figure 1
Case Study One Site Plan

Planning

The following principal objectives were established for this environmental assessment:

- Identify potential areas of contamination present on the interior and exterior of buildings at the site
- Review and summarize available site hydrogeologic/geologic information
- Estimate the nature and extent of contamination based on specific and finite data
- Identify and evaluate alternatives for cleanup or mitigation of contaminated areas

Exterior areas of potential contamination were identified by the facility owners. Areas were targeted based on their current or past use or storage of hazardous material. The following major exterior areas were focused upon:

- Underground storage tanks
- Acetylene generation sump
- Roof surfaces near paint and body shop ventilation exhausts
- Above ground tank farm
- Hazardous waste storage areas

Interior areas of concern were selected by identifying elements of the production process involving regulated materials. Examples of interior areas of concern include the following:

- Train wells for delivery and disposal of materials
- Paint removal molten salt bath and salt bath baghouse
- Paint storage areas
- Paint booths and drying ovens
- Metal coating areas
- Metal assembly areas
- Welding and soldering areas
- Elevators and equipment storage areas

Implementation

All soil boring and monitoring well locations were reviewed and approved by a facility representative prior to drilling. A major concern was location of utilities (i.e., fire, electrical and gas lines). The sampling team had requested and received complete and detailed site plans identifying underground utility locations. Current utility information along with facility personnel approval of sampling locations reduced the risk of conflicts with underground utilities.

The site investigation was conducted in two phases. The Phase I investigation was conducted in August, 1987. The site exterior was the main focus of Phase I with the objective being to identify specific contaminants in the soil, underlying groundwater and on specific areas of the plant roof (i.e., paint booth exhaust areas).

The Phase I investigation resulted in the completion of 41 soil borings to a depth of 30 ft each with one soil sample collected at each 5-ft depth interval and a groundwater sample taken from each boring. Permanent monitoring wells were installed at five of these locations. In addition, 12 soil borings were completed to a depth of 5 ft each with one soil sample collected from each boring. Phase I field activities were completed in approximately 10 working days.

The Phase II investigation was complete in January, 1988. This investigation's primary objective was to identify areas of concern in the plant interior with additional sampling on the plant exterior to better define the extent of soil and groundwater contamination identified during Phase I. The Phase II site investigation was completed in 12 days with one interior and two exterior sampling teams. The investigation resulted in an additional 24 soil borings, 12 of which were completed as permanent monitoring wells.

Results

The two-phase field investigation effort resulted in collection of over 800 samples including concrete and roof core samples, wipe samples, scrape samples, soil samples, water samples and groundwater samples.

The final site investigation report identified several areas on the exterior and interior of the facility requiring some form of cleanup or mitigation. Based on the results of the investigation, alternative cleanup technologies were identified and recommendations were presented to remove, contain or treat contaminants in the unsaturated soil and the groundwater at the site and in selected areas of the plant interior. The estimated cost for recommended remediation alternatives total \$2.7 million.

CASE STUDY TWO

Case Study Two involved the investigation and assessment of an inactive railroad locomotive maintenance facility. The facility had been in operation for approximately 100 yr, its principal function being to rebuild locomotive and railcar component parts for supply to individual repair locations. Shop operations ended in January 1989, and various site closure activities are currently being conducted. The Case Study Two site is shown in Figure 2.

Significant past operations on the property include an open drum storage area, buried fuel lines, closed underground storage tanks, oil sumps, hazardous waste storage area, drum washing area, electrical transformer storage area and an industrial wastewater treatment plant.

Planning

The following principal objectives were established for this environ-

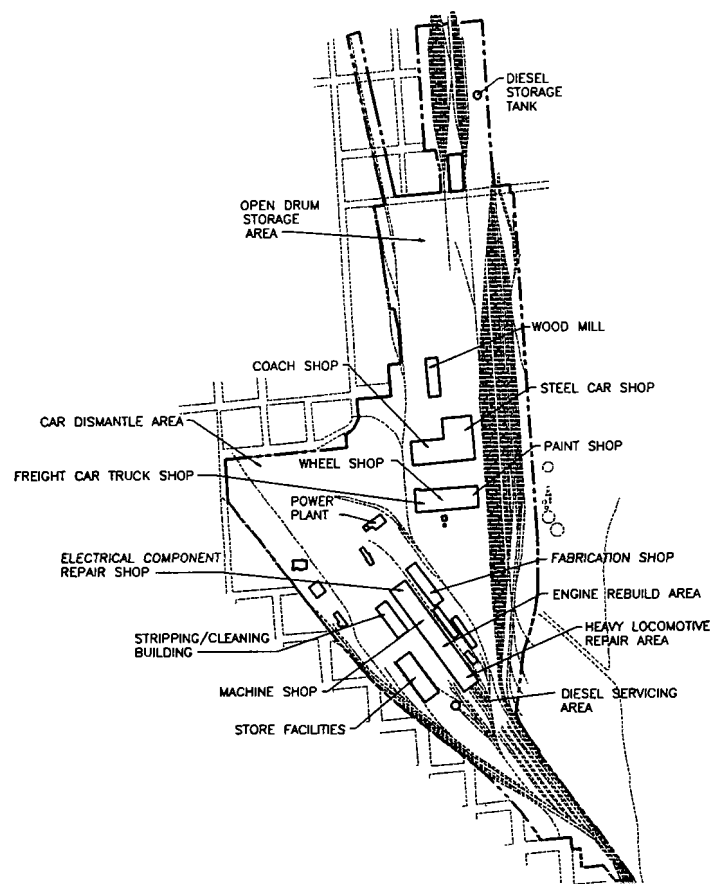


Figure 2
Case Study Two Site Plan

mental assessment:

- Identify areas of contamination at the site which may limit future use and/or result in significant remediation costs that may restrict its use due to the contamination
- Identify site conditions which may, depending upon anticipated future use, expose site occupants to potentially hazardous substances
- Identify areas of contamination which exhibit contaminant concentrations which may be of environmental concern

Areas of potential contamination were identified by the facility owners. Documentation showed these areas had used hazardous materials in their respective processes. The following major areas were focused upon:

- Above ground and underground storage tanks
- Open drum storage area
- Hazardous waste storage area
- Fuel storage areas
- Electrical transformer storage areas
- Power plant
- Car demolish area
- Car dismantle area
- Locomotive fueling area
- Car switching/holding areas
- Car shop
- Wheel shop
- Paint shop
- Traction motor shop
- Bearing removal shop

Developing the site history required reviewing archived facility site plans. Many of the drawings are estimated to be 70 to 80 yr old. Areas which may represent potential environmental hazards were identified and addressed in the site investigation plan.

Senior and retired facility personnel were interviewed to help identify

the locations of facilities which had previously been removed or demolished. The following operational areas were focused upon:

- Wheel babbitt shop
- Oil/gasoline unloading house
- Oil pump/sump area
- Acetylene generation sump
- Paint barrel disposal pits
- Steam locomotive asbestos removal area
- Old traction motor shop

Implementation

Utility locations presented a major concern, given the long history of the site. As old operational areas were closed, destroyed and replaced, underground utility lines were drained, capped and abandoned in place. These utility line modifications often were not included when blueprints of the facility were updated. To compensate for this potential lack of data, all soil boring and monitoring well locations were reviewed and approved by the facility electrical and water departments prior to drilling to reduce the risk of utility conflict.

The site investigation was conducted in two phases. The Phase I investigation was conducted in February, 1989. This phase included the collection of 26 area soil composite samples at depths ranging from 1 to 10 ft. In addition, 12 permanent monitoring wells were installed to a depth of 20 ft each. Due to weather delays this phase was completed in approximately 3 wk.

The Phase II investigation was completed in August, 1989. This investigation's primary objective was to characterize the historical production areas. The Phase II investigation was completed in approximately six days. The investigation included installation of an additional 5 monitoring wells and 41 soil borings to a depth of 5 to 10 ft each.

Results

The overall field investigation effort resulted in the collection of over 200 soil and groundwater samples. At the time of this writing, the final site investigation report was in final production. Several areas of the facility will likely require some form of cleanup or mitigation. Based on the results of the investigation, alternative cleanup technologies will be identified and recommendations will be presented to remove, contain or treat contaminants in the soil and groundwater at the site.

CONCLUSION

Industrial property environmental assessments have become an integral part of industrial property closures and transfers. Property assessments can identify potential environmental liabilities and assist the owner in evaluating their impact on property values. The information provided by environmental assessments allows the owner to understand the environmental condition of the property and develop strategies for implementation of remediation, closure and transfer of the property.

Property Transfer Evaluations: What Have We Learned About Limiting Liability?

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ABSTRACT

In our 1988 Superfund Conference paper that discussed liabilities associated with the performance of Property Transfer Evaluations (PTEs), we examined several areas of possible liability for consultants. These areas of potential liability included contractual language, time-frame, proper sampling and analytical techniques, interpretation of results and integrating PTEs into business decisions regarding a property purchase. In the past year, several other factors that can affect consultants' liability have arisen, including definition of state-of-the-art methods, qualifications of personnel conducting PTEs, release of PTE reports, incorporation of other consultants' reports, confidential acquisitions and disposal of investigation-derived waste materials.

This paper, however, will focus on methods to limit PTE liabilities for the owners/operators of existing facilities. Such methods include environmental compliance audits, waste minimization programs, recycling/reuse/recovery, completion of remedial and corrective actions, compliance and management monitoring, record-keeping and employee training. We will show that a realistic assessment of facility compliance, coupled with a comprehensive management program, will reduce liabilities associated with property transfers when the facility is sold.

REVIEW OF CONSULTANT LIABILITY

Our 1988 paper¹ focused on methods to reduce consultants' liabilities associated with the performance of Property Transfer Evaluations (PTEs). Some of these liabilities included those associated with contractual language, time-frame, proper sampling techniques and integrating PTE results into business decisions.

Consultant liability can be limited with effective contract language, including a well-defined scope of work, clauses indemnifying the consultant against third-party actions and limitation-of-liability clauses.

The time-frame is important for two reasons: (1) the schedule for the project and (2) the schedule for the transaction closing. It always seems that the call for the PTE comes on the Tuesday before the Friday closing. The client must allow adequate time to plan and complete the project before a final decision can be made regarding property purchase.

Proper sampling and analytical techniques are essential to a properly conceived and executed PTE. We recommend U.S. EPA-approved sampling and analytical protocols, or applicable state regulatory agency-approved protocols, since the data may ultimately be compared to agency data. In addition, agency-approved protocols can be regarded as standard practice.

Integrating the PTE into business decisions regarding the purchase is the client's responsibility. Factors such as cash flow, tax rates and property values are beyond the scope of the PTE. The client must take the environmental information provided in the PTE and add it to these other factors to make an informed decision. The consultant is not in a position to make a recommendation regarding purchase.

RECENT LIABILITY CONCERNS

In the last year, other situations that can contribute to consultants' liability have been identified and should be taken into account when performing a PTE. These considerations include definition of state-of-the-art methods for PTEs, qualifications of personnel performing PTEs, release of PTE reports, incorporation of other consultants' reports, confidential acquisitions and disposal of investigation-derived wastes. Each of these matters can become important both in completing the PTE and in limiting the consultant's liability.

State-of-the-art methods for PTEs have not been successfully defined yet. As case law builds, however, it appears that a PTE conducted without subsurface investigations may not be classified as "appropriate inquiry." It is important for PTE consultants to closely follow developments on the legal front and seek appropriate legal counsel. Other attempts at method definition include the National Sanitation Foundation attempts to formulate a "standardized" method for PTEs. There may be some inherent problems in standardizing an approach to investigations that, by their nature, differ on a case-by-case basis, but we should watch for developments on this front.

Qualifications of personnel conducting PTEs is another area where there have been recent developments. The State of California sponsors a registration program for environmental assessors based on their relevant experience. The State of Indiana recently passed a law requiring that environmental documents signed by a Professional Engineer also be signed by a Certified Hazardous Materials Manager. While it may be some time before this system is implemented, a responsible consultant will use personnel whose background and experience match the demands of the specific investigation.

Release of PTE reports can become an issue if a property is resold in a short period of time or if the original sale does not occur and a new buyer is found. The report should state that it was prepared under a specific circumstance and may not be applicable to any other situation.

Similarly, incorporation of other consultants' reports into a PTE should be done with appropriate disclaimers, especially if the other reports are investigative in nature, since liability for the conclusions of one consultant might accrue to another who used the report.

Confidential acquisitions, especially of operating facilities, can present difficulties for the completion of a PTE. Since every situation is different, the exact scope must be discussed with and agreed upon by the client. If access to the plant or property is not included in the contract, the scope must state the limitations under which the report can be used. The report itself should mention that the investigation and recommendations were based only on the activities that actually took place.

The last area of potential liability that should be mentioned here is the disposal of investigation-derived wastes. It is critical that the con-

tract specify who is responsible for the manifesting, transport and disposal of such wastes, especially if they are hazardous. This responsibility is usually the owner's, but can be placed, if appropriate, on the potential buyer. It also may be possible that such wastes can be left on-site for disposal during the cleanup activities. If storage is used, regulatory requirements regarding storage must be observed.

LIMITING OWNER/OPERATOR LIABILITY

The main topic of this paper concerns ways to limit owner/operator liability associated with an operating facility when the time comes for a property transfer. In general, we believe that a realistic compliance assessment combined with a comprehensive management program can reduce the potential liabilities and problems associated with PTEs.

Specific activities that should be included in this liability reduction program include a complete environmental compliance audit, waste minimization surveys, recycling/reuse/recovery studies, implementation of remedial or corrective actions, compliance and management monitoring, record-keeping and employee training.

Environmental Audit

The first step is a complete, realistic environmental compliance audit. We say realistic because some compliance audits reflect only one area of environmental compliance, such as wastewater discharges. A realistic audit evaluates all applicable environmental regulations and the state of current and historic compliance within the facility. Such audits have been recognized by the U.S. EPA as effective means of controlling discharges to the environment, documenting facility compliance, determining the facility's ability to maintain compliance and identifying needs for corrective actions. The audit report should present a detailed picture of facility compliance with air, water, solid waste, hazardous waste, toxic substances, drinking water, community right-to-know, underground storage tanks and other applicable environmental statutes and regulations. In addition, recommendations for corrective actions to achieve compliance should be included.

The compliance audit is important for a property sale because it documents areas of potential liability for the owner/operator, whether buyer or seller. The audit document can be an important source of data for the background information review.

Waste Minimization Survey

Coupled with the compliance audit, a waste minimization survey can identify methods or areas where waste generation can be reduced. In general, facility operations can generate wastes at the raw materials handling, storage, process chemical use, maintenance, finished materials handling and disposal stages of operations. Improved "housekeeping," use of only necessary amounts of chemicals, safe storage procedures, good maintenance practices and proper treatment or disposal methods, all represent target areas where waste generation can be minimized. Sometimes process engineering changes are required to reduce waste generation, but in many facilities, a simple commitment to more effective storage, handling and maintenance practices can result in a significant waste volume reduction.

The waste minimization survey is important for a property sale because it provides process and raw material documentation, along with methods used to reduce wastes and discharges.

Similar to a waste minimization survey is a study of recycling, reuse and recovery options within the facility. The study can identify: process streams that can be recycled or reused in operations; areas where raw

materials or wastes can be recovered and reused; and methods to alter process operations to reduce the required amounts of chemicals needed, therefore reducing the amounts of waste generated. This study also can provide detailed process documentation at the time of a property sale and economic data on materials and process costs that may figure into the structuring of the property transaction.

Corrective Actions

As a result of the above studies, the need for corrective actions or remedial cleanups will be identified. Implementing these actions and documenting their completion are critical elements in both improving facility compliance and reducing potential liabilities associated with waste management practices. Even though some remedial actions, such as groundwater treatment, can be expensive, implementing them can be cheaper in the long run than waiting for a regulatory agency to institute cleanup actions. In addition, the cost of a remedial action can affect the final sale price of a property, especially if hazardous substance releases have been cleaned up.

Monitoring

Keeping the facility in compliance once the above studies and corrective actions have been completed requires monitoring, record-keeping and training. Compliance monitoring for permit restrictions and facility performance usually is specified, but an effective management monitoring program is necessary to implement waste control measures. Management monitoring entails oversight of general work practices and continuous investigation for ways to further reduce waste generation. Management monitoring also includes close attention to record-keeping and reporting requirements under the various environmental regulations. In addition to fulfilling these requirements, a well organized record-keeping system can speed up the background data review if the facility is to be transferred. Additionally, it can provide documentation of corrective actions and other cleanup activities.

Employee Training

A management commitment to facility compliance is only as good as the employees' commitment to work practices that support compliance. A comprehensive training program is necessary for employees to understand the management philosophy regarding environmental compliance and to implement proper work practices. The management commitment must extend beyond simply providing required training programs. It should include opportunity for meaningful employee input on compliance issues, work practices, continuous training programs and employee incentives where appropriate. The importance of training programs to a property sale is apparent if waste generation is reduced, compliance is maintained and releases of hazardous substances are eliminated.

CONCLUSION

In summary, existing owner/operator liabilities associated with hazardous wastes can be significantly reduced or even eliminated at the time of a property transfer through a combination of compliance assessment, waste minimization, corrective actions and a comprehensive management monitoring program.

REFERENCES

- 1 Duffala, D.S. and Boyd, K.A., "Methods for Conducting Property Transfer Evaluations: Limiting Liability," *Superfund '88, Proc. of the 9th National Superfund Conference*, pp. 55-66, Silver Spring, MD, 1988.

Monitoring in Reduced Oxygen Atmospheres Using Portable Survey Direct Reading Instruments (PID and FID)

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ABSTRACT

Portable Survey Direct Reading Instruments (DRIs) utilizing both photoionization and flame ionization detectors play important roles for organic contamination delineation in both air, soil and water. These instruments have been used extensively in industrial hygiene applications and most response patterns are well documented. Key to this documentation is that most sensitivity values, and response factors are measured in ambient air, with oxygen levels at normal breathing levels.

For the vast majority of DRI applications, such as air monitoring for personnel exposure, the normal operating procedures and instrument calibration are satisfactory to obtain reliable exposure assessments. However, some waste site applications often have requirements that go beyond normal conditions. Applications that require special consideration are; soil gas analysis for an underground plume identification, soil sample biasing for choosing a worst case sampling location and confined space entry into petroleum storage tanks or chemical tank cars. A key factor that can influence the exposure results of DRIs is the effect of reduced levels of oxygen present in the sampling atmosphere.

The focus of this paper is to examine the performance of DRIs in monitoring applications where reduced oxygen levels are present. By examining calibration standards prepared with various reduced levels of oxygen in the background air matrix, we can establish the performance characteristics of the various DRIs. In turn, this performance should establish trends that will demonstrate the overall effect oxygen has on general survey readings.

The effect of reduced oxygen and the varying humidity levels are significant factors why DRIs analytical information can be improperly biased, making the field data unrepresentative of the actual concentrations present. Therefore, the overall goal of this paper is to suggest potential correction factors that will allow the analyst to better use DRIs to provide a more realistic and informative assessment of organic contaminate exposures when analyzing reduced oxygen atmospheres.

INTRODUCTION

Monitoring atmospheres with reduced levels of oxygen is always a key personnel safety concern when accessing potential hazards at waste sites. For site personnel, once an oxygen-deficient atmosphere has been established, proper precautions can be taken for entry and other environmental hazards can be accessed. What is not so apparent to most analysts is how the effects of an oxygen-deficient atmosphere can influence the measurement of volatile organics on portable survey direct reading instruments. Therefore, in applications where there is a possibility of less than normal breathing levels of oxygen present, the readings that DRIs establish will be influenced. Applications where

this oxygen influence can occur are survey soil gas analysis, plume identification, sample biasing and confined space entry. A generalized effect that monitoring in reduced oxygen atmospheres has on all survey FID and PID instruments is the following: the oxygen level goes down, the instruments' response ratios will go up, thereby inflating the true survey concentration that would be expected under normal operating conditions. As the following experimental data indicate, all instruments tested exhibited an effect when operating in reduced oxygen atmospheres. A response difference that probably was expected using an FID detectors also was found when PID detectors were employed, with some designs showing more effects than others.

INSTRUMENTAL

Nearly all of the direct reading instruments that are used in environmental applications were designed for industrial hygiene use for occupational exposure to chemicals. The primary instruments using photoionization based detectors are HNU Systems PI 101, Thermo Environmental 580A and Photovac Tip II. The primary flame ionization system is the Foxboro Century OVA128.

The basic principle of operation of all of these instrument is the ability to perform real-time air analysis to determine the level of volatile organics and, in some cases, inorganics. For field environmental applications, these instruments are used as screening tools. They are able to provide a unique survey analysis capability allowing a qualitative trending of environmental contamination.

These instruments provide survey concentration values in ppm equivalents, either isobutylene benzene or methane that can be related to other pure substances by response factors. All of these equivalents are based on the use of air that is the matrix for the introduction of the trace contaminants. Air contains approximately 20 to 21% oxygen and all DRIs calibrations are based on this. When the oxygen ratio changes, the instrument calibrations are no longer valid in reference to the equivalent readings under normal conditions. Unfortunately, there are many applications where the ratio of nitrogen and oxygen change, which can cause the trace organics to either be enhanced or reduced from their true concentrations. Therefore, in approaching anaerobic or oxygen enhanced atmosphere, one must first determine the oxygen level present before analyzing for volatile organics.

GENERAL APPLICATIONS

Soil Gas, Plume Identification

When performing soil gas analysis, many different methods are employed. However, the most important aspect is the subsurface gas sampling technique. Ideally, the gas to be examined is only subsurface at a known depth representing a generalized area. This gas is collected by the evacuation of the interstitial soil space. A device that allows the

passage of the atmosphere is driven into the soil to the depth of interest, sealed off at the point of entry and then the gas is collected and is directly or indirectly (Tedlar bag) analyzed by a survey DRI to determine the relative concentration present.

The problem with this approach is not in the analysis technique, but is in the subsurface atmosphere which does not necessarily contain the same atmospheric gas concentration as the surface air. Depending on the geological features, the ratios of nitrogen to oxygen can affect the survey DRI values quite substantially. The net effect can cause suspended contamination to be greatly misrepresented as to its actual equivalent value. This effect in soil gas is demonstrated by analysis at various depths in order to determine the downward contamination migration. If the permanent gas ratios become anaerobic (i.e. diminishing oxygen concentration) as you explore deeper contamination then the results will be based on different gas ratios which will affect the basis of the instrument's direct reading survey equivalent calibration. Therefore, when using a survey direct reading instrument as a diagnostic tool for relative organic contamination the oxygen level also must be evaluated in order to truly compare the instrument analysis results at locations that may differ in oxygen concentration.

This effect of reduced oxygen can be expected to effect applications such as plume identification, and soil sample biasing where the soil is disturbed in order to allow gas trapped to migrate to an area where it can be directly sampled. The analysis effects would be similar, reporting higher than expected organic concentrations in areas that are anaerobic and also have organic contamination present. This would be less subject to large shifts as atmospheric mixing would reduce the level of anaerobic character.

Another area where incorrect volatile assessments could be made is in the area of confined space entry, i.e. refinery tanks. These cases do have the advantage of a known reduced oxygen atmosphere yet not applying a correction factor again would misrepresent the volatile hazard present as toxic gases.

EXPERIMENTAL

Each instrument was calibrated to the manufacturers specification. The photoionization instruments were calibrated by using a prepared cylinder of isobutylene gas $\pm 5\%$ at four concentration levels. The calibration concentrations were 9.1, 49.7 ppm, 94.1 and 290 ppm. The Photovac Tip II and the 580A report their data in isobutylene equivalent; the HNU PI 101 was adjusted to read isobutylene equivalent form benzene equivalent. This process allowed all PID instruments to be examined on a comparative basis. Since the flame ionization Century OVA reports its data in methane equivalent, a multipoint response table was created so it also would report its data in isobutylene equivalent. The OVA demonstrated good linearity with isobutylene and the response factor determined was twice the methane equivalent reading.

The reduced oxygen atmospheres were made using prepared cylinders of five different oxygen balance nitrogen mixtures. The value of oxygen used were 17.56%, 14.6%, 11.56%, 8.46% and 0.0%. The standards were made by flowing known volumes of the nitrogen-oxygen mixtures into a 10-2 Tedlar Bag, injecting a known amount of pure isobutylene via a syringe into the bag and mixing it with H_2O/N_2 mixtures. Each bag was then analyzed via a FID gas chromatograph to determine the actual amount of isobutylene present.

In order to examine every DRI's stability, each was span checked for drift using 49.1 ppm isobutylene calibration mixture. Upon successful examination of the span check, each instrument was connected and allowed to sample the prepared isobutylene reduced oxygen bag until the maximum instrument reading was observed. In all cases the time allowed for sampling was greater than the manufacturer suggested response time in order to assure 95% of value recorded.

Each instrument then evaluated each reduced oxygen atmosphere at four to five different isobutylene concentrations, between 0 to 300 ppm, in order to determine its performance over a typical analysis range. All data were measured in progression from high concentration to low concentration levels.

FLAME IONIZATION DATA

Century OVA128

The Century OVA uses a two gas FID instead of a three gas FID that usually is found in laboratory equipment. A two gas FID does not require a cylinder of air to support the combustion of the flame; instead, it uses the oxygen present in its sample matrix to support its combustion. The OVA uses a fixed flow of hydrogen, approximately 10 to 12 ML/min and sample air from a diaphragm pump approximately 1 to 1.2 L/min to achieve the detector state required for volatile organic detection. Therefore, when the oxygen concentration is reduced, the ratio of hydrogen to oxygen changes and affects the detector chemistry of the hydrogen flames' combustion until a point is reached where the flame no longer will burn.

Using a Century OVA128 without the GC option, we determined that detector flame-out will occur in atmospheres less than 11% oxygen. Therefore, the OVA was tested in only three reduced oxygen concentrations in which it could successfully operate. When using OVA with the GC option, this flame-out level could shift to higher oxygen levels due to the back pressure that can occur because of the GC column.

The response curves illustrating OVA's performance are found in Figure 1. In general, as the level of oxygen is reduced, the response from the OVA becomes non-linear. At the 17.56% level, the instrument maintains a slight non-linear response showing greater distortion at high levels and minor change at low levels. The 14.6% level followed a similar pattern, with the response factors increasing to 2.32 or 132% increase at about the 14.6 high value. This effect continued to grow larger as the 11.56% level was evaluated. At this concentration, we found the most excessive non-linearity; at the highest concentration level, the OVA reading was 444% above the known concentration. At levels lower than 11.56%, the OVA flamed-out.

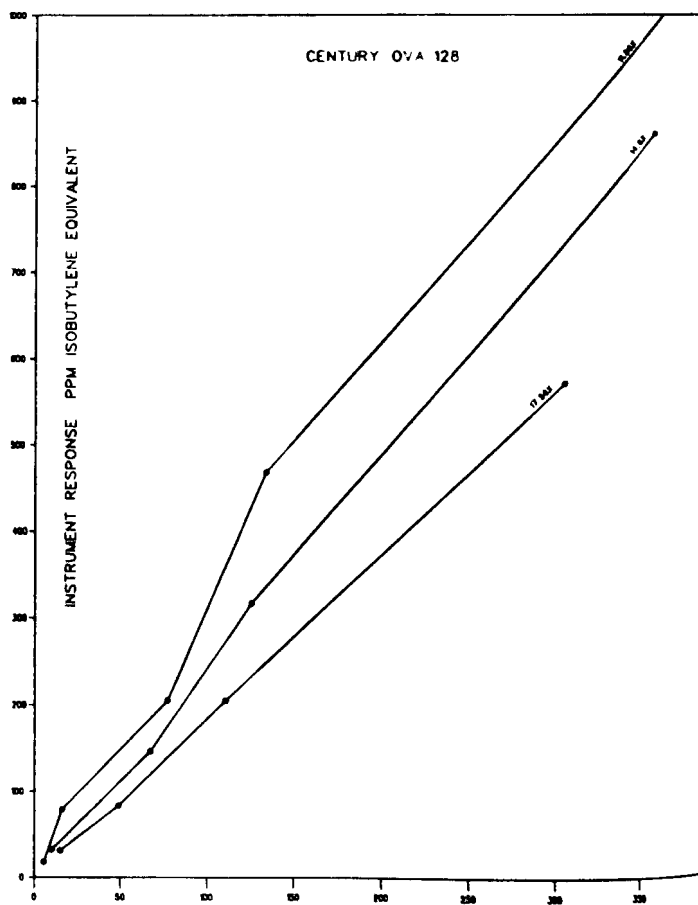


Figure 1
(Known Concentration) PPM Isobutylene

The OVA was tested to examine its behavior in clean non-spiked atmospheres of reduced oxygen. Here we found that as the oxygen level was reduced, the OVA responded by shifting its baseline to lower levels, in effect producing negative readings. This is shown in Fig. 1A. The greater the oxygen levels, the less the magnitude of the negative shift. This shift and the creation of a hydrogen rich flame might help provide an answer to negative field readings with an OVA. Examining the 10 x level, one can see a 24% negative shift in the OVA response when sampling the 11.56% and only an 8% negative reduction in the 17.56% oxygen atmosphere.

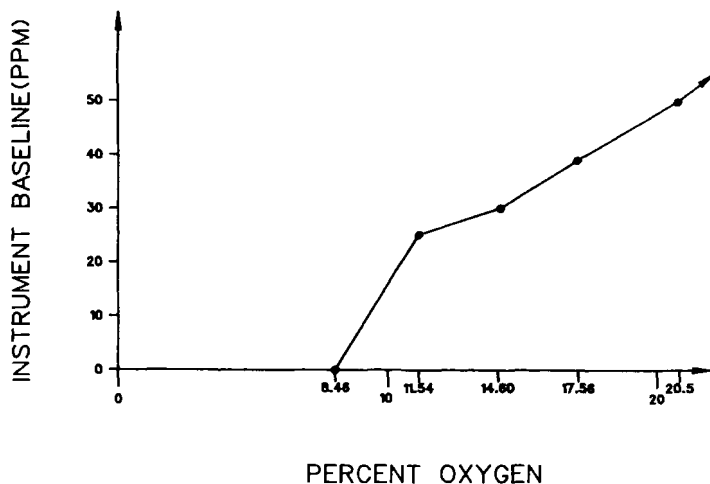


Figure 1A
OVA Reduced Oxygen Baseline Shift

PHOTOIONIZATION DATA

Photoionization-based instruments have been reported to be matrix-independent and specific to the relationship of lamp energy and the substances ionization potential being examined. If this principle can be applied to reduced oxygen atmospheres, then PID could be the instrument of choice for this application. However, recent papers have suggested that the above observation is flawed. The fact that relative humidity¹ and percent levels of methane² have demonstrated a substantial effect on PIDs has greatly complicated the normal waste site assessment methods.

The mechanism for a PID is described by the following equation where: $R + h\nu \rightarrow R^+ + e^-$ where R is an un-ionized ionizable species, R^+ is the ionized species, $h\nu$ is an ultraviolet photon and e^- is a free electron.

Since oxygen has the ability to absorb ultraviolet light, then calibrations in a normal air matrix will be dependent on the amount of oxygen present³. Therefore, the operation of a PID in a normal air matrix 20 to 21% oxygen is present in the steady-state of the detectors operation. If the level of oxygen is reduced, more UV photons will be available for ionizing extra ionizable molecules, if the lamp energy remains constant. Therefore, given a fixed concentration of isobutylene, as the oxygen level declines, the instrument response increases, which is illustrated by the graphs of the various PID analyzers. In contrast to FID performance, PID do not show significant effects from reduced oxygen until the atmospheres reach the 11% to 14% level.

HNU PI 101

Figure 2 demonstrates the oxygen response curves of the PI 101 using a 10.2eV lamp. Examination of the 17.56% oxygen level show a limited effect from atmospheric response levels. The effect appears mainly in the four other oxygen levels; 14.6%, 11.56%, 8.46% and 0.0%. The PI 101 showed the most significant effect at levels under 100 to 150 ppm, exhibiting lesser effects at higher ranges causing the graphs to be non-linear assuming a parabolic shape. In general, a comparison

of mid-range average concentration of 50 ppm provided an oxygen enhancement effect of 188% for 0.0%, 60% for 8.46%, 40.0% for 11.56% and 40% at 14.6% oxygen vs the known concentration value. This effect at the 17.56% oxygen level only enhanced the reported value by 12%.

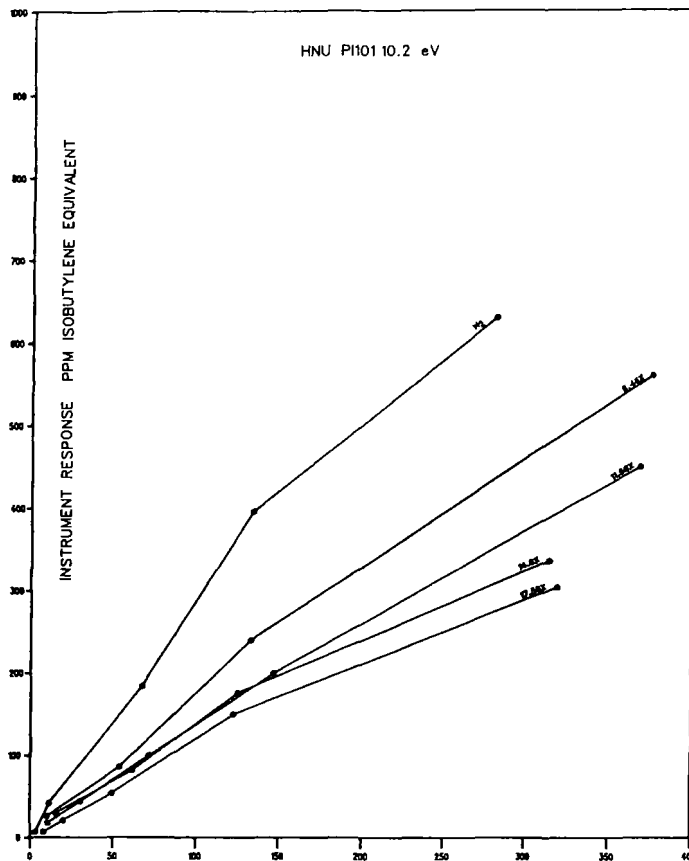


Figure 2
(Known Concentration) PPM Isobutylene

Our efforts to examine the 11.7eV lamp clearly showed that oxygen falls somewhat within the ionization window of Argon lamp. The effect of lower oxygen levels has an exponential effect and therefore it has limited useful application in areas where reduced oxygen monitoring is required.

Thermo Environmental 580A

We evaluated the 580A using 10.0eV lamp and found its performance patterns to be good at low level concentrations. However, at concentrations above the 70 to 300 ppm range, the response ratio increased significantly, causing a non-linear response in this region. The oxygen response curve is shown in Figure 3. In general, the 580A reported less oxygen enhancement at the 50 ppm level than the HNU PI 101.

In 0.0% oxygen, the 580A responded 84% higher than the known concentration, which is an improvement from the PI 101 value of 188%. We were unable to examine an 11.8eV lamp in the 580A but, based on design similarities between the instruments, we would expect comparable performance and caution the use of 11.8eV ionization source in a reduced oxygen environment.

Photovac Tip II

The Tip II uses a microwave method of source excitation, and in this application clearly performed well in reduced oxygen atmospheres. We examined the Tip II using its standard 10.6 eV ionization source. The Tip II showed only minor oxygen enhancement in all reduced oxygen atmospheres under 100 ppm. For example, at a mid-range 50 ppm

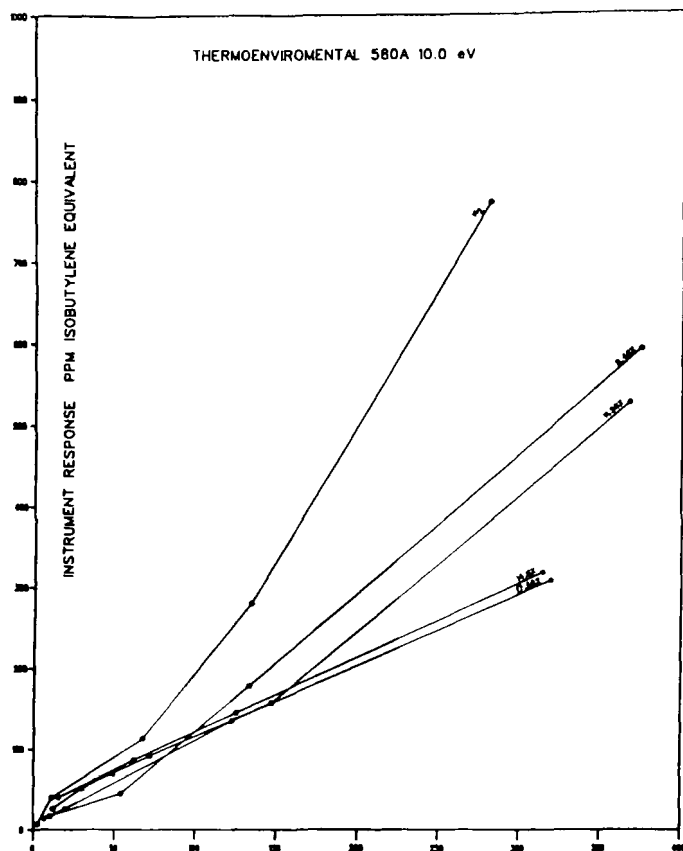


Figure 3
(Known Concentration) PPM Isobutylene

isobutylene concentration in 0.0% oxygen (pure N_2), the instrument only exhibited at 23% enhancement. In comparison, both the PI 101 and 580 were eight to three times more responsive at the same calibration concentration. In values above 100 ppm, the Tip II also showed non-linearity. However, its slope was much more mild, with the response factors generally increasing. Figure 4 shows the reduced oxygen plot for the Tip II. Overall, the Photovac Tip II exhibited the most limited effect from reducing the oxygen levels.

CONCLUSIONS

As the data illustrate, it is important to monitor for reduced concentration of oxygen when performing survey analysis with a PID or FID DRI. In both cases when the oxygen levels are lowered the instruments are no longer reporting data in a methane- or isobutylene-equivalent calibration. The relative effect of reducing the oxygen level enhances the reported values. This effect can be quite large in anaerobic atmospheres and can vary among the instrument types. Based on our experiments, we found that Photovac Tip II showed the most limited effect for general use in reduced oxygen atmosphere with no compensation for the fact of less oxygen.

Every instrument evaluated demonstrated enhanced performance in reduced oxygen environments. With that in mind, each instrument

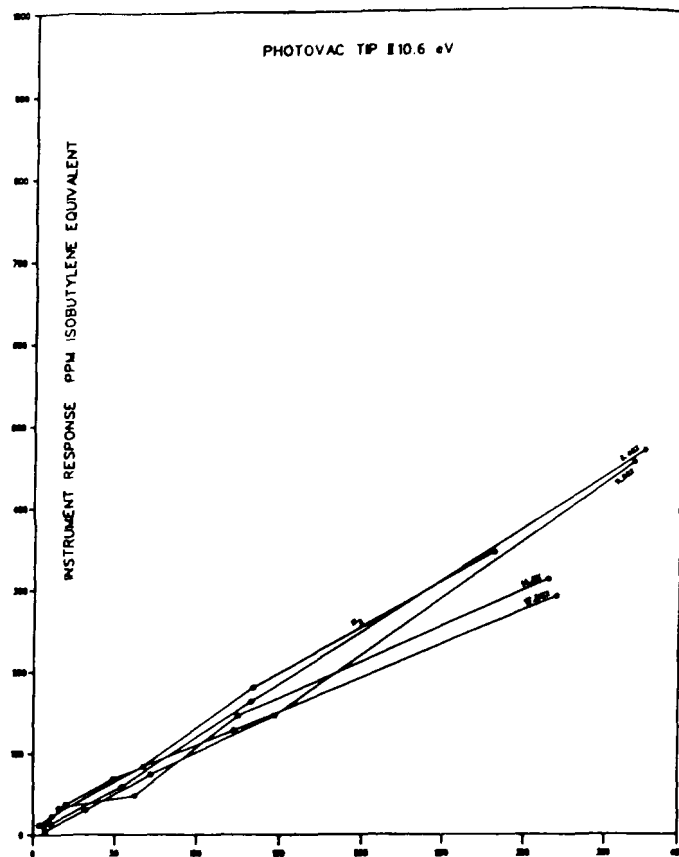


Figure 4
(Known Concentration) PPM Isobutylene

should be mathematically corrected to properly reflect the true volatile organic concentration present. The primary objective of this paper is to provide more information about the performance of DRIs in different applications so their information can be better understood and the instruments can be better used in environmental applications.

REFERENCES

1. Barsky, J.B. Que Hee, S.S. and Clark, C.S., "An Evaluation of the Response of Some Portable, Direct-Reading 10.2eV and 11.0 eV Photoionization Detectors, and a Flame Ionization Gas Chromatograph for Organic Vapors in High Humidity Atmospheres, pp 46 9-14, 1985.
2. Nyquist, J.E., Wilson, D.L., Norman, L.A. and Gammage, R.B., "Decreased Sensitivity of PID Total Organics Vapor Detectors in the Presence of Methane," *Health and Safety Research Division, Oak Ridge National Laboratory*, Oak Ridge, TN.
3. Senum, G.I., Quenching or Enhancement of the Response of the Photoionization Detector, *J. Chromatog.*, 205 pp 412-418, 419.

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Advantages of a Field Screening Method for Mitigating PCBs in Soils

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ABSTRACT

The high costs of analytical services should be considered when planning a remedial project at a hazardous waste site. Field analyses of samples may be used to complement the work performed by an off-site analytical laboratory by reducing the sample load. Alternately, if field analyses are conducted without the support of an off-site laboratory, an on-site mobile laboratory can be designed to meet necessary data quality objectives. Field screening and/or approved U.S. EPA methods for soils can be performed at an on-site mobile laboratory.

An on-site mobile laboratory can also expedite remediation through real-time data production, which an off-site laboratory cannot provide. This can result in substantial cost savings during excavation projects which might otherwise require standby time for equipment pending laboratory results.

The site discussed in this paper is the Swanson River Field oil and gas production field, located in a remote area of the Kenai National Wildlife Refuge in Alaska. PCBs were used in a compressor station as a heat-transfer oil in the process heat system of propane recovery units, in electrical switches and in transformers. After an explosion at the compressor station, the PCB-contaminated soils were stored in a waste oil pit/stockpile and later were applied to more than 2 mil of gravel roadway to suppress dust emissions.

During a 3-yr, \$35-million project for the remediation of the PCB-contaminated soils, the on-site mobile laboratory analyzed more than 16,000 soil samples to manage and verify the effectiveness of the cleanup. By analyzing soil samples using a modification of U.S. EPA Method 608 as a screening tool, the excavation proceeded expeditiously and economically, minimizing downtime for excavation equipment and controlling the amount of material requiring excavation and treatment. Cleanup levels also were verified on-site by analyzing samples according to a modification of U.S. EPA Method 8080 in order to comply with site-specific regulatory requirements.

The objective of this evaluation is to describe one application of field analysis at an on-site mobile laboratory used to support PCB-contaminated soil remediation at a remote site. The field analyses (screening and verification) will be described, and the discussion will focus on how an on-site mobile laboratory can provide an efficient, economic and innovative approach for supporting excavation of PCB-contaminated soils to an established cleanup level. The costs of using a conventional remote laboratory will be compared to the costs of using the more efficient on-site mobile laboratory to illustrate the cost benefit of the latter approach.

INTRODUCTION

This remedial project took place on the Swanson River Field oil and gas production field in the Kenai National Wildlife Refuge in Alaska.

From 1962 to 1972, Aroclor-1248 was used as a heat transfer oil in the process heat system of the propane recovery units, and fluids containing Aroclor-1254 were used in electrical switches and transformers. PCB contamination of soils occurred in 1972 after an explosion at the compressor plant. The contaminated soils were disposed of on-site in an oil waste pit/stockpile. Other contaminated materials (metal debris, etc.) were stored in areas throughout the oil and gas field.

The heat transfer system was refilled with Therminol FR-1, which contained Aroclor-1242. This fluid was replaced with a non-PCB containing oil, Therminol 66, upon enactment of the Toxic Substance Control Act in 1976.

In 1983, PCB-contaminated soils from the oil waste pit/stockpile inadvertently were applied to more than 2 mi of roadway for the suppressive of dust emissions and for road maintenance. After completion of a comprehensive site investigation in 1985 designed to verify preliminary data and document the approximate extent of contamination, a risk assessment was conducted to evaluate potential exposure and effects of the PCBs on wildlife in the area. Based on the environmental risk assessment, cleanup levels of 12 ppm for roads and 24 ppm for the compressor plant and waste oil pit areas were negotiated with the overseeing agency, the U.S. Fish and Wildlife Service (USFWS), and a number of other agencies also involved in the negotiation process.

One major problem associated with site remediation was the lack of qualified analytical support services within 1,500 mi of the site. If an off-site laboratory were chosen, significant costs for sample packaging, express shipping and quick turn-around of results would be incurred. The premium for quick turn-around (i.e., 24 hr) of results range from 150% to 300% more than the normal turn-around of results (approximately 2 wk) by a conventional analytical laboratory. Additionally, the inability of an off-site laboratory to meet a quick turn-around could delay the excavation process, thereby increasing the excavator's costs because of standby time. Additional factors considered included the need to accurately communicate vast quantities of data to the site and to review and validate QA/QC acceptance. A conventional laboratory also is restricted by the number of samples it can process, its manpower resources and other competing demands.

This paper presents an approach for mitigating PCB-contaminated soils with the support of field screening at an on-site mobile laboratory. An on-site mobile laboratory, as opposed to an off-site laboratory, offers many advantages on a large-scale PCB remediation project. A unique feature of this approach is that the on-site mobile laboratory can be tailored to any configuration in order to meet the data quality objectives of the particular PCB mitigation project as well as the project's QA/QC requirements.

Sample field screening by a shortened U.S. EPA method and sample

verification by an approved U.S. EPA method were the two functions of the on-site laboratory that satisfied the remedial data quality objectives of this project. Field screening was used to delineate areas requiring excavation and/or reexcavation, while verification was performed to provide the USFWS with valid results which illustrated that the cleanup criteria were met.

METHODOLOGY

Sampling Design

Several U.S. EPA publications have presented guidelines for preparing plans for soil sampling^{1,2,3}. All of these documents discuss statistical considerations when sampling soils and methods to calculate the numbers of samples and sampling locations. For a planned removal project, the recommended confidence limit is 95% or better with analytical precision at 10% to 20%, if possible².

The ideal mixture of a contaminant in soils would be its uniform distribution, represented by a "bell curve." However, natural variables exist in any soil system and should be accounted for when sampling. The effects of these variables upon the statistical analysis of the soil data can be reduced by dividing the sampling area into smaller, more homogeneous subareas. The objective of the sampling effort is to collect a prescribed number of samples needed to estimate at what point the appropriate cleanup level has been achieved. Therefore, relatively homogeneous subareas may require a smaller number of samples in order to satisfy the data quality objectives of the remediation.

Systematic sampling is the preferred method for a PCB sampling design effort, due to the ease with which the method is implemented in the field and its efficiency in detecting residual zones of contamination³.

The subareas can be designed in a grid-like pattern to locate the sampling points once the number of samples has been determined. There are three formulae used to generate the minimum number of samples required to assure that mitigated areas are below the cleanup levels^{1,3,4}.

Of the three formulae, the second formula, proposed by the USFWS, provides the highest minimum number of samples to be collected within a defined grid area⁴. The formula takes into account the small sample size for each discrete subarea to be mitigated and defines the total number of samples required to assure compliance with established cleanup level.

By using the mean PCB concentration of the subarea and several statistically derived variables, the minimum number of samples that would be required in each subarea can be calculated according to the following formula:

$$N = \frac{(t^2)(s^2)}{(a y)^2} \quad (1)$$

where N is the sample size required; t is the t-value obtained from a t-table at n-1 degrees of freedom using a two-tailed test; s² is the variance or standard deviation squared; a is the accuracy desired in describing the mean; and y is the mean concentration in a group of n samples.

Analytical Design

The data quality objectives of this remediation required two levels of analytical uses. The first analytical level required the sensitivity to detect PCB contamination at or below the cleanup level of 12 ppm and required real-time determination of sample results. This screening tool was needed to accurately delineate areas of contamination requiring excavation, thereby reducing the unnecessary probability of excavating soils at concentrations below the cleanup level. The second analytical level was required to meet the USFWS criteria that an approved U.S. EPA method be followed to verify the cleanliness of the excavated areas. These results allowed the USFWS to approve the release of these areas as clean. Split sample were taken by the USFWS to ensure the quality of the verification samples.

Using a conventional off-site laboratory, soils within a specified grid would be excavated to a predetermined depth based on the previous

data of a site investigation. The highest minimum number of samples (calculated by the above formula) would be collected, shipped to the laboratory by overnight courier and analyzed by the screen method the next day. A report of the results would be sent within 24 to 36 hrs. If the sample results were found to be above the cleanup level, re-excavation would be required and the process of sampling and analysis repeated until the concentrations were below the cleanup level. Then samples could be analyzed by the U.S. EPA verification method.

The excavation process followed for this remedial project proceeded similarly but much more rapidly and economically with the support of field screening. After the contaminated soils were excavated to a predetermined depth, unlimited samples within the grid were collected and screened by the on-site laboratory. This sampling procedure provided a confidence limit of greater than 95% that zones of contamination were sampled, therefore optimizing the sampling grid. With an analytical precision and accuracy of 20% and a detection limit of 1 ppm, the screening method met with data quality objectives for excavation to 12 ppm. Nearly real-time decisions were made to determine if re-excavation was required, and the process was repeated until the grid area was ready for resampling and analysis by the verification method, U.S. EPA Method 8080.

By field screening on-site, the minimum number of samples requiring verification within the grid was calculated and sampled. Field screening of soil samples in the on-site mobile laboratory was performed at a rate of approximately 25 samples per man-day; this rate of analysis provided almost real-time data from the time of sample collection and allowed for effective management of the entire excavation process.

Once the iterative process of excavation/sampling was completed and the screening sample results were less than or equal to the adjusted cleanup level, the verification sampling and analysis data were used by the USFWS to determine if the cleanup level was actually below

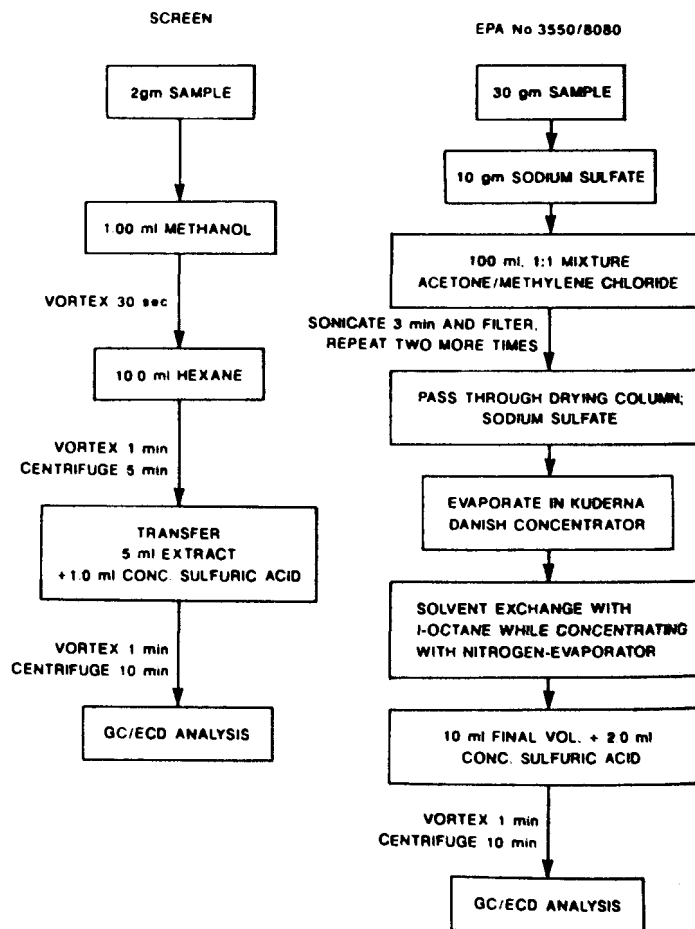


Figure 1
Extraction Procedures

12 ppm. The USFWS permitted only the use of U.S. EPA Method 8080 results to determine if areas were completely remediated.

Analytical Methods

A modification of U.S. EPA Method 608 was developed to rapidly analyze soil samples. Figure 1 illustrates the modified extraction procedure.

A 2-g portion of a soil sample was placed in a test tube and 1.0 mL of methanol added to assist in partitioning water moisture from the extraction solvent, hexane. The mixture was vortexed for 30 sec; then 10.0 mL of hexane were added; the sample was vortexed for 1 min and centrifuged for 5 min. Approximately 5.0 mL of extract were transferred into a clean test tube and treated with 1.0 mL of concentrated sulfuric acid. This cleanup step essentially removed oil and chlorinated pesticide interferences⁵. The mixture was vortexed for 1 min and separated by centrifuging for 10 min.

The hexane layer then was injected onto a gas chromatograph (GC) with an electron capture detector (ECD) and quantified as the appropriate Aroclor based on retention times and relative peak height (area) intensities. A Shimadzu GC-Mini 2 equipped with a glass, 2m x 3mm, 1.5% SP-2100/1.95% SP-2401 on 100/120 mesh Supelcoport column and a Shimadzu Chromatopac CR-3A data processor were used on analyze for Aroclors. A second column, packed with 3% OV-1 on 100/120 mesh Supelcoport, also was used for Aroclor identification when necessary. Redundant GC systems were available to increase productivity and provide a backup system if one GC failed. This feature was important when working in a remote location where instrument servicing was limited. The average analysis time for Aroclor-1248 on mixed-phase columns was approximately 15 min.

The verification extraction and analysis procedure followed U.S. EPA Method 3550/8080⁶. Figure 1 provides a comparison of the verification procedure to the screening procedure. Modifications to the procedure consisted of sulfuric acid cleanup in place of Florisil, use of iso-octane as the final solvent rather than hexane and the final concentration step by nitrogen-evaporation instead of a micro-Snyder column.

A larger portion of each soil sample (30 g) was taken and actively extracted by sonicating in a mixture of acetone and methylene chloride with sodium sulfate. This step was repeated two more times to assure that the sample was effectively extracted. Excess moisture was removed by passing the extract through a column of sodium sulfate used as the drying agent. The extract volume was reduced via a Kuderna-Danish concentrator with iso-octane as the final extract solvent. Sulfuric acid was also used for the cleanup⁵. The extract was similarly quantitated by GC/ECD analysis.

The advantage of the field screening procedure were that less quantitative transfers were involved, thereby reducing analytical errors; extraction time was approximately four times faster than the standard method (approximately 25 screen samples could be processed versus six verification samples in an 8-hr day by one chemist); smaller volumes of waste extract and acid were generated, thereby reducing disposal costs; and minimal expendable materials were required, thereby lowering the cost per sample.

Besides the obvious differences in extraction procedures and timeliness, these methods also met different data quality objectives. The detection limits were 1 ppm for the screening method and 0.15 ppm for U.S. EPA Method 3550/8080. In addition to the higher detection limits, the screening method may be less representative of the sample because of the smaller sample size and the resulting dependency on the homogeneity of the soil matrix.

The on-site mobile laboratory used on the PCB remediation project was designed to accommodate soil extractions using U.S. EPA Method 3550/8080 and modified U.S. EPA Method 608 procedures as well as two GCs. Typically, up to two chemists per shift would work in the laboratory with a maximum of three shifts per day. Figure 2 shows the floor plan for the on-site laboratory which highlights three main areas: (1) a GC instrument room, (2) an extraction area and (3) a storage room (total area is 500 ft²). Utilities necessary for the laboratory were 160 amp of 110-V electricity, water and heat/air conditioning. If only

field screening were to be performed, approximately 250 ft² would be adequate.

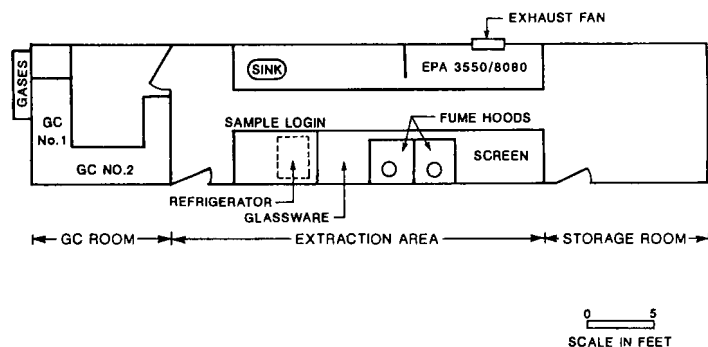


Figure 2
On-Site Mobile Laboratory For PCB Analysis

RESULTS

The results of the screening procedure were compared to the results of U.S. EPA Method 3550/8080 procedure used at the on-site mobile laboratory and to the results of the split samples analyzed at a USFWS laboratory. Data analysis by linear regression was used for the two comparison. Generally, a correlation coefficient of greater than 0.9 is classified as a good match between data sets and less than 0.7 a moderate fit⁷. The confidence limits that apply to the whole regression line for screening data are estimated at single values of the U.S. EPA method or USFWS split sample data⁷. Figures 3 and 4 present graphs of these regression analyses, using the screening data results from the on-site mobile laboratory as the independent variable on the y-axis and U.S. EPA Method 8080 (performed by on-site mobile laboratory) and USFWS method results as the dependent variable on the x-axis. Confidence bands, or limits, of 95% are shown as two branches of a hyperbola to predict the variability of screening data compared to a given EPA/USFWS method result.

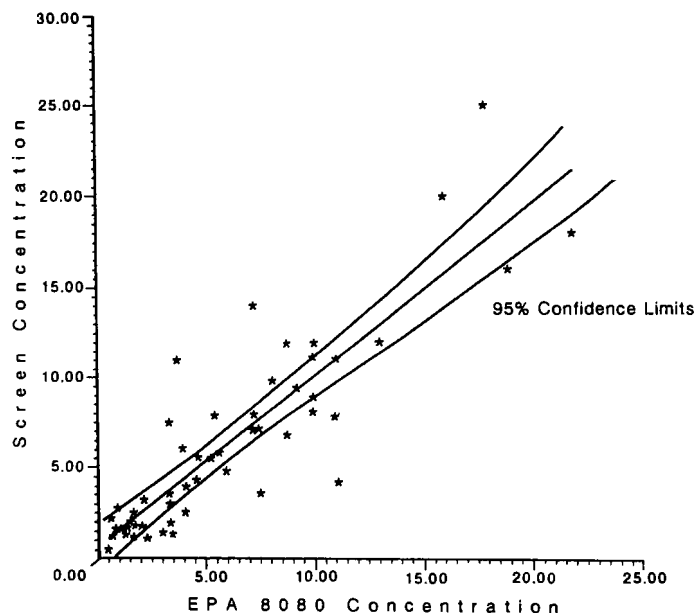


Figure 3
Screen vs. EPA 8080, ppm AR-1248 ($Y=0.67+0.94 X$)

In Figure 3, the results of 55 samples, analyzed for screening (modified U.S. EPA Method 608) and for verification (U.S. EPA Method 808), with concentration ranges between 0.42 and 25 ppm Aroclor-1248, have a correlation coefficient of 0.883. The regression analysis is considered statistically significant at the 95% confidence limit. The

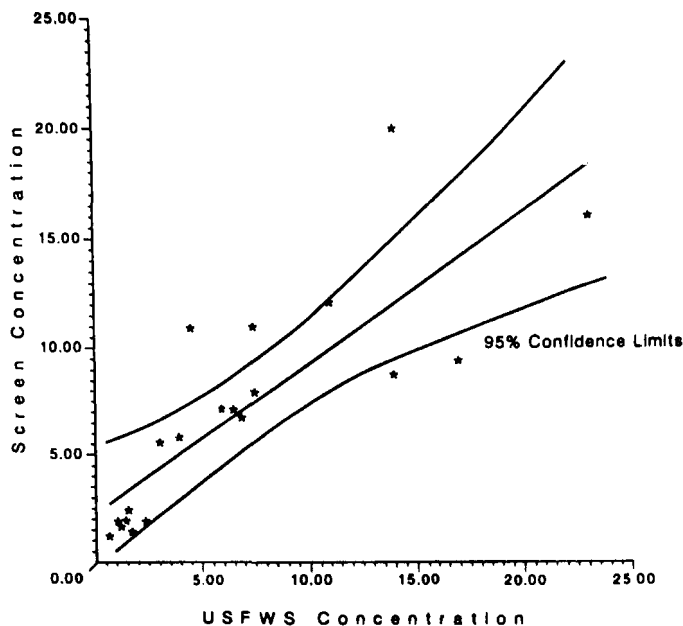


Figure 4
Screen vs. USFWS 8080, ppm AR-1248 ($Y = 2.39 + 0.69 X$)

narrow width of the confidence bands shows that the variability of the screening data from the on-site mobile laboratory is small compared to the verification sample data analyzed by U.S. EPA Method 8080. The equation of the regression line also indicates a slope ratio of nearly unity (slope = 0.94) and the y-axis intercept close to zero (intercept = 0.67 ppm).

Screening results of 20 samples from the on-site mobile laboratory correlate similarly with the USFWS results shown in Figure 4, with a correlation coefficient of 0.817 in the concentration range of 0.6 to 23 ppm Aroclor-1248. The regression line did not fit as well as in Figure 3, with a slope of 0.69 and an intercept of 2.39. The data pairs in Figure 4 are not statistically significant at the 95% confidence limit; however, the data pairs are significant at a 90% confidence limit. This result is indicated by the wider confidence bands bordering the regression line. The statistics may be improved by increasing the sample size of paired data sets greater than 22.

These correlations indicate that the results of the screening method agree with those of U.S. EPA Method 8080 at less than 25 ppm Aroclor-1248, as do the results from an independent laboratory for the USFWS. Data points outside the 95% confidence bands may be due to sample heterogeneity, grain size variability and the original content of the PCBs in the oily gravel applied to the roads.

CONCLUSIONS

A combination of screening and verification analyses at an on-site mobile laboratory has been shown to be a useful tool for a

multimillion-dollar remedial project. Over 16,000 soil samples were analyzed, of which 14,200 samples were screened and 2,500 samples used to verify the effectiveness of remediation.

Approximately 80,000 tons of soil were excavated during the remediation. Based on a scenario that an additional 5% of the soils below the cleanup level would have been excavated if an off-site laboratory were used and assuming a rate of \$190 per ton for excavation, standby time and treatment costs, approximately \$760,000 in excavation and treatment costs probably were saved.

The estimated cost savings for analytical services of the on-site laboratory were approximately \$580,000. This estimate was based on the assumption that remote laboratory analytical fees would be \$50 per screen sample and \$350 per verification sample, including express shipping and a 24-hr turn-around of results. Considering operating costs of the on-site mobile laboratory other than capital expenses for instruments and equipment, sample unit costs were approximately \$40 per screening sample and \$175 per verification sample, based on a turn-around time of results of 25 screen and six verification samples in 8 man-hours.

The remedial technique of field screening soil samples at an on-site laboratory with the additional capabilities of U.S. EPA-approved verification analyses has been demonstrated to be economical and provide valid analytical results in approximately real-time. The large number of samples processed through the on-site laboratory has also resulted in significant cost per sample savings, when compared with the costs of a remote laboratory.

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REFERENCES

1. Mason, B.J., *Preparation of Soil Sampling Protocol: Techniques and Strategies*, U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, EPA-600/4-83-020, Aug., 1983.
2. Barth, D.S. and Mason, B.J., *Soil Sampling Quality Assurance User's Guide*, U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, EPA 600/4-84-043, May, 1984.
3. Boomer, G.A. et al., *Verification of PCB Spill Cleanup By Sampling and Analysis*, Interim Report No. 2, Work Assignment 37, U.S. EPA, Office of Toxic Substances, Washington, D.C., EPA-560/5-85-026, Aug., 1985.
4. Burns, J.W., *Inland Fisheries Management*, State of California, The Resource Agency, Department of Fish and Game, p. 162, 1966.
5. Hutzinger, O. et al., *The Chemistry of PCBs*, Krieger Publishing, New York, NY, 1983.
6. U.S. EPA, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, SW-846, 3rd ed., Office of Solid Waste and Emergency Response, Washington, D.C., Sept., 1986.
7. Snedecor, G.W. and Cochran, W.G., *Statistical Methods*, 7th ed., Iowa State University Press, Ames, IA, 1980.

Use of Bioassays to Monitor Polycyclic Aromatic Hydrocarbon Contamination in Soil

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ABSTRACT

Prior to implementing on-site bioremediation for polynuclear aromatic hydrocarbon (PAH) contaminated soils, the soil-based detoxification and degradation of hazardous constituents in the waste should be evaluated. Treatability studies combined with site-specific characterization can be used to obtain specific information, including migration potential, chemical partitioning among soil-waste fractions, treatment efficiencies and approaches to enhancing treatment.

As well as presenting an approach, this paper presents results in which information from an array of bioassays have been combined with information about fate mechanisms; together, these techniques will enable the evaluation of the extent of detoxification and degradation of hazardous constituents in soil systems.

The approach consisted of three phases. Phase one was designed to determine the degradation rate and extent of the radiolabeled portion of selected PAHs. Phase two involved monitoring the radiolabel and toxicity of aqueous extracts of soil to estimate partitioning of parent compound and metabolites into the water fractions. Phase three encompassed the evaluation of the soil solid fraction, including the tendency of PAHs to become progressively more associated with the solid phase (humic material). The framework described in this paper provides an approach, based upon integrated chemical and bioassay evaluations, for assessing management options at uncontrolled, PAH-contaminated waste sites.

INTRODUCTION

Polynuclear aromatic hydrocarbons (PAHs) include a group of organic pollutants that are of critical concern to public health and the environment because of their potential carcinogenicity, environmental persistence, high bioaccumulation and low removal efficiency in traditional wastewater treatment processes¹. PAHs have been identified in soils and groundwater at uncontrolled disposal sites, including wood preserving, petroleum, oily wastes and coal gasification sites^{2,3,4}. On-site biological remediation of soil contaminated with PAHs is a treatment technology that provides permanent cleanup as encouraged by the U.S. EPA for implementation of SARA.

Prior to implementing on-site biological remediation technology for PAH-contaminated soil, the potential for the contaminated system to accomplish detoxification and degradation of hazardous constituents present in the waste should be evaluated. Treatability studies, combined with site-specific characterization, can be used to: (1) determine migration potential at the site, (2) correlate chemical disappearance with changes in bioassay response, (3) evaluate treatment efficiencies under different experimental conditions, and (4) evaluate approaches for enhancing treatment.

Treatment of PAH-contaminated soil generally has been reported in

terms of the decreasing PAH concentration over time^{5,6,7,8,9}. Typically, soil samples are taken from a field site or laboratory microcosm and extracted with a solvent. The concentration of PAH compounds in the solvent extract is measured using gas or liquid chromatography. The change in concentration of a PAH compound over time often is used to calculate a rate of decrease in the concentration of PAH compound in soil. The rate of PAH compound decrease can be used to estimate time requirements for remediation of soil and to attain target cleanup levels. Also, the effects of environmental factors (such as temperature, moisture and pH) on treatment rate can be estimated.

Additional information concerning mechanisms by which PAH compounds interact with a soil environment is necessary to understand whether a compound is transferred from one soil phase to another or is chemically altered so that the properties of the parent compound are changed. To evaluate the behavior of PAH compounds in contaminated soil systems, the compound distribution among the physical phases that comprise a soil system must be measured. For monitoring the potential environmental and public health impact of intermediate products, the water soluble toxicity must be determined.

This paper presents an approach as well as specific results in which information from an array of bioassays have been combined with information concerning fate mechanisms to evaluate the extent of both detoxification and degradation of hazardous constituents in soil systems and to characterize the toxicity of potential leachates.

MATERIALS

Chemicals

Radiolabeled [¹⁴C] benzo(a)pyrene [B(a)P] was obtained from Chemsyn Laboratories (Lenexa, Kansas) through the National Cancer Institute (NCI). ¹⁴C labeled pyrene was supplied by Dr. Ingeborg Bossert, Texaco (Beacon, New York). Unlabeled B(a)P and pyrene were purchased from Sigma (St. Louis, Missouri). Algal metabolite standards—benzo(a)pyrene-trans-9,10-dihydrodiol, 11,12-dihydrodiol, 11,12-dione and 1,6-dione—were obtained from the Midwest Research Institute through the NCI. Standard chemicals were dissolved in ethylene glycol monomethyl ether (EGME) so that the EGME concentration did not exceed 0.1 mL/L diluent¹⁰.

Propylene oxide was used to sterilize control microcosms by fumigation in an airtight hood. Sterilization was checked by plating 1 mL and 0.5 mL from a 1 g.:10mL distilled, deionized water suspension of soil from the controls on nutrient agar and tryptic soy agar plates and by GC analysis of the flash headspace for CO₂.

Scintillation cocktails, Ready-Safe™ and Ready-Gel™ were purchased from Beckman Instruments (Fullerton, California).

McLaurin soil samples from the Wiggins, Mississippi site were sup-

plied by Dr. Gary McGinnis, Mississippi State University, Forest Products Utilization Laboratory (Mississippi), and were characterized by the Utah State Soil Science Laboratory, Utah State University (Logan, Utah).

Biota

Daphnia pulex were purchased from Carolina Biological, collected locally and identified by Edmundo Moreno, Fisheries and Wildlife Department, Utah State University. Daphnids were maintained in water collected from the Logan River, Utah. The river water was analyzed for organic contaminants by HPLC.

Selanastrum capricornutum were supplied by Linda Abbott, Biology Department, Utah State University, and cultured in our laboratory according to the procedure described by Miller, et al¹¹.

Glassware

Flasks used for microcosms (1 L) were purchased from VWR Scientific (Salt Lake City, Utah) and were washed, rinsed three times with distilled, deionized water (DDW), rinsed with methylene chloride and placed in a muffle furnace for 1 hr at 500°C.

Beakers, flasks and aquaria used in toxicity and bioaccumulation tests were washed with soap and water, rinsed with DDW, then rinsed sequentially with a 10% HCl solution and a saturated solution of sodium carbonate; then, they were rinsed five times with tap water and five times with DDW and dried at 50°C.

Equipment

Soil and leachate samples were analyzed by the Microtox™ bioassay according to the procedure in the Beckman Microtox™ System Operating Manual^{12,13}.

Soil samples, the insoluble humin and the humic-fulvic fractions, were combusted in O₂ using a Harvey Biological Material Oxidizer with the evolved CO₂ collected in an ethanolamine-methanol-scintillation cocktail mixture.

Chemical extraction of soil samples was done according to the tismizer homogenization system of Coover, et al¹⁴, using a Tekmar (Cincinnati, Ohio) Model SDT-1810 motor, Model SDT-182EN shaft and generator assembly and Model TR-10 speed controller.

Water samples generated from the water extraction were extracted from Sep-Pak® C₁₈ columns (Waters Association, Milford, Massachusetts).

Evolved ¹⁴C from the combustion of samples and portions of the leachate, Sep Pak eluates and organic solvent extracts were counted in a Beckman LS1701 Liquid scintillation counter (Beckman Instruments, Fullerton, California).

Algal, daphnid and fish test cultures were incubated under GE-40 gold fluorescent lights, and each soil microcosm was wrapped in black plastic to avoid photo-oxidation¹⁵.

EXPERIMENTAL DESIGN

The flowchart (Fig. 1) provides an overview of the experimental design and illustrates the three phases of this study.

The objective of Phase 1 was to determine the rate and extent of degradation of the labeled portion of two specific PAHs. Phase 1 involved incubation of material, collection of the carbon dioxide evolved and any volatilized chemical, and extraction of soil subsamples through time.

Phase 2 involved liquid scintillation counting of the phase samples and toxicity testing of the aqueous extract. Results were used to estimate the rate and extent of partitioning of parent compounds and their metabolites into the water phase and to evaluate the toxicity of the generated leachate.

Phase 3 involved non-polar chemical and acid/base-neutral (humic material) extractions of the solid fractions of the sub-samples to determine the partitioning of the chemicals and the toxicity of the solid fraction.

METHODS

Phase 1

One gram of the unlabeled chemicals, (B(a)P and pyrene, was dis-

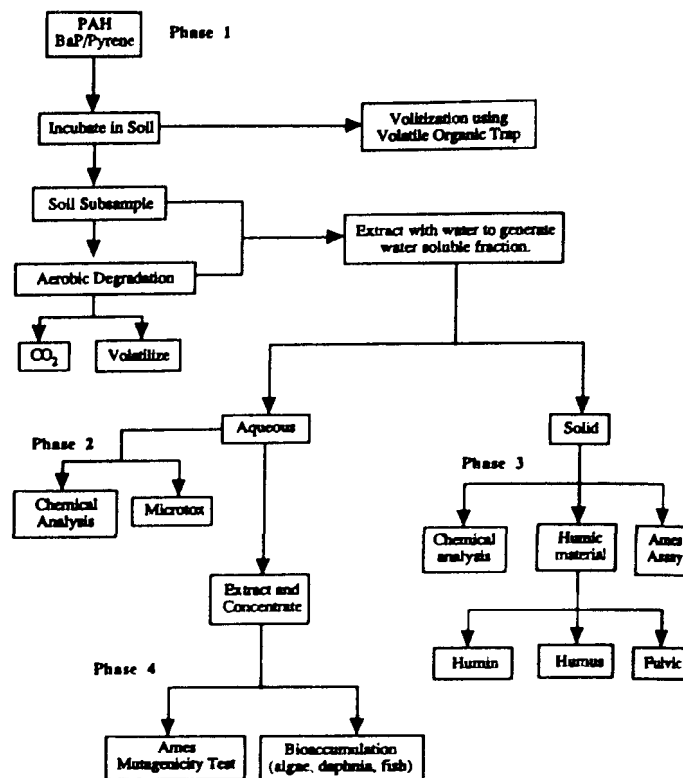


Figure 1
Flow Chart For Analytical Procedure

solved in a flask in ethylene glycol monomethyl ether, spiked with labeled compound ($\approx \mu\text{Ci}/\text{flask}$) and added in small increments to 700 g of the vadose zone soil in the appropriate flasks; after each addition of chemicals, the soil was mixed thoroughly.

At each sampling, 1 g and 70 g soil subsamples were taken, and the flasks were stoppered and returned to the incubation box. The 1-g sample was used to estimate immobilized ¹⁴C through autooxidation. Evolved CO₂, collected in a solvent trap, was assayed for ¹⁴C by liquid scintillation (LS). The 70-g soil sample was tumbled for 24 hr with DDW (4 x soil weight) to estimate water soluble organics.

Phase 2

Supernatant generated in Phase 1 was divided into several portions for counting by LS, Microtox testing and use in the daphnid toxicity testing. The remaining supernatant was extracted using Sep-Pak® C-18 columns.

Phase 3

Sediment extracts were analyzed by reverse phase LC, using a gradient mobile phase program consisting of 2 min isocratic elution with 40% acetonitrile in water followed by 15 min linear gradient to 100% acetonitrile at a flow rate of 2 mL/min. Analytes can be detected at a wavelength of 254 nm¹⁴.

After chemical extraction, the sediment was allowed to air dry. One gram samples were taken and combusted. The remaining sediment was extracted using the Skujins and Richardson¹⁶ method.

The insoluble (humin) portion was combusted in the Harvey Biological Combuster, and the carbon dioxide evolved was collected in an ethanolamine:methanol:scintillation cocktail trap and counted by LS.

Statistical Methods

Statistical methods were used to evaluate the hypotheses stated in this study. These methods assisted in determining the reliability of measurements, estimating PAH compound degradation rates, determining the significance of differences between replicates and evaluating treatments for individual compounds.

One-way analysis of variance and the Duncan's multiple range test were used to evaluate differences in concentrations of PAH compounds between sampling times. Multiple-way analysis of variance was used to determine the effects of methane as a growth substrate and the difference of PAH degradation between the singly applied chemical and the creosote waste.

All statistical procedures were performed using the SPSS computerized statistical package (SPSS, Inc., 1986).

Results

Results from Phase I demonstrate that the percent recovery of the radiolabel by chemical means was dependent on the chemical species, polarity of solvent and time spent in soil. Through radiolabel (^{14}C) mass balances over all sample fractions, it was determined that 99% of the radiolabel remained associated with the soil. Actual mineralization of B(a)P and pyrene systems was insignificant over the duration of this study. However, significant differences in sterile and nonsterile labeled carbon dioxide were observed for both chemicals.

Phase I results of aqueous extractions of the soil suggested that the radiolabel associated with the aqueous fraction increased over time. Subsequent extraction of the water soluble fraction with methanol and methylene chloride showed an increase in the amount of label associated with methanol, while the amount of radiolabel associated with the methylene chloride fraction remained constant (Figs. 2 and 3). The same trend was observed in the sterile controls, although the total amount of activity was greatest in the polar solvent from the nonsterile systems (Figs. 4 and 5). These effects suggest that the initial transformations of the PAH compounds result in the generation of more polar intermediate compounds which prefer the methanol solvent. The total radiolabel associated with aqueous phase averaged approximately 1% at each sampling, with the majority of label found in the methanol eluate.

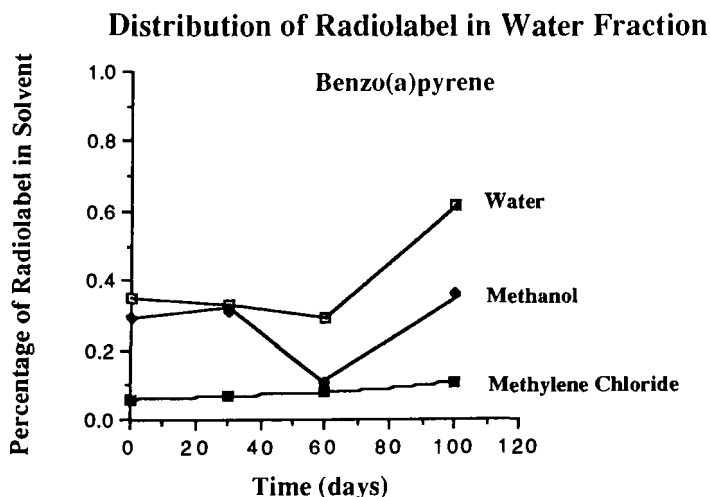


Figure 2
Distribution of Radiolabel in Water and
Water Fraction Extracts

Up to 100 days, the toxicity resulting from the introduction of both B(a)P and pyrene to soil microcosms was low. This result was not surprising given the fact that the amount of radiolabel associated with the water soluble fraction was insignificant. An increase in radiolabel concentration in the water soluble fraction at 100-day incubation resulted in a simultaneous increase in toxicity as indicated by both the Microtox™ and daphnid toxicity tests. This toxicity remained constant through 130 days with continued incubation, showing no apparent decrease in toxic levels.

In Phase III, the partitioning of the radiolabel into methylene chloride soil extracts decreased with time. The percent of radiolabel in the B(a)P study associated with the soil fractions was higher than the percent of radiolabel in the pyrene study. This result also was not surprising given

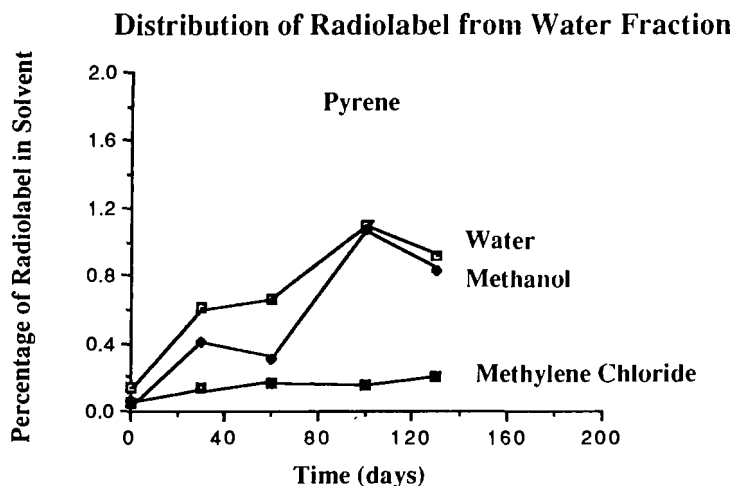


Figure 3
Distribution of Radiolabel in Water and
Water Fraction Extracts

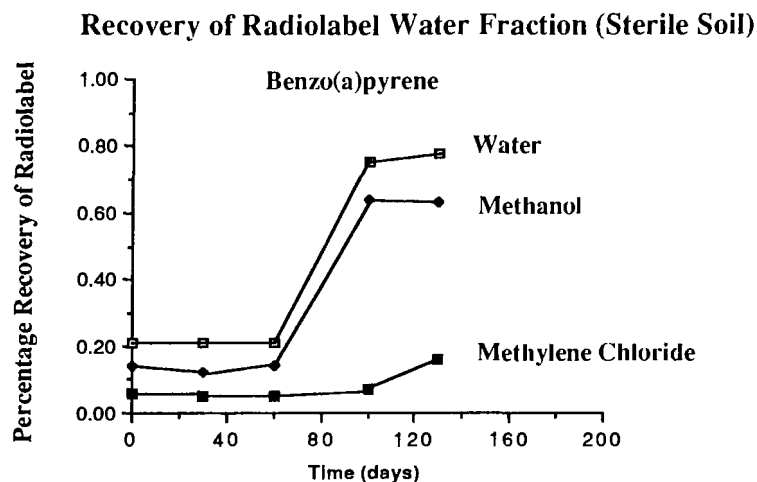


Figure 4
Distribution of Radiolabel in Water and
Water Fraction Extracts

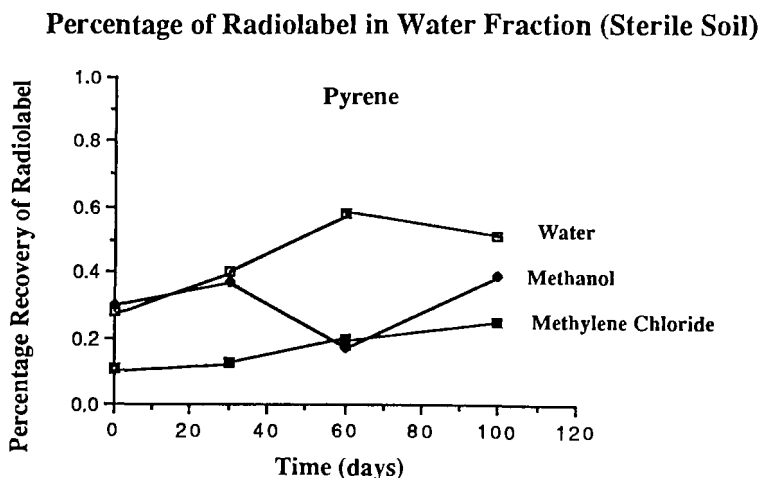


Figure 5
Distribution of Radiolabel from Water and
Water Fraction Extracts

the greater insolubility of B(a)P compared to pyrene. With a decrease in the amount of radiolabel in the methylene chloride extracts, there was an increase in the radiolabel found associated with the sediment.

Further evaluation of the sediment with acid/base extraction procedures indicated that approximately 75% of the label contained in the sediment was associated with the inorganic fraction while 25% was found associated with the organic fraction.

DISCUSSION

The conclusions from this study can only be interpreted for the particular soil used. Soil used in this study was McLauren sandy loam from a Mississippi hazardous waste site and was acidic (pH \approx 5.4) with very little organic carbon content (<0.5%). Soils with more organic carbon (e.g., humus) may show larger increases of radiolabel concentration in acid/base extractions. The vermiculite clay in this soil does not hydrate easily, nor does it have the absorption properties of other clays, such as montmorillonite. Soils with hydratable clays should show a greater affinity for chemicals which would influence the rate of disappearance of the parent compound.

Through capture of evolved radiolabeled carbon dioxide, mineralization of B(a)P and pyrene was demonstrated to occur albeit at extremely slow rates.

Increase toxicity from the water extract together with the greater amounts of radiolabel in the methanol eluate compared to methylene chloride eluate suggests formation of oxidized intermediates or by-products. Identification of the polar intermediates is being evaluated through HPLC fractionation and GC/MS spectrometry.

The increase in partitioning of radiolabel into the acid/base-extracted fractions suggests adsorption of the parent compound and/or transformation products on inorganic and organic soil fractions. This result also implies the possible increase in number of ionizable functional groups causing chemical coupling or polymerization (e.g., humification) which renders the radiolabel immobile. Increased association of the radiolabel with the organic fraction over time suggests that the kinetics of humification and/or absorption of the organic contaminant may be an important factor to consider when developing detoxification measures for polluted soils. Results from the comparison of sterile vs. nonsterile microcosms suggest that immobilization as well as humification may be mediated abiotically and biotically.

An important observation from this study is that half-lives of chemicals in soil determined by chemical extractions should not be confused with biodegradation or mineralization. Without further investigation into the actual fate of the chemical in the extraction sediments, including a complete mass balance analysis, complete detoxification cannot be properly evaluated.

Further investigation of abiotic and biotic reactions of soil with chemical components describing the nature of the adsorption mechanisms needs to be performed. This information can then be correlated with the chemical or physical characteristics of soils.

Site-specific, soil characteristic studies must be conducted if we are to successfully detoxify the many hazardous waste sites located in the United States. Due to the different localities, types of soil, weather conditions, etc., site-specific information should be considered when evaluating detoxification approaches.

CONCLUSIONS

Association of the chemical with the inorganic fraction was a dominant partitioning process. This reaction could account for the largest decrease

in concentration of label to the methylene chloride extract. Despite the large amounts of inorganically associated label, there were significant amounts of the radiolabel associated with the organic fraction. The primary mechanisms of disappearance of the parent compound appeared to include partial chemical oxidations together with adsorption of compounds to spoil components.

ACKNOWLEDGEMENT

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REFERENCES

1. Herbes, S.E., Southworth, G.R. and Gehrs, C.W., "Organic Contamination in Aqueous Coal Conversion Effluents: Environmental Consequences and Research Priorities," in *Trace Substances in the Environment*, ed. D. D. Hemphill, Univ. of Missouri, Columbia, MO, 1976.
2. Mahmood, R. J., *Enhanced Mobility of Polynuclear Aromatic Hydrocarbons in Unsaturated Soil*, PhD Dissertation, Department of Civil and Environmental Engineering, Utah State University, Logan, UT, 1989.
3. Sims, R. C., "On-site Bioremediation of Wood Preserving Contaminants in Soils," *Proc. of the Forum: Technical Assistance to U.S. EPA Region IX: Forum on Remediation of Wood Preserving Sites*, ed. E. F. Barth and J. E. Matthews, U.S. EPA, Oct. 24, San Francisco, CA, 1989.
4. U.S. EPA, *Bioremediation of Hazardous Waste Sites Workshop*, CERL-89-11, U.S. EPA Center for Environmental Research Information, Cincinnati, OH, 1989.
5. Bossert, L., Kachel, W. M. and Bartha, R., "Fate of hydrocarbons during oily sludge disposal in soil," *Appl. Environ. Microbiol.*, **47**, pp. 764-767, 1984.
6. Bulman, T.S., Lesage, S., Fowle, P. J. A. and Weber, M. D., *The Persistence of Polynuclear Aromatic Hydrocarbons in Soil*, A report prepared for the Petroleum Association for Conservation of the Canadian Environment (PACE) Report No. 85-2, by Environment Canada, Wastewater Technology Centre, Burlington, Ont., 1985.
7. Coover, M. P. and Sims, R. C., "The rate of benzo(a)pyrene degradation in a manure amended sandy loam soil," *Haz. Waste/Haz. Mat.*, **4**(2), pp. 151-158, 1987.
8. Sims, R. C. and Overcash, M. R., "Fate of polynuclear aromatic compounds in soil-plant systems," *Residue Reviews*, **88**, pp. 1-68, 1983.
9. Sims, R. C., Sims, J. L., Sorensen, D. L. and Hastings, L. L., *Waste/Soil Treatability Studies for Four Complex Industrial Wastes: Methodologies and Results*, EPA-600/6-86-003a,b, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, U.S. EPA, Ada, OK, 1986.
10. Schoeny, R., Cody, T., Warshawsky, D. and Radike, M., "Metabolism of mutagenic polycyclic aromatic hydrocarbons by photosynthetic algal species," *Mutation Research*, **197** pp. 289-302, 1988.
11. Miller, W. E., Greene, J. C. and Shiroya, T., "The *Selenastrum capricornutum* Printz algal assay bottle test experimental design, application, and data interpretation protocol," U.S. EPA, EPA-600/9-78-018, 1978.
12. Beckman Instruments, Inc., *Beckman Microtox Systems Operating Manual*, Microbial Operations, Carlsbad, Ca, 1982.
13. Symons, B. D. and Sims, R. C., "Assessing detoxification of a complex hazardous waste, using the Microtox™ Bioassay," *Arch. Environ. Contam. Toxicol.*, **17**, pp. 497-505, 1988.
14. Coover, M. P., Sims, R. C. and Doucette, W. J., "Extraction of polycyclic aromatic hydrocarbons from spiked soil," *J. Assoc. Off. Anal. Chem.*, **70**, pp. 1018-1020, 1987.
15. Schoeny, R., Cody, T., Radike, M. and Warshawsky, D., "Mutagenicity of algal metabolites of benzo(a)pyrene for *Salmonella typhimurium*, *Environmental Mutagenesis*," **7**, pp. 839-855, 1985.
16. Skujins, J. and Richardson, B. Z., "Humic matter enrichment in reclaimed soils under semi-arid conditions," *Geomicrobiology J.*, **4**, pp. 299-311, 1985.

Comparison of Shallow Electromagnetic and the Proton Precession Magnetometer Surface Geophysical Techniques to Effectively Delineate Buried Wastes

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ABSTRACT

During the ground preparation for the construction of a building, buried drums were encountered and the construction was halted. Geophysical techniques were used to rapidly delineate the location and extent of the buried waste. The results of the geophysical survey were used immediately to direct waste excavation.

The primary objective of this paper is to compare two surface geophysical techniques, an electromagnetic conductivity meter (Geonics EM-31) and a proton precession magnetometer (Geometrics 856A), and their use at a hazardous waste site. The instrument responses were compared using statistics. Combined responses lead to an improved interpretation of the subsurface. The EM-31 was less affected by man-made surface features.

This paper compares the anomalies seen in the geophysical data with field-verified physical and chemical features. The intent is to help the reader determine which instrument to use, given knowledge of the field conditions, and to aid in interpretation of anomalies.

INTRODUCTION

This paper presents the results of a surface geophysical investigation at a hazardous waste site. All geophysical anomalies suspected of corresponding to buried waste were investigated directly with excavation equipment. Verification trenching was conducted in non-anomalous areas. This direct investigation of the anomalous and non-anomalous areas, along with a thorough analysis of the anomalies created by man-made and geologic features, provided the authors a unique opportunity to evaluate fully the effectiveness of the geophysical techniques used.

The surface geophysical techniques used to delineate buried paint and paint process waste were an electromagnetic (EM) terrain conductivity meter (Geonics EM-31) and a proton precession magnetometer (Geometrics G856). Preceding the survey, historic aerial photos were gathered and employee interviews were conducted to determine the approximate locations of the waste pits and gain an understanding of the burial practices employed on-site. This information was used to identify patterns in the former disposal practices that could be used to define the investigation boundaries and estimate the probable size and depth of the waste disposal area(s).

It is a common practice to use several geophysical techniques to investigate the subsurface. Neev¹ used electromagnetics and a magnetometer to do preliminary site investigations looking for buried ordnance. McGuinness² used ground penetrating radar and magnetometer techniques to locate buried drums. Benson³ suggests that a combination of techniques will aid in the interpretation of the data.

The objective of this paper is to compare the EM and magnetometer responses to buried waste and other anomalous cultural and geologic features at the site. Although both instruments are used widely in geo-

physical investigations, their result have not often been compared.

It became very important to show that the geophysical data were useful in delineating areas where no waste burial had occurred because the area being investigated was the future site of a 250,000-ft² building. Backhoe trenching operations generated information to verify these data. The verification trenching provided a high level of confidence in the geophysical data, suggesting that all of the buried waste pits had been found and removed. In light of this confidence, the state environmental agency involved approved the placement of the building over the site.

BACKGROUND

When a manufacturing company began ground-clearing for its new warehouse, a bulldozer doing surface leveling encountered some shallow buried waste. The company's environmental manager halted the construction work and hired Metcalf & Eddy, Inc. to locate and characterize the waste and coordinate its removal and proper disposal.

Through initial soil sampling, employee interviews and the review of historical aerial photographs, it was determined that the waste was the result of former disposal practices used by the company from 1961 through 1979 (just prior to the enactment of RCRA).

Paint process wastes generated prior to 1980 were disposed of on-site. It is unclear whether these paint wastes, which include ashes, solvents, charred timbers, scrap metal and buffing pads, were disposed of in burial pits after being burned in an on-site incinerator, or whether



Fig. 1
1973 Aerial Photograph

the waste was set on fire after being placed in the pits. A 1973 aerial photograph (Fig. 1) shows the rough outlines of three small pond-like areas with a road leading from the manufacturing facility. The photograph gave an indication of the probable dimensions and locations of the waste pits in 1973. Although this was just one point in time, and there was no way of knowing exactly how representative this photograph was, it does suggest a systematic process of waste disposal. This was valuable information for the design of the investigation.

The topography is extremely flat, with less than 2 ft. elevation change across the site. An initial review of the geological literature suggests that the site is underlain by approximately 10 ft. of glacial till over more than 300 ft. of shale. Groundwater occurs in fractures and other permeable zones in the shale.

Site leveling and landscaping associated with a building expansion in 1980 had erased any surface evidence of the waste pits, as seen in the 1973 aerial photograph. Because the bedrock was so near the surface (approximately 10 ft.) and because of comments about the disposal practices from long-time employees, it was believed that the waste was buried in very shallow pits. The aerial photographs suggested that the size of the waste pits was on the order of 10 by 20 ft. to as much as 50 by 60 ft.

Employee interviews and a review of the manufacturing and painting operations prior to 1980 (when on-site waste disposal was active) were used to estimate the physical and chemical characteristics of the former wastes.

Description of Equipment

Benson⁴ presents a methodology for deciding which geophysical technique is appropriate based on site conditions. Based on the evidence presented above, a decision was made to use a shallow electromagnetic technique and a magnetometer to locate the buried waste.

A brief description of the basic theory and use of the Geonics EM-31 electromagnetic conductivity meter and the Geometrics 856A proton precession magnetometer follows.

Electromagnetic techniques measure the terrain conductivity by imparting an alternating current to a transmitter coil placed on or near the earth's surface⁵. The current passing through the transmitter coil produces a magnetic field, which in turn induces small currents in the underlying strata. Currents within the strata produce a secondary magnetic field, which is sensed by a receiver coil. It has been shown that the ratio of the electromagnetic field detected by the receiver coil to the electromagnetic field produced by the transmitter coil is directly proportional to terrain conductivity. This allows terrain conductivity to be read directly from the instrument in millimhos per meter (mmhos/m).

The terrain conductivity value read by the instrument is an average conductivity over the effective depth of the survey. The effective depth is determined by the intercoil spacing (i.e., distance between the transmitting and receiving coils) used in the survey. The Geonics EM-31 electromagnetic terrain conductivity meter was used at this site. It has an intercoil spacing (distance between receiver coil and transmitter coil) of 3.66 m and an effective depth of approximately 6m.

A proton precession magnetometer, such as the Geometrics G-856A portable proton magnetometer used at this site, utilizes the precession of spinning protons or nuclei of the hydrogen atom in a hydrocarbon fluid to measure the total magnetic intensity⁶. The spinning protons in the fluid behave as small, spinning magnetic dipoles. These magnets are aligned or polarized temporarily by the application of a uniform magnetic field generated by a current in a coil of wire in the G-856A. The precessing protons then generate a small signal in the same coil used to polarize them. This signal has a frequency that is precisely proportional to the total magnetic field intensity and independent of the orientation of the magnetometer. The proportionality constant, which relates frequency-to-field intensity, is the atomic constant, the gyromagnetic ratio of the proton. The precession frequency is measured by digital counters as the absolute value of the total magnetic field intensity with an accuracy of 1 gamma in the earth's field of approximately 50,000 gammas.

The total magnetic field intensity, as measured by the proton magnetometer, can be looked upon as the magnitude of the earth's field

vector, independent of its direction. Local disturbances, as might occur near buried metal objects, will add to the earth's magnetic field in the usual manner of vector addition. The local disturbances leave signatures (anomalies) in the data that can be very useful for locating buried metal objects.

Limitations in the use of the instrument come about when local large magnetic anomalies that are not the target of the investigation distort the signal greater than the targeted anomaly, effectively masking the target anomaly. This problem is common when magnetometer surveys are conducted near buildings, power lines, underground pipelines, etc.

Multiple techniques can be used with the EM, including vertical vs. horizontal dipole, profiling and phasing.⁷ Magnetic gradient measurements can be taken with the magnetometer.⁸ None of these techniques were used since the additional information they would have provided was not necessary for this particular site. However, these applications may be very useful elsewhere.

COLLECTION OF DATA

The aerial photograph (Fig. 1) indicates three areas of possible waste disposal. The first geophysical survey was made over a 200 x 400 ft. area covering the locations of the suspected areas and conducted on evenly spaced 20 ft. grids running north and south parallel to the existing building.

After the grids were set up, the instruments were calibrated and data were collected on every node. Terrain conductivity readings using the EM-31 were made in a north-south and east-west orientation over each node. The differences in readings at a node were later used as an additional criterion for determining anomalies. The readings were observed when walking between nodes, and any changes of over 5 mmhos/m dictated collecting mid-node readings. Total field magnetic intensity readings were made at each node using the Geometrics 856A proton precession magnetometer.

Following the initial survey, the grid was expanded to 400 x 700 ft. to collect data over the entire area on which the new building was to be built.

PRESENTATION OF DATA

This section presents the data collected with the EM and magnetometer. Figures 2 and 3 show topographic contour maps of the data from the EM and the magnetometer (entire 400 x 700 ft. survey). Note that magnetometer data in Figure 3 show a decrease in intensity on the eastern edge. This decrease is due to the magnetic properties of the steel-frame building that is 50 ft east of the survey area.

Building Anomaly correction

The magnetometer anomaly caused by the steel-framed warehouse 50 ft. from the eastern edge of the survey area can be modeled. Because the southern half of the survey was relatively free of anomalies (except for the building), the effect of the building can be calculated. Taking the average of each north-south line in the southern half of the survey (0 to 300 ft north) and comparing these values to the average values for the western part of the survey, the change due to the building is determined.

Figure 4 is an x-y graph showing the deviation in gammas versus the distance from the building. The actual deviation as well as the modeled theoretical deviation are shown. The modeled deviation treats the building as a series of monopoles and varies as the inverse square of the distance from the source (i.e., $1/r^2$)⁹. Now the building anomaly (900 gammas at the eastern-most edge) can be subtracted from the raw data and the data re-analyzed. The replotted magnetometer data are shown in Figure 5.

Defining Anomalies Using Statistics

The geophysical anomalies were defined using a simple statistical approach. The data were resolved by taking the average and standard deviation of the population and then considering as anomalous any data points outside plus or minus one standard deviation from the mean. This approach was intended to remove the subjective nature of deciding what is anomalous and assumes that the background readings, including

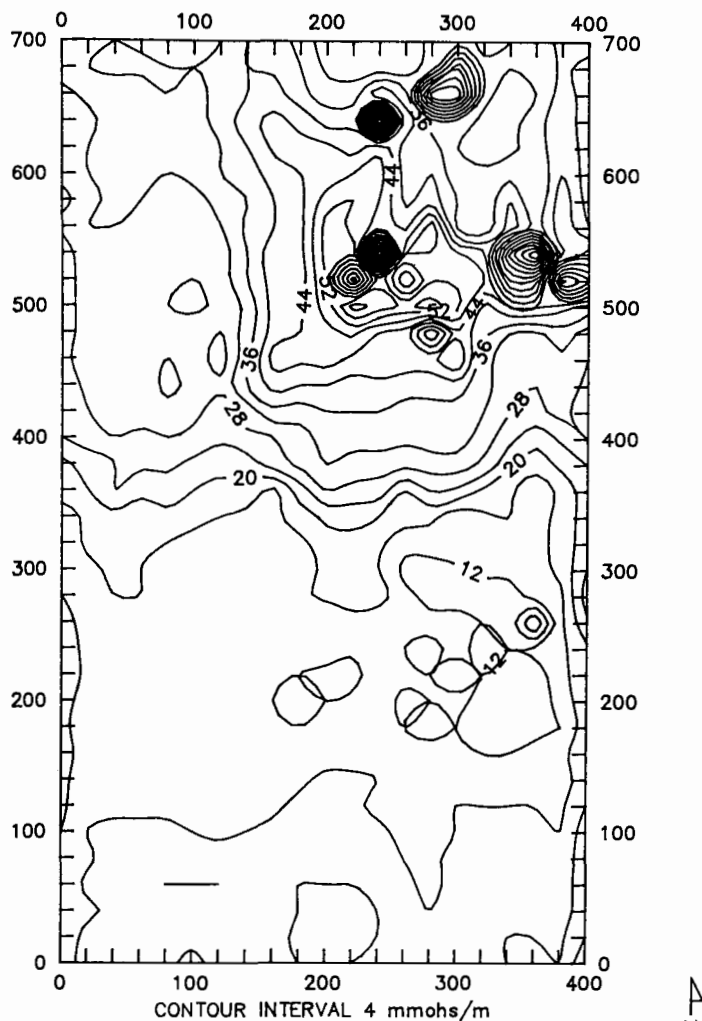


Fig. 2
Electromagnetic Conductivity Date.
N-S Orientation.

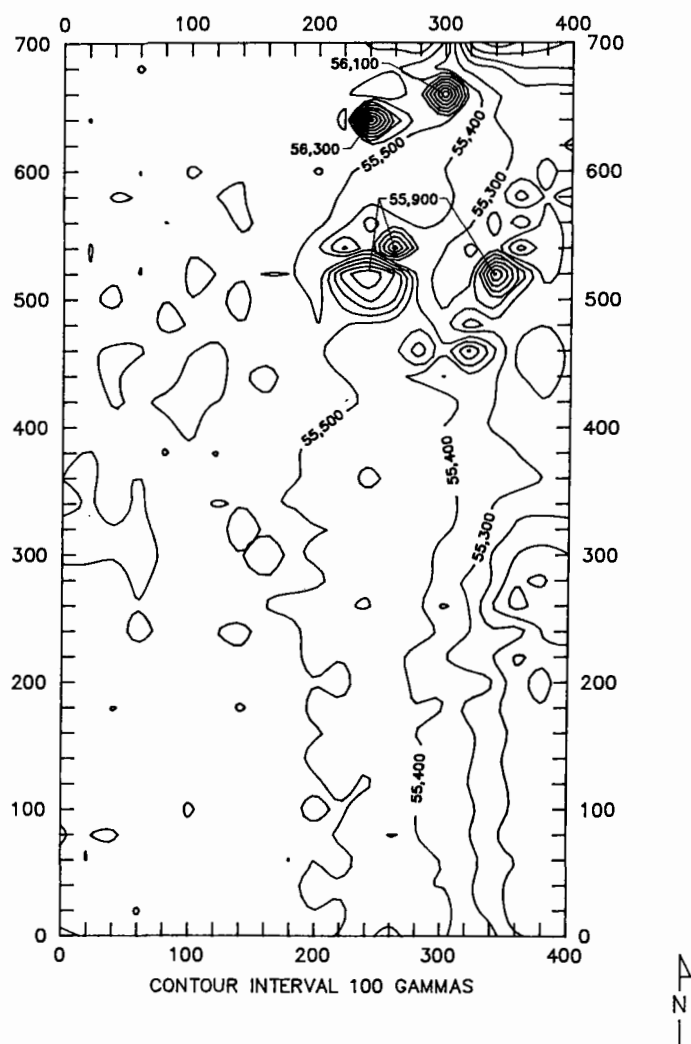


Fig. 3
Total Magnetic Field Contour Map

noise, fall inside one standard deviation and that the anomalous readings fall outside that range. The success of this approach is discussed later.

Analyzing the 762 data readings collected on the magnetometer survey, the mean was 55,408 gammas, with a range from 53,380 to 56,361 and a standard deviation of 254 gammas. Using the approach mentioned above, an anomaly would have to be more than 250 gammas to be distinguished.

Statistical analysis was performed on the modified readings that accounted for the building anomaly (values plotted in Figure 5). Using this approach, the mean is 55,529 with a standard deviation of 148 gammas. Based on this approach, any variation over 150 gammas was considered an anomaly. This second set of statistics was used in this paper.

EM Statistics

The same statistical approach can be used with the EM data as the magnetometer. Using all the data, the mean was 24.6 mmhos/m with a range from 0 to 69 and a standard deviation of 12 mmhos/m.

As with the magnetometer data, the desire is to determine the changes from the surroundings rather than the absolute readings. As seen in Figure 2, the values of conductivity are of two distinct levels; in the 30 range in the northern section and in the teens in the southern section. The transition between these two levels occurs at between 350 and 450 ft north on the grid.

Upon further investigation of the geotechnical borings gathered during the building design, a change in depth to bedrock was noted. Figure 6 shows the depth to bedrock along a north-south section of the site and

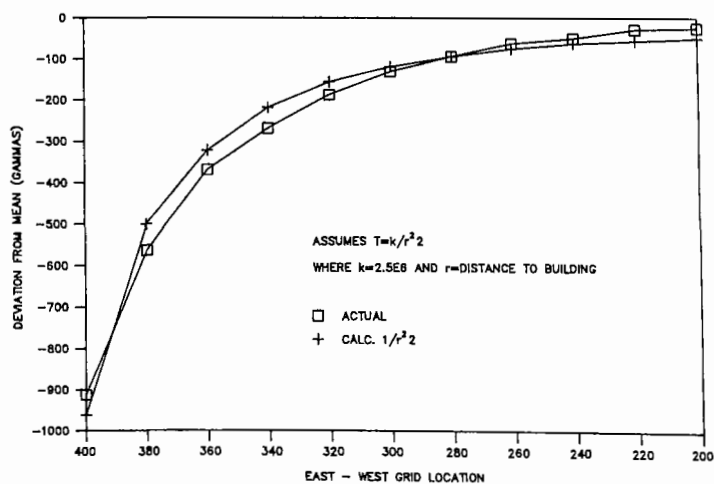


Fig. 4
Building Anomaly.
Actual Deviation vs. Calculated

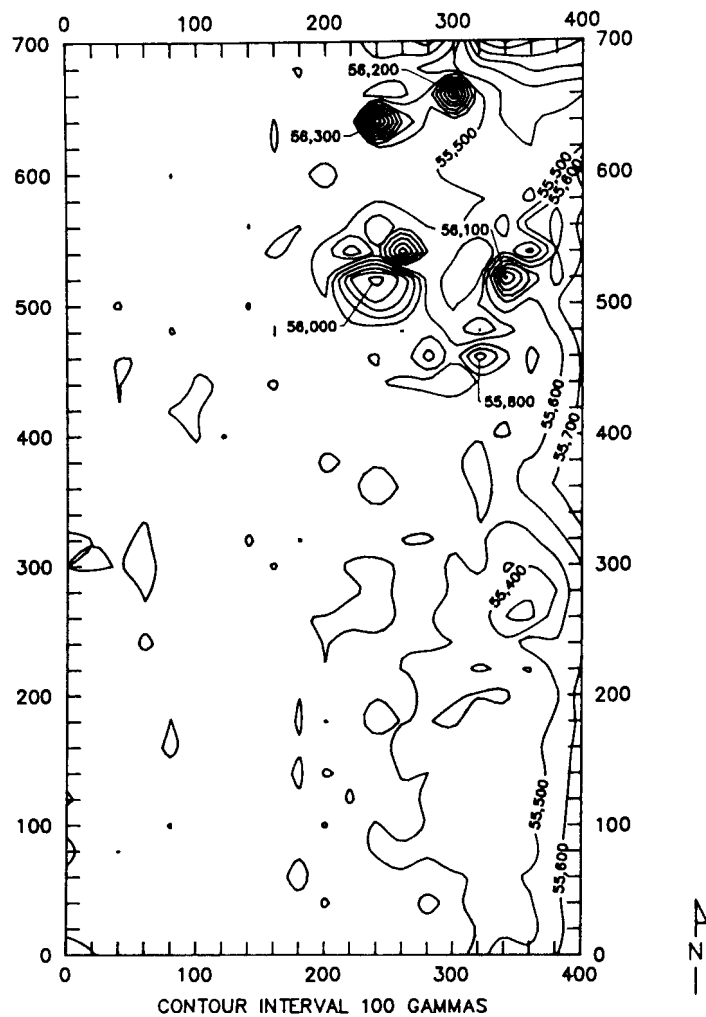


Fig. 5
Total Magnetic Field Contour Map
After Removal of Cultural Anomalies

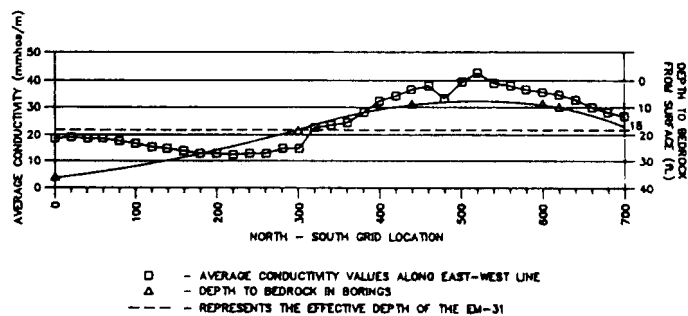


Fig. 6
Conductivity Change Due to Geological Structure

the corresponding average EM readings. The northern section is 7 to 10 ft to bedrock; the middle section is approximately 15 ft and the southern section did not encounter bedrock in the first 30 ft.

Recall that the depth of investigation of the EM-31 is approximately 18 ft. The EM-31 in the northern section was responding to a two-layer system of glacial till and shale, and the southern section was responding to only the till. Because the fractured shale has a higher conductivity, a higher reading in the north resulted.

With this observation in mind, the EM data were separated into two sections prior to statistical analysis (as northern and southern segments).

Area	Mean	Range	Statistical Analysis of EM Data (mmhos/m)
			Standard Deviation
Southern	15.3	0 - 27	3.3
Northern	35.6	0 - 69	9.6

Using this approach, two criteria arise for determining an anomaly: greater than 4 mmhos/m in the southern section and greater than 10 mmhos/m in the northern.

Absolute Difference Approach With the EM-31

It is very likely that the waste in the burial pits was placed randomly and of varying conductance. Therefore, electrical conductivity readings from varying directional orientations of the EM-31 could have different values.

Figure 7 is a plot of the absolute value of the difference in EM conductivity from the north-south and east-west orientations. This method identified all of the anomalies related to buried waste, plus additional responses to subsurface features.

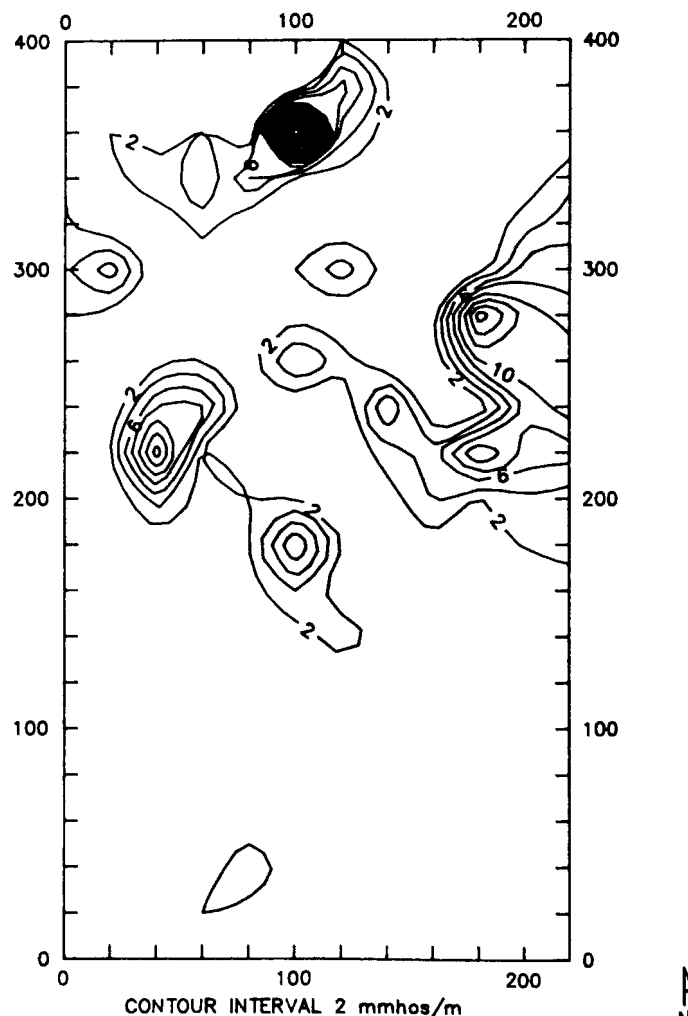


Fig. 7
Electromagnetic Conductivity Data.
Absolute Value of the Difference Between the
N-S and E-W Orientation.

Applying statistics to this set of data yields an average value of 1.2 mmhos/m, with conductivity differences ranging from 0 to 30 mmhos/m and a standard deviation of 2.1 mmhos/m.

Man-Made Anomalous Features

There were three man-made surface features on this site that created anomalies in the geophysical data (Figs 8 and 9): the building, a trailer on-site for personnel decontamination and a paved road.

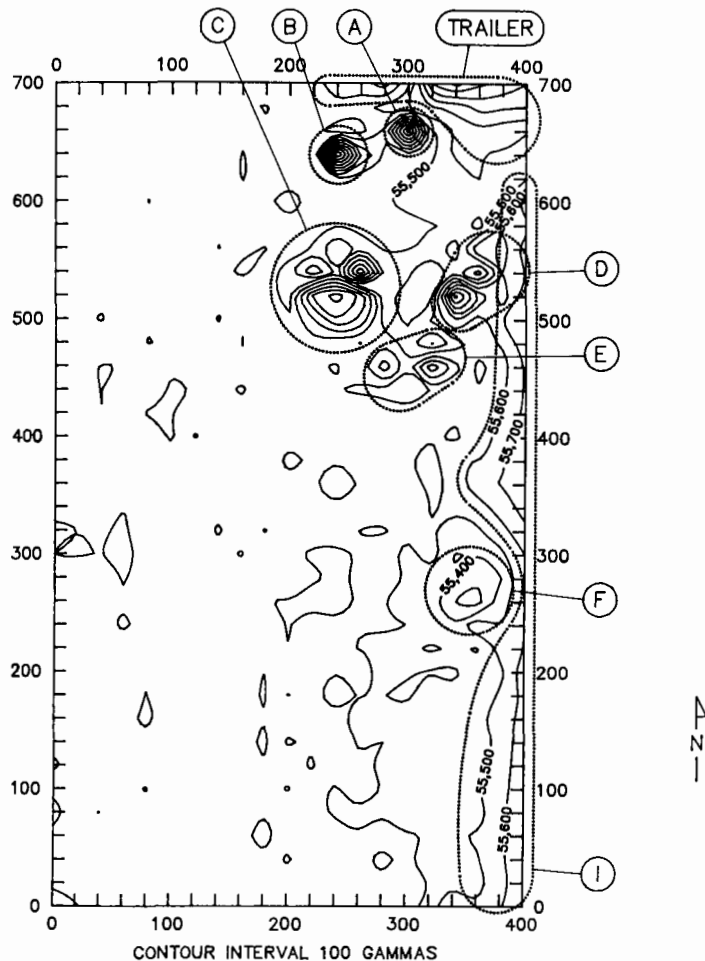


Fig. 8
Total Magnetic Field Contour Map
After Removal of Cultural Anomalies.
Anomalous Areas Delineated.

The building had a large impact on the magnetometer data, even though the survey never got closer than 50 ft to the building. The building had no significant anomalous effect on the EM data.

The decontamination trailer was located on the northern edge of the site. The trailer had a steel frame, aluminum body and dimensions of 10 x 25 x 10 ft (high). Anomalous values were seen in both the EM and magnetometer data due to this feature, although the effect on the EM was only at one point (this point, 700 north - 360 east, was not used in the analysis of the EM data). The trailer created an anomalous feature in the magnetometer data that extended up to 60 ft radially (Fig. 11), but did not affect the resolution of other anomalies.

The blacktop road (Fig. 11), given the accuracy of the magnetometer data and its close proximity to another anomalous feature (the building), had no distinguishable impact on the magnetic data. The effect of the road on the EM data was fairly uniform and consisted of elevated conductivity values of 6 to 8 mmhos/m.

Several other anomalies identified by the data are shown and labeled A through K on Figures 8, 9 and 10. Since all the anomalies related

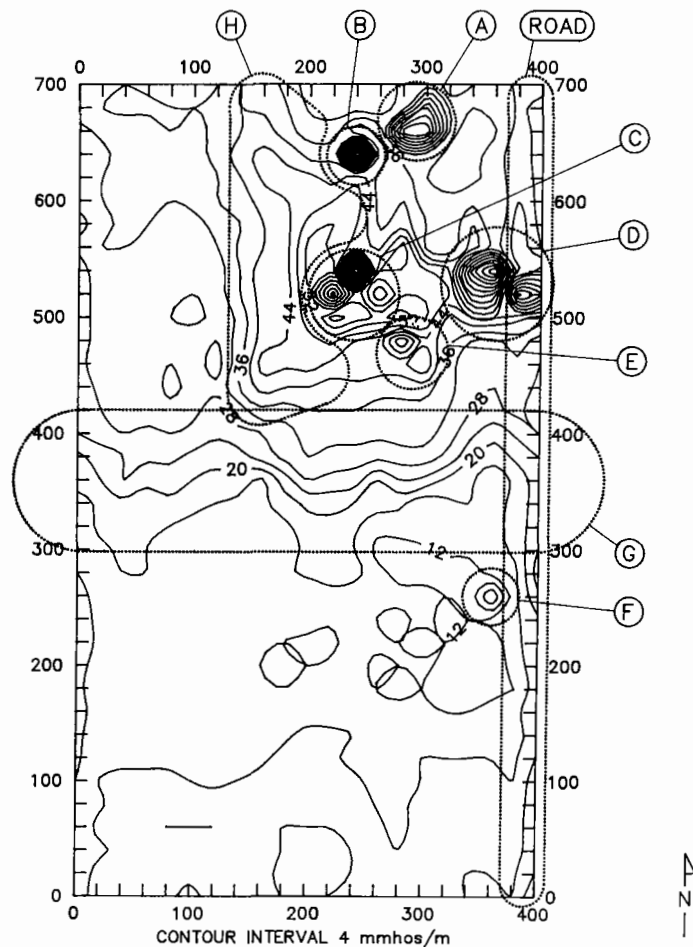


Fig 9
Electromagnetic Conductivity Data.
N-S Orientation.
Anomalous Areas Delineated.

to known man-made surface features have been identified and delineated, these labeled anomalies represent subsurface features with electromagnetic or magnetic properties significantly different from ambient conditions.

INTERPRETATION AND VERIFICATION OF ANOMALIES

All of these anomalies (A through K on Figures 8, 9 and 10) were then investigated directly by excavating the waste and digging additional confirmation trenches with a backhoe. Buried waste was removed to a temporary storage pad away from the proposed building site. Borings, both from a geotechnical investigation for the building site and from monitoring well installations, supplied additional correlative data.

The waste excavation, verification trenches and soil borings created a unique opportunity for the authors to compare each geophysical instrument's response to anomalous features at a hazardous waste site.

Figure 11 outlines excavated waste pits, verification trenches and soil borings with respect to the geophysical anomalies. The waste pit excavations shown in Figure 11 include the excavation of natural soils under and around the waste pits that had been contaminated by an organic leachate from the pits. The actual dimensions of the waste pits are somewhat less than shown. This organic leachate was not detected by the geophysical instruments.

Table 1 summarizes each geophysical anomaly detected. Included in the table are a physical description of what was found during excavation and trenching, the maximum instrument responses of each technique in relation to surrounding values and whether these responses were sufficient to be called an anomaly (> 1 standard deviation above the surrounding values).

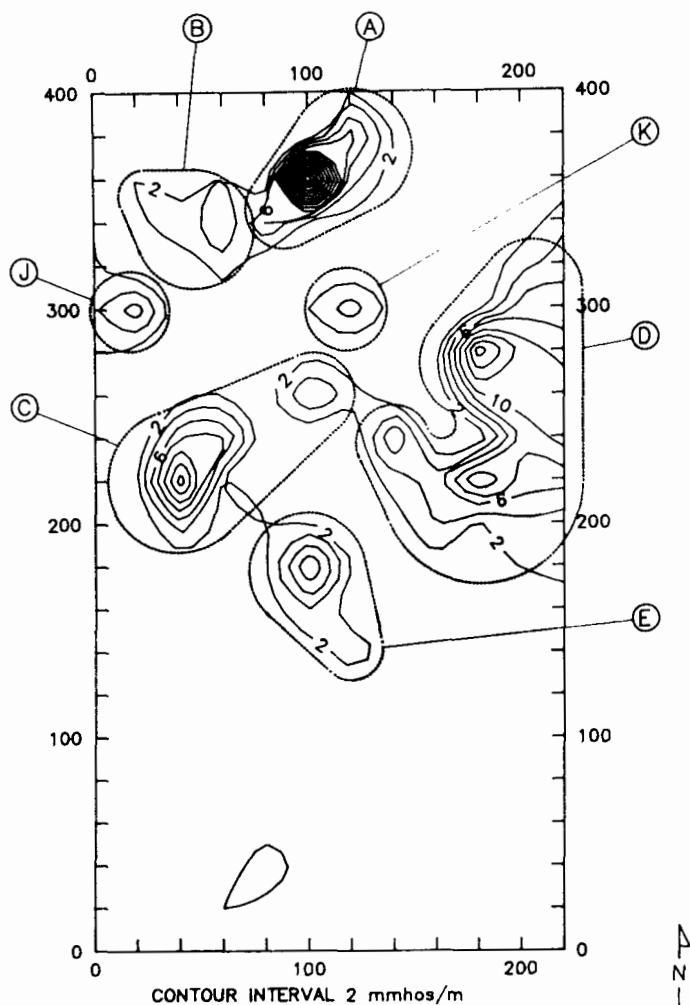


Fig. 10
Electromagnetic Conductivity Data.
Absolute Value of the Difference Between the
N-S and E-W Orientation.
Anomalous Areas Delineated.

All these techniques detected the waste pits (Anomalies A to E), but each instrument also responded to additional surface and subsurface features. The EM readings also detected two natural subsurface features (bedrock slope and subsurface tree roots). Taking the difference between EM orientations at a node eliminated these two, but detected two additional features (concrete slab and surface material). The magnetometer was not affected by the natural subsurface features and the smaller man-made features, but it was highly affected by the nearby building. Each instrument was "fooled" by extraneous geologic or man-made features, but had a high correlation in detecting waste when all three techniques detected an anomaly.

Figure 12 shows the geophysical properties of anomalies detected and also highlights the anomalies where buried waste was found. The wastes detected were either ferromagnetic (responded to magnetometer), possessed a significantly different conductivity value than background (responded to EM reading) or were heterogeneous (responded to EM orientation). Using the multiple property approach yielded a much higher success at predicting where the buried waste was located. The only feature that "fooled" all three techniques was the buried tin building, which coincidentally possessed the same three properties of the buried waste.

Each instrument responded to different physical properties of the buried material. Given a different set of field conditions, one instrument may perform better than another.

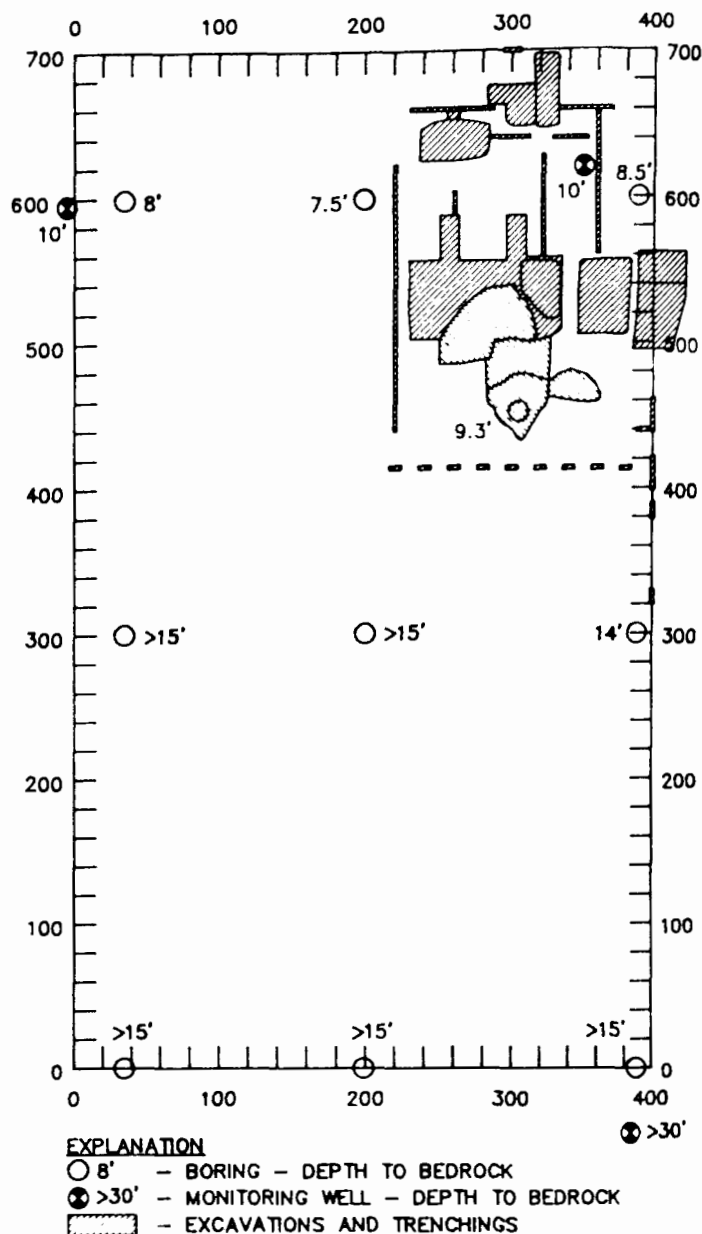


Fig. 11
Location of Waste Excavation,
Trenching and Soil Borings

The desire is to compare how well each instrument responded to each anomaly, but the magnetometer reads in gammas and the EM in mmhos/m. To be able to compare the two instruments, a "signal-to-noise ratio" was calculated using the maximum response divided by the standard deviation of the readings for the survey. In this manner, the relative responses of each instrument can be compared. Table 2 shows the signal/noise ratio of each anomaly using the three techniques.

The EM and magnetometer both responded to all five of the waste areas (anomalies A to E). Additionally, the EM responded to four more subsurface features (a buried tin building, shale escarpment, a buried copper pipe and tree roots) and the magnetometer to one more subsurface feature (a buried tin building) and one cultural feature (the building).

The magnetometer had an average signal-to-noise ratio of nearly four in the waste areas (anomalies A to E), compared to approximately three for the EM. This suggests that the magnetometer may have been slightly

Table 1.
Anomalies Defined

Anomaly Location ¹	Maximum Instrument Response Above Background		EM - Difference N-S less E-W Orientation	Does Response Meet Statistical Criteria?		EM Difference ≥ 3.3 mmhos/m	Physical Description Based on Excavation Work ³
	EM (milliMhos/m)	Mag (gamma)		EM (10 mmhos/m in North, 4 mmhos/m in South) ²	MAG (150 gammas)		
A	28	250	28	Yes	Yes	Yes	Waste pit: 12' x 50', 6' depth, 2' below surface containing two drums.
B	40	900	4	Yes	Yes	Yes	Waste pit: 15' x 25', 7' depth 2' below surface, no drums.
C	23	500	12	Yes	Yes	Yes	Waste pit: 50' x 60', 3' - 5' depth, 1' below surface, some drum pieces.
D	37	700	14	Yes	Yes	Yes	Two waste pits: 20' x 60' and 30' x 40', 3' - 5' depth, more scrap metal, eastern pit: 25 drums, scrap copper wire and 5-gallon cans.
E	11	400	8	Yes	Yes	Yes	Waste pit: numerous pits 5' - 10' diameter, 4' depth, 1' below surface, some drums, numerous 5-gallon cans.
F	13	200	8	Yes	Yes	Yes	Tin battery remains: 7' x 15', 4' depth, 2' below surface, sheets of tin, lumber, nails, concrete; no waste.
G	15	0	0	Yes	No	No	Geologic feature: bedrock; slopes to the South.
H	12	0	0	Yes	No	No	Tree Root Zone: Aerial photo shows wooded zone between disposal area and farm field. 4' depth, 2' below surface.
I	0	900	0	No	Yes	No	Man-made feature: building 50' east of survey area.
J	0	0	4	No	No	Yes	Concrete slab: 3' x 5' x 6", 2' below surface, contained 1/2" copper pipe; used as a ground in prior field office.
K	0	0	4	No	No	Yes	Surface material: no subsurface feature found.

¹ Location as shown on Figures 10, 11, and 12.

² Statistical Criterion: > 1 standard deviation response.

³ Waste pits contained an assortment of waste, including ash, paint sludge, miscellaneous scrap metal, and occasionally partially intact 55-gallon drums.

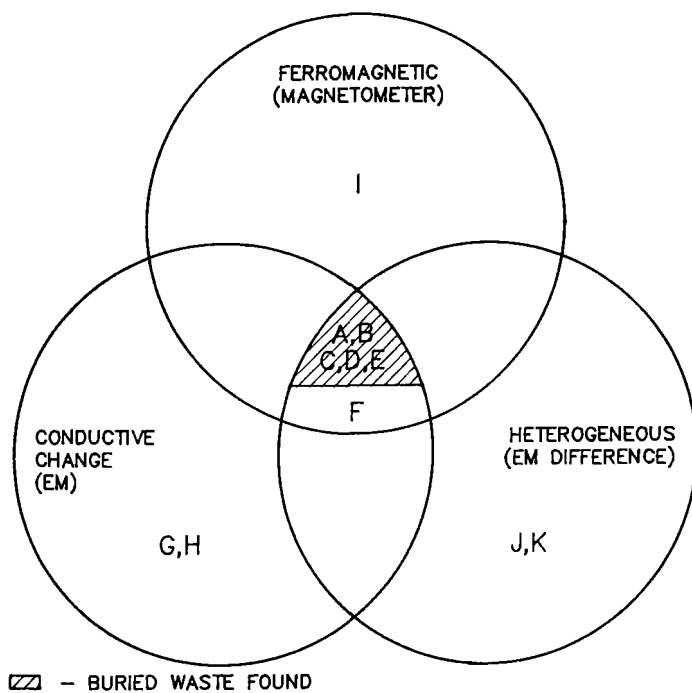


Fig. 12
Property of the Geological Anomalies
Comparing the Response of the Instruments

Table 2
Relative Response to Anomalies

Anomaly	Relative Response ¹		
	EM	EM-DIF	MAG
A	2.9	7.8	1.7
B	4.2	1.1	6.1
C	2.4	3.3	3.4
D	3.9	3.9	4.7
E	1.2	2.2	2.7
F	3.9	2.2	1.3
G	1.0	0.0	0.0
H	1.0	0.0	0.0
I	0.0	0.0	1.1
J	0.0	1.1	0.0
K	0.0	1.1	0.0

¹Relative Response is the maximum instrument response divided by the standard deviation of the data. Analogous to a signal-to-noise ratio.

more responsive to the waste than the EM.

The magnetometer is much more sensitive to cultural features such as buildings. Although the authors later accounted for the response due to the building, other less intense anomalous features near the building would have been difficult to distinguish from the building anomaly, making the analysis more complex. The EM, on the other hand, was not affected by the building and at 50 ft from the building did not show a measurable instrument response.

CONCLUSIONS

The hazardous waste disposal practices used at this manufacturing facility are most likely similar to many of those that can be found at hundreds of other small- to medium-size manufacturing facilities that were operating prior to the enactment of RCRA. It is likely that the majority of these small waste sites will have to be dealt with in the future. As with this site, there usually is very limited information available. The surface geophysical techniques discussed in this paper can very effectively locate and delineate suspected waste disposal sites. The information presented here should provide valuable help to others faced with similar problems relative to the effective use and interpretation of the surface geophysical data at a hazardous waste site.

The use of multiple geophysical techniques is much more diagnostic than the use of only one instrument. By using two techniques, different properties of a buried material are being tested. The presence of a positive response for both properties, conductivity and ferromagnetism, consistently detected the buried waste and yielded a false positive less frequently.

Each individual technique was "fooled" due to geologic or man-made features. When two out of three techniques responded positively, buried waste was found.

Considering all the information derived from the geophysical survey, the EM-31 proved to be a more versatile investigative tool. It identified all the waste pits and provided information about the subsurface, the location of a buried bedrock escarpment and the extensive root zone, which was valuable to the hazardous waste site investigation.

REFERENCES

1. Neev, D., "Application of Geophysical Methods for Subsurface Metal Screening: A Case Study," *Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, SAGEEP, Mar. 1988.
2. McGinnis, L.D., Winter, R.C., Miller, S.F. and Tome, C., "Decision Making on geophysical techniques and results of a study at a hazardous waste site," *Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, SAGEEP, Mar. 1988.
3. Benson, R.C., Glaccum, R.A. and Noel, M.R., *Geophysical Techniques for Sensing Buried Wastes and Waste Migration*, U.S. EPA. Contract No. 68-03-3050: Technos, Inc., Miami, FL, 1983.
4. Benson, R.C., *Surface and downhole geophysical techniques for hazardous waste site investigation*, HML pp 9-18, 53-60, April/May 1988.
5. Geonics Limited, *Operating Manual for EM-31-D Non-contacting Terrain Conductivity Meter*, June 1984.
6. Breiner, S., *Applications Manual for Portable Magnetometers: Geometrics*, Sunnyvale, CA, 1973.
7. McNeil, J.D., "Advances in Electromagnetic Methods for Groundwater Studies," *Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, SAGEEP, Mar. 1988.

Detection and Location of Leaks in Geomembrane Liners Using an Electrical Method: Case Histories

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ABSTRACT

A field-proven electrical technique, developed at Southwest Research Institute, San Antonio, Texas, is commercially available to detect and locate leaks in geomembrane liners. The electrical technique is used to inspect 100% of the geomembrane material that is covered by a conducting liquid. A voltage applied across the liner produces a uniform electrical potential distribution in the liquid or soil above the liner when no leaks are present in the geomembrane. If leaks are present, they are detected and located by searching for localized anomalies in the potential distribution caused by current flowing through the leak in the geomembrane liner. Sixty-one new or in-service geomembrane-lined waste storage facilities were investigated using the electrical leak location method. An average of 3.2 leaks per 10,000 ft² were located with a range of 0.3 to 5 leaks per 10,000 ft² of liner surveyed. Many leaks were located in new installations that had been tested using conventional inspection tests.

INTRODUCTION

Survey Method

Figure 1 shows a diagram of the Southwest Research Institute electrical leak location method which illustrates the technique described in this paper. When no leaks are present, the high electrical resistivity of the geomembrane liner material will prevent electrical current flow from the liquid in an impoundment to the earth ground or leak collection zone beneath the geomembrane liner. When a voltage is impressed across a geomembrane liner with no leaks, a relatively uniform potential voltage distribution is found in the liquid or soil cover above the liner. If a leak exists in the liner, conductive fluid will flow through the leak establishing a path for electrical current. An anomaly in the measured electrical potential is generated in the immediate vicinity of the leak through which electrical current is flowing. Leaks can be accurately located to less than 1 in. by searching for the point of highest electrical potential.

Survey Equipment

The equipment used in a manual leak location survey consists of a DC power source, lightweight man-portable electronic detector, scanning probe and associated instrumentation as shown in Figure 2. The probe is most conveniently used while wading in the liquid. However, with an extension, it can be used from a floating platform in deeper liquid applications.

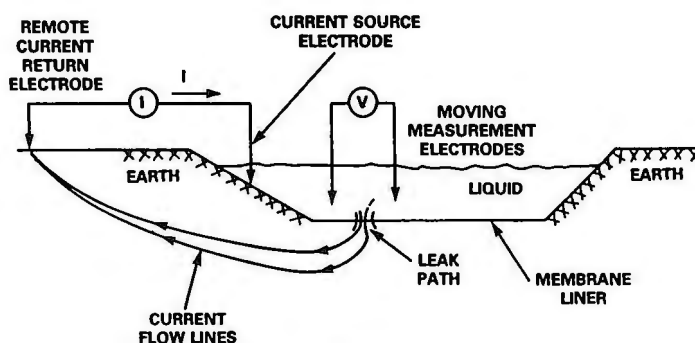


Figure 1
Diagram of the Electrical Leak Location Method



Figure 2
Manual Leak Location Equipment Consisting of an Electrode Probe and Electronics Unit

MANUAL LEAK LOCATION SURVEY IN LIQUID IMPOUNDMENT

To conduct a manual leak location survey, a minimum of 12 in. of a conducting liquid and a maximum of 30 in. of conducting

liquid (preferably fresh water) must cover the liner. Filling the impoundment to the operating depth with fresh water is recommended to hydrostatically load the liner prior to the leak location survey. Testing the liner after hydrostatically loading it is a valid method to determine if the liner will perform satisfactorily under the intended operating conditions. The water is then lowered in stages as the side slopes of the impoundment are electrically tested. After the water has been lowered to 30 in. in depth, the bottom floor area is surveyed.

In surveying a double liner impoundment, provisions must be made to ensure that the material between the geomembrane liners provides electrical conduction to a return electrode placed in the leak collection zone. The test is best accomplished by flooding the leak collection zone with fresh water. To provide electrical contact to the leak collection zone, a stainless steel return electrode with connecting wire is placed in the zone prior to the installation of the primary liner. The return electrode also can be temporarily placed in the leak collection drain pipe if access is available. In both cases, the return electrode must be covered with water.

Air vents should be provided along the perimeter edges of the primary liner near the top of the berm to vent air trapped between the liners. This procedure will help prevent damage to the liner caused by trapped air floating the liner during flooding of the leak collection system. Impoundments that use sand as the material in the drainage layer usually do not require water flooding of the leak collection zone. This is because the sand contains sufficient residual moisture to allow electrical current flow in the sand drainage layer. However, a permanent stainless steel electrode placed in the sand drainage layer prior to the placement of the primary liner will greatly facilitate electrical leak location surveys.

Electrical conduction paths, other than leaks, such as steel piping, piers, fasteners and battens must be electrically isolated for best leak location results. Certain preparations such as rubber packers in inlet and discharge pipes will prepare most geomembrane lined impoundments for a successful leak location survey. The electrical leak location survey method can be most effectively and economically applied if the impoundment or landfill is designed such that electrical conduction paths between the liquid in the impoundment and the earth ground are eliminated or can be electrically insulated.

SURVEYS OF SOIL-COVERED GEOMEMBRANES

A protective soil cover often is placed over the primary geomembrane liner of landfills to protect the liner from mechanical damage when placing the waste material in the landfill. In addition, a sand drainage layer often is used as the drainage medium in the leak detector zone of double liner installations. However, during the placement of the protective soil cover or the sand drainage layer, the liner can be damaged by the equipment used to place the soil cover, tools used to spread the material, sharp rocks in the soil or by a variety of other mechanical mechanisms. Often the mechanical damage to the liner is undetected and covered by the placing of the protective soil cover. The electrical leak location survey technique has been successfully adapted to locate leaks in geomembranes covered with up to 2 ft of a protective soil cover or sand drainage layer. Leaks were located and later verified beneath protective soil cover, sand drainage layers and thin sediment layers at several sites surveyed.

A protective soil cover or sludge cover over a geomembrane can decrease the effectiveness of a leak survey in three ways:

- (1) The strength of the signal received may be reduced because of inhomogeneities in the soil cover or sand drainage layer
- (2) The ability of the electrodes to detect leak signals is decreased because of the dissimilarity of the soil and water medium contacting the electrode, resulting in undesirable transient signals caused by polarization of the electrodes

- (3) The scanning probe cannot be scanned close to the geomembrane liner

The first condition is solved by systematically conducting the survey on an established survey grid and recording the current signature every 24 in. The acquired data are analyzed in the field and a plot of anomalies is produced which allows for a resolution of the leak locations. The dissimilarity or polarization problem is overcome by using specially designed electrodes to eliminate electrode polarization.

TYPES OF FACILITIES AND MATERIALS SURVEYED

Facility Types Surveyed

The electrical leak location survey method was used to survey geomembrane lined facilities ranging in size from 970 to 584,800 ft². The facilities tested include:

- Primary and secondary liners at landfills
- Concrete vaults for solid waste storage
- Wastewater storage ponds for sewage treatment facilities
- Above ground steel tanks for storage of hazardous materials
- Brine storage impoundments
- Descaling ponds for natural gas transmission companies
- Cooling water ponds

Materials Surveyed

Approximately 92% of all materials by area surveyed were high density polyethylene (HDPE). At installations lined with HDPE, the predominant material thickness was 60 mil. The remainder of the HDPE material had a thickness of 80 or 100 mils. The other liner materials were polyvinyl chloride (PVC), oil-resistant polyvinyl chloride (XR-5) and oil-resistant chlorosulfonated polyethylene (OR-CSPE). Generally, the seams at a given facility had been inspected using conventional inspection techniques such as visual inspection, air-lance, spark testing or vacuum box prior to the electrical leak location survey. After the electrical leak location survey was completed, the presence of the leaks detected and located by the electrical method was verified at several of the facilities using the vacuum box technique.

DISCUSSION OF LEAKS DETECTED AND LOCATED

Leak Statistics

Sixty-one sites with an approximate total area of 4,368,785 ft² of liner material have been commercially surveyed. Tables 1, 2 and 3 present a summary of all the commercial leak surveys conducted to date using the electrical method developed at Southwest Research Institute. A total of 1409 leaks were located at the 61 sites surveyed which equates to an average of 3.2 leaks/10,000 ft² of liner material inspected.

Figures 3 through 7 are plots of the data as a function of the area surveyed and the leak location on seams or sheet, total number of leaks or area ratio of the leaks located. Figure 7 is a plot of the number of sites surveyed vs. the area ratio of the leaks located which indicates that there may be between 0.3 and 0.5 leaks/10,000 ft² of geomembrane liner.

Leaks on Side Slopes

The side slopes were surveyed at approximately 25% of the liners surveyed. The majority of leaks on the side slopes occurred on the seams. At the facilities where the side slopes were tested, leaks on the side slopes comprised approximately 20% of the total leaks located.

Leaks in the Bottom of the Liner

Leaks on the bottom of liquid impoundments were found in the parent material, field seams and factory seams. Eighty-seven

Table 1
Leak Detection and Location Survey Data for Impoundment Where the Bottom Floor Area was Surveyed.

SURVEY NO.	SIZE SQ. FEET	TOTAL LEAKS	LEAKS LOCATED IN			LEAKS PER 10,000 SQ. FEET
			BOTTOM	SEAM	SHEET	
1	958	2	2	2	0	20.9
2	958	3	3	3	0	31.3
3	958	3	3	3	0	31.3
4	1,000	4	4	3	1	40.0
5	1,798	0	0	0	0	0.0
6	2,625	6	6	6	0	22.9
7	3,000	21	21	21	0	70.0
8	3,000	4	4	4	0	13.3
9	3,200	0	0	0	0	0.0
10	4,951	0	0	0	0	0.0
11	4,951	17	17	17	0	34.3
12	4,951	2	2	2	0	4.0
13	5,175	2	2	1	1	3.9
14	7,007	4	4	4	0	5.7
15	12,600	7	7	7	0	5.6
16	18,346	50	50	35	15	27.3
17	26,016	7	7	7	0	2.7
18	26,016	4	4	4	0	1.5
19	27,297	8	8	6	2	2.9
20	32,292	25	25	25	0	7.7
21	43,560	2	2	2	0	0.5
22	45,345	4	4	4	0	0.9
23	50,000	6	6	6	0	1.2
24	50,400	193	193	188	5	38.3
25	54,500	29	29	18	11	5.3
26	55,025	12	12	12	0	2.2
27	58,900	8	8	6	2	1.4
28	62,500	21	21	19	2	3.4
29	64,583	29	29	21	8	4.5
30	65,340	56	56	55	1	8.6
31	65,369	6	6	6	0	0.9
32	65,369	7	7	5	2	1.1
33	65,369	5	5	3	2	0.8
34	65,500	7	7	5	2	1.1
35	65,500	5	5	3	2	0.8
36	74,088	20	20	19	1	2.7
37	82,500	18	18	15	3	2.2
38	87,120	8	8	7	1	0.9
39	87,120	17	17	17	0	2.0
40	99,050	18	18	14	4	1.8
41	135,036	17	17	16	1	1.3
42	150,781	64	64	46	18	4.2
43	152,460	2	2	2	0	0.1
44	152,460	7	7	7	0	0.5
45	157,584	12	12	10	2	0.8
46	164,085	18	18	16	2	1.1
47	362,690	51	51	37	14	1.4
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TOTALS	2,769,336	811	811	709	102	2.9

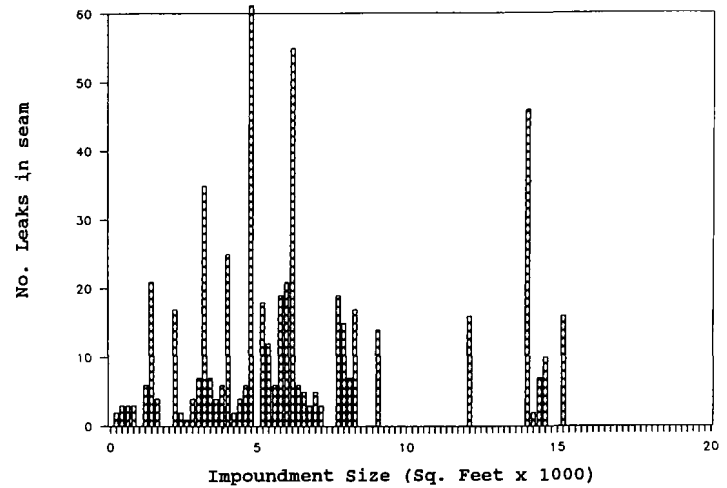


Figure 3
Histogram of Total Leaks Located vs. Bottom Floor Area Surveyed

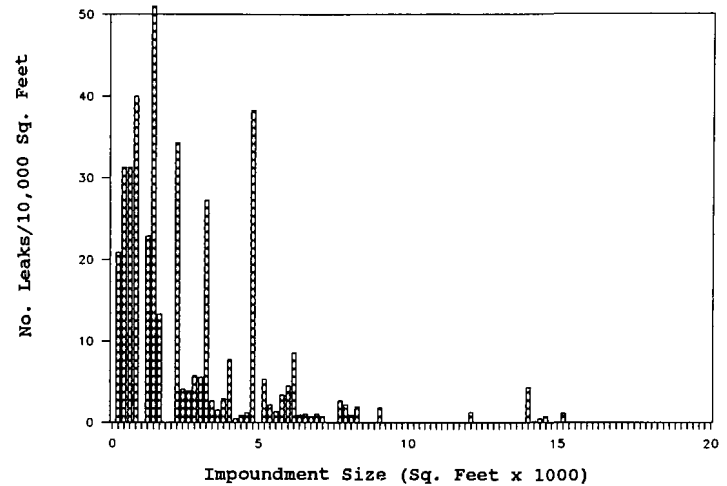


Figure 4
Histogram of Leaks per 10,000 ft² of Liner Surveyed

Table 2
Leak Detection Data for Impoundment with the Side Slopes and Bottom Floor Area Surveyed.

SURVEY NO.	SIZE SQ. FEET	TOTAL LEAKS	LEAKS LOCATED IN			SIDE SLOPE	LEAKS PER 10,000 SQ. FEET
			BOTTOM	SEAM	SHEET		
1	9,620	16	12	14	2	4	16.6
2	12,540	16	12	12	4	4	12.8
3	24,000	40	33	33	7	7	16.7
4	24,272	47	31	46	1	16	19.4
5	25,000	22	10	15	7	12	8.8
6	25,000	15	7	10	5	8	6.0
7	35,291	42	31	33	9	11	11.9
8	42,022	14	7	12	2	7	3.3
9	50,000	4	4	3	1	0	0.8
10	51,000	20	13	19	1	7	3.9
11	62,500	50	26	44	6	24	8.0
12	130,680	192	183	183	9	9	14.7
13	522,720	41	31	31	10	10	0.8
14	584,804	79	54	61	18	25	1.4
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TOTALS	1,599,449	598	454	516	82	144	3.7

Table 3
Survey Data for All Impoundments Inspected.

	SITES	TOTAL AREA	TOTAL LEAKS			SIDE SLOPE	LEAKS PER 10,000 SQ. FEET
			LEAKS BOTTOM	LEAKS SEAM	LEAKS SHEET		
BOTTOM AREA ONLY	47	2,769,336	811	811	709	N/A	2.9
BOTTOM AND SIDE AREA	14	1,599,449	598	454	516 *	82	3.7
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TOTAL	61	4,368,785	1,409	1,265	1,225	184	6.7

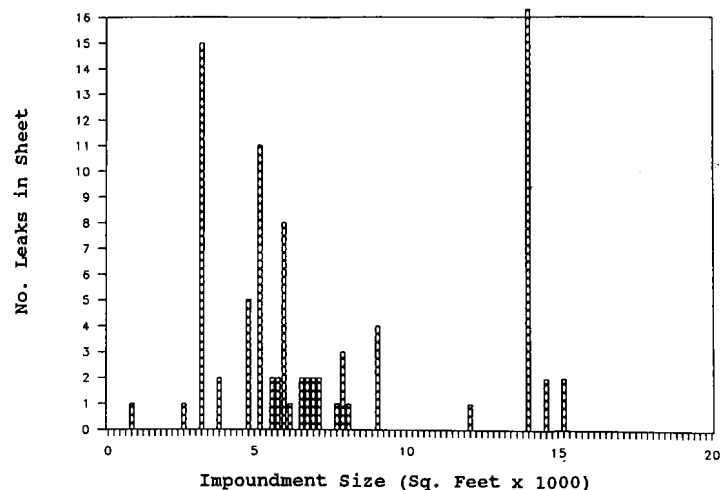


Figure 5
Histogram of Leaks in the Parent Material vs. Impoundment Size

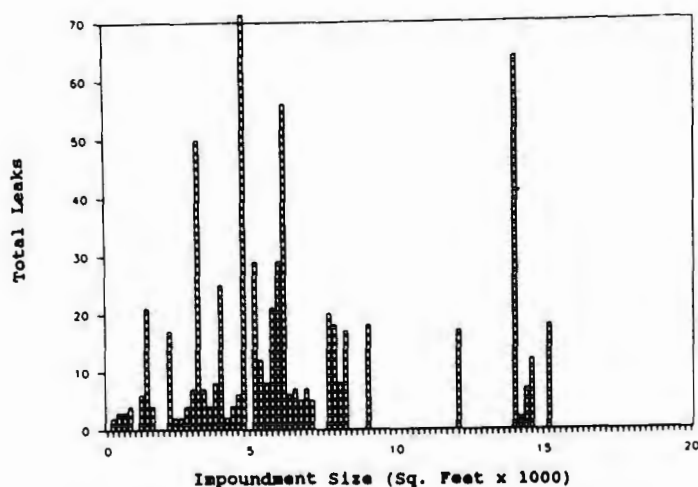


Figure 6
Histogram of Leaks in Seam vs. Impoundment Size

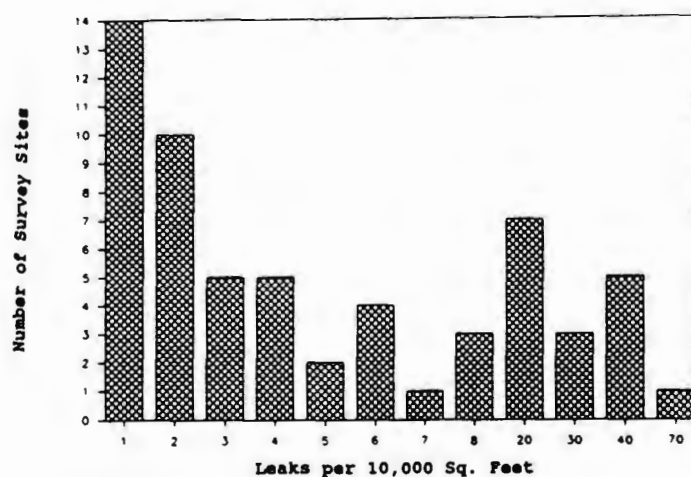


Figure 7
Histogram of Number of Sites Surveyed vs. Number of Leaks Located per 10,000 ft² of Geomembrane Liner

percent of the leaks were in seams, and the remaining 13% were in the parent material. Figures 8 and 9 show examples of seam leaks detected with the Southwest Research Institute electrical leak location system. Leak sizes and shapes ranged from relatively circular holes from less than 0.025 to 1 in. in diameter, to slits from 0.25 to 12 in. long, to gashes and gouges up to 6 by 8 in., to evidently tortuous paths through seam welds.

Leaks in Parent Material

The leaks in the parent material generally can be attributed to accidental damage from equipment or tools, crescent-shaped cracks due to equipment being dropped, slits due to razor-edged tools cutting the liner, burns from cigarettes, gashes and gouges. Figures 10 and 11 show typical leaks in the parent material. Some of the leaks in the parent material probably were caused by improper material handling or wind buffeting. Many leaks in the parent material of installations with a protective soil cover appeared to have been created during the application of soil cover over the liner.

The observed ratio of parent material leaks to seam leaks may be slightly less than actual because the seams are double-checked during the leak location survey process. While rechecking the seams, the search probe tip is scanned within 1 in. from the leaks in the seams. However, during the general survey of the geomembrane, the parent material is swept at 12 in. intervals placing the



Figure 8
Leak in HDPE Seam. Approximate Leak Size 0.025 in. (Note: Leak not apparent in reproduced photograph.)



Figure 9
Leak in Parent Material



Figure 10
Large Leak in HDPE Parent Material

electrical probe as much as 6 in. from a potential leak point. Because the probe tip is approximately six times closer to potential leaks when surveying the liner seams, it is probable that very small leaks found in the seams are not detected in the parent material.



Figure 11
Cut in HDPE Parent Material

Leaks in Seams

Inadequate field seaming appears to be the primary cause of leaks in geomembrane lined impoundments. Eighty-seven percent of the total number of leaks were in field welded or bonded seams. Many of the leaks occurred at T-joints, patches and at seams in highly-stressed areas such as at the base of the sideslope. Some leaks were found in seams which previously had been repaired and tested. Figures 12, 13 and 14 show typical leaks located in seams. Leaks may not develop in the seams until a hydrostatic load is placed upon the liner. Cases were documented where obviously poor seaming techniques resulted in seams failing indiscriminately after repair and hydrostatic loading. In such cases, it is suggested that the entire liner installation be redone.



Figure 12
Leak in Seam

Leaks Associated with Penetrations and Structures

In some facilities, numerous leaks were found around penetrations or structures in an otherwise excellent field installation. Many designs incorporate complex seam requirements when attempting to isolate drainage cribs, separation walls, concrete sumps, concrete pads and other structures. Where such structures are necessary, the electrical method may be the only method which can be applied to test for leaks.

Leaks Associated with Material Types

Because of the limited use of materials other than HDPE in the

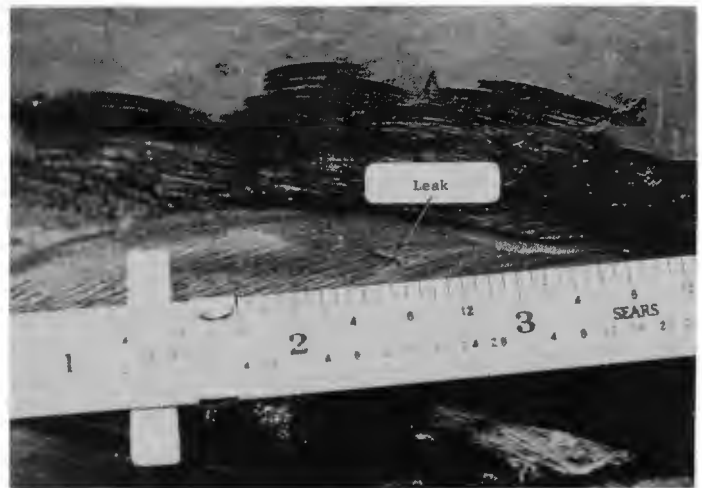


Figure 13
Leak in Seam After Grinding, Just Prior to Repair



Figure 14
Leak in Seam Where Seaming Material Did Not Bond to Sheet

facilities tested by the Southwest Research Institute electrical method, it is not possible to formulate any valid conclusions on the relationship of material type to numbers and types of leaks.

Leaks Beneath Soil Covers and Sludge

The Institute has successfully located leaks beneath installed soil cover up to 2 ft thick. Leaks have been found beneath chemical precipitate sludges, but the application of the electrical method in the sludge environment is extremely tedious and demanding. The leaks found beneath soil covers have included seam leaks and leaks in the parent material apparently caused by the heavy equipment which was placing the protective soil cover material. Figures 15, 16 and 17 show leaks located under 2 ft of sand placed over the primary geomembrane liner. No significant numerical relationships between leaks, leak occurrence and types of leaks can be developed on leaks discovered beneath soil covers because of the limited field testing experience in such environments.

CONCLUSIONS

The electrical leak location method is a very sensitive, accurate and valid method for locating leaks in geomembrane liners. Leaks were found in every liner surveyed except for three liners that were less than 500 ft² in area. Leaks were located in liners that had been rigorously tested using one or more of the conventional methods for testing geomembrane liners.



Figure 15
Leak Under 2 ft of Protective Sand Cover



Figure 17
Tear in Liner Covered with 2 ft of Sand



Figure 16
Mechanical Damage to Liner Under 2 ft of Sand Cover

The number of leaks per 10,000 ft² of surveyed area typically ranged from 0.3 to 5 with an average density of 3.2 leaks/10,000 ft² of geomembrane liner. Several liners had greater than 20 leaks/10,000 ft² of area surveyed.

The density of leaks generally decreases as the liner size increases. Possible explanations for this are:

- Smaller installations have proportionally more complex features such as corners, sumps and penetrations
- Small installations tend to have higher proportions of hand seaming
- Larger installations tend to have better QA/QC programs
- Larger installations generally receive proportionally less traffic

From our experience, and knowledge of the history of some of the liners surveyed, the major factors for minimizing the number of leaks in geomembrane liners in the general order of importance are: the professionalism and skill of the seaming machine operator; environmental factors such as moisture, temperature and wind; simplicity of the liner design; thickness and weldability of the liner material; and liner care and handling procedures.

The electrical leak location method has demonstrated that geomembrane installations can benefit from an electrical method leak location survey as a part of the construction quality assurance program. Pre-service testing of new installations using the electrical leak location method will enhance the overall performance of the containment facility.

Field Analytical Screening of Soil for Preremedial Hazardous Waste Site Investigations by Thermal Chromatography/Mass Spectrometry

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ABSTRACT

The Field Analytical Screening Project (FASP) for the U.S. EPA preremedial program requires rapid and chemically specific analyses of samples for hazardous substances. The preremedial U.S. EPA Region 2 FASP program is also an interactive program that requires the field project manager and the FASP analytical manager to make field decisions on the data generated in the screening process.

For soil organic analyses, the U.S. EPA's Contract Laboratory Program (CLP) requires extensive wet chemical extraction and cleanup before mass spectral analysis. These time-consuming methods can only be done effectively in conventional fixed-base laboratories. Therefore, samples from a preremedial site investigation are transported to CLP labs for extraction and analysis. This procedure can cause delays of weeks or even months between sample collection and return of the results. This delay hinders efficient site evaluation efforts and can result in repetition of work. The development of analyte-specific alternative methods for use by the FASP program can complement the CLP program while decreasing the sample turn-around time.

In an effort to obtain fast organic results to guide screening and cleanup work, in-field portable gas chromatographs (GCs) have been utilized. Unfortunately, the low specificity of these instruments and the broad gap between in-field protocols and CLP methods can lead to poor correlation with CLP results. Laboratory tests done in the last few years indicate that a new technique known as thermal extraction/gas chromatography (TC) can give results comparable to conventional wet chemical extraction of soils. TC is fast and since no sample preparation is necessary, it can speed up considerably the time from sample receipt to analytical data.

Coupling the TC to a mass spectrometer (MS) leads to a new era for organic analysis. Analytical equipment with excellent data systems and small, rugged thermal extractors and mass spectrometers have been improved and downsized to the extent that they are easily transporta-

ble. In light of these developments, transportable equipment of this nature has been added to the FASP organic protocols in U.S. EPA Region 2. This paper reports the results of a site investigation using a transportable TC/MS system for the FASP organics investigation.

INTRODUCTION

The preremedial program of the U.S. EPA involves the investigation of suspected hazardous waste sites for inclusion on the NPL. The investigation includes a preliminary assessment (PA), a screening site inspection (SSI) and a listing site inspection (LSI). These investigations assess the relative threat associated with actual and/or potential releases of hazardous substances from the site's soil, surface water, groundwater or air. At the end of the investigation phase, the site is ranked by using the Hazard Ranking System (HRS) model⁽¹⁾, which evaluates and assigns a numerical score to each potential pathway of exposure. This numerical score depends to a great extent on the evaluation of the analytical data from the investigations of the contamination of the existing air, soil, groundwater, and surface water from the site.

In U.S. EPA Region 2, NUS Corporation, the Field Investigation Team (FIT) contractor for the U.S. EPA, introduced an interactive Field Analytical Screening Project (FASP) program for the LSI preremedial stage of the investigation. The FASP program provides the field project manager with on-site unambiguous analytical data of high quality in a timely manner and complements the existing fixed-base Contract Laboratory Program (CLP) by prioritizing and screening the samples sent for analysis.

Since the biggest advantage of on-site analysis is the ability to provide the project manager with immediate results, the U.S. EPA Region 2 FASP program performs analysis for target chemicals only, rather than general unknowns. It also utilizes methods and instrumentation that require minimal sample preparation and provides unambiguous high-quality data. Small portable nonspecific instrumentation is not used

in the U.S. EPA Region 2 FASP program because the lack of analyte specificity coupled with the lack of continuing quality assurance cannot provide data of sufficient quality for scoring purposes. The FASP program instituted by U.S. EPA Region 2 FIT utilizes open-path FTIR/UV remote sensing techniques for air investigations^{2,3,4,5}, secondary target X-Ray Fluorescence⁶ (XRF) for soil inorganic analysis investigations, and thermal extraction/gas chromatography/mass spectrometry (TC/MS)^{7,8} for soil semi-volatile organic investigations.

The TC/MS was chosen for the U.S. EPA Region 2 FASP program because it requires no sample preparation and produces unambiguous data in a limited amount of time. Thermal extraction is a relatively new technique which is very simple in principle. Basically, a sample is placed in a sealed chamber where it is heated, with the resulting gases being passed through to a detector (in this case a mass spectrometer) for identification and quantification. Recent instrument advances have seen the development of thermal extraction systems with flow-through extraction cells and fused quartz systems. Fused quartz systems allow for quick heating and cooling of the instrument with no loss of instrument integrity. Mass spectrometers have also undergone a revolution in pumping capacities, total glass systems and software simplification that has moved MS out of the specialty laboratory to the routine analytical services. These advances made TC/MS even more applicable to the U.S. EPA Region 2 FASP preremedial program.

This paper discusses the utilization of a thermal chromatograph/mass spectrometer (TC/MS) for the interactive FASP soil semi-volatile organics program at a site in U.S. EPA Region 2. CLP analyses of samples from previous sites allowed for the selection of four target semi-volatile organic compounds. Based upon these determinations, a mass spectral library with corresponding gas chromatographic retention times was established prior to site arrival. The equipment is set up in a transportable mode; i.e., the equipment is not mounted permanently in a vehicle but is cart-mounted and is moved into a vehicle prior to travel. The vehicles used to transport the analytical equipment are standard vans equipped with generators and air conditioning. Processing of samples can be started within 1 hr of site arrival.

SYSTEM DESCRIPTION

The U.S. EPA's Region 2 FASP program's transportable TC/MS consists of a Ruska thermal extractor and gas chromatograph coupled to a Finnigan INCOS 50 mass spectrometer. The TC/MS system (Fig. 1) is permanently mounted on two specifically designed and constructed carts, which enable the system to be easily loaded onto the vehicle. Each cart consists of a shock-mounted table on an aluminum frame with heavy-duty wheels for ease of maneuverability. One cart carries the TC/MS and the other cart is used for the computer systems necessary for control of the instruments. The carts can be loaded onto or off the vehicle in less than 1 hr to allow the flexibility of use either in the field or in a fixed-base application.

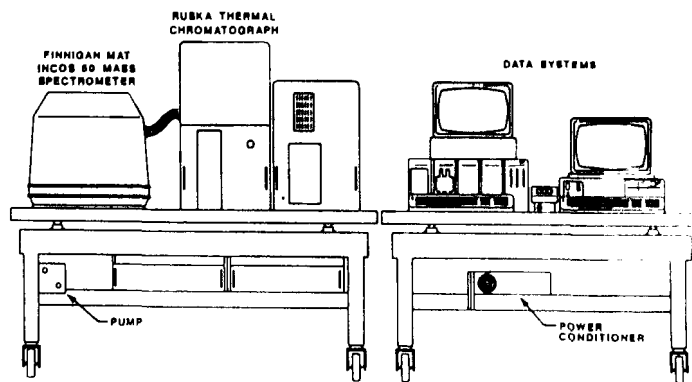


Figure 1
Region 2 TC/MS Organic Soil Analyzer

The vehicle used to transport and house the TC/MS system for field analysis is a Chevrolet UtilMaster stepvan. Vehicle modifications include: a liftgate on the rear for ease of loading and unloading; two 6,500-W undercarriage generators to provide electrical power; two air conditioners and heaters to provide a stable environment; a ceiling vent; cabinetry and shelving for storage of necessary equipment; and a bench top for work space. A portable hood can also be used in the vehicle for samples, standards and solvents. The vehicle has two separate electrical systems: one generator provides both 220V and 110V power for the instruments; the other generator provides 110V power for the air conditioners, heaters, lights and additional outlets. The quality of the power supplied to the instruments is ensured by the use power conditioner transformers that eliminate voltage fluctuations, sags, surges and transients. Figure 2 presents an illustration of the TC/MS system installed in the vehicle for field analysis.

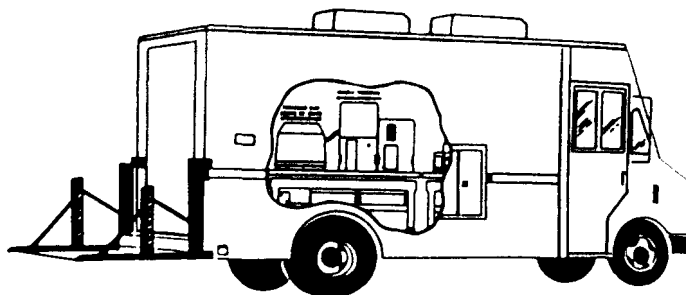


Figure 2
Transportable TC/MS

The thermal chromatograph consists of a fused quartz thermal extractor coupled with a capillary column gas chromatograph. The thermal extractor uses temperature programmed heating, cooling and isothermal methods to thermally extract a sample. The thermally extracted organic compounds are then further separated in the integrated capillary gas chromatograph system prior to mass spectrometric identification. The TC system (Fig. 3) consists of four controlled thermal zones in a vertical stack: the pyrocell, the trap, the splitter and the column. Three of these zones, the pyrocell, the trap or column, can be controlled via linear temperature programming (LTP), held isothermally or cooled with liquid CO₂. The fourth zone, the splitter, can only be controlled isothermally. The pyrocell is the portion of the thermal chromatograph where thermal extraction takes place and can be programmed for temperatures from 0° to 625°C.

The trap can be operated from -70° to 625°C, but for our applications it is used not as a trap but rather as a hot, pass-through zone. The splitter is also maintained at a high temperature, the maximum being 350°C, to ensure column flow. The temperature of the column thermal zone can range from -60° to 400°C, depending on the upper limit of the stationary phase of the column being used.

The sample is placed in a porous fused quartz cup which is inserted into the pyrocell where it is heated while helium flows through the pyrocell. In the splitter zone, a portion of the sample is passed onto the column while the remainder is vented into a carbon filter and released outside the instrument. The column is initially maintained at a cryogenic temperature to trap the sample on the head of the column. The column is then heated via LTP for further separation prior to identification in the mass spectrometer.

The column is inserted into the Finnigan INCOS 50 mass spectrometer (Fig. 4) through a heated transfer line into an evacuated analyser assembly. The Finnigan uses a quadrupole positive ion mass analyser with a corresponding vacuum system consisting of a high-speed 170-L/s turbomolecular pump, rotary vacuum forepump and a glass vacuum manifold. The extra capacity pumps are required to enable the system to pump down and be ready for analyses in less than an hour.

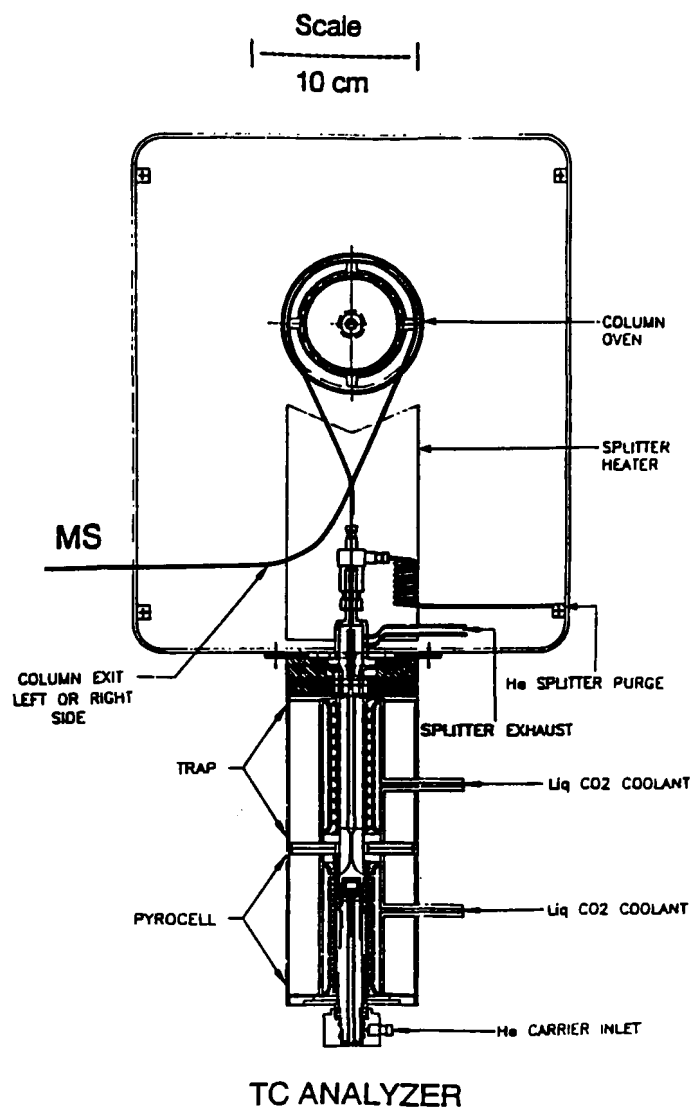


Figure 3
Ruska Thermal Chromatograph

EXPERIMENTAL

This section of our paper discusses the project design, project- and instrument-specific quality assurance/quality control (QA/QC), sample collection and preparation, and instrument operating conditions for the TC/MS semi-volatile organic FASP analysis.

Project Design

The FASP semi-volatile organic analysis concentrates on target compound analyses. Following the SSI, the CLP data were reviewed by the FASP manager, project manager and U.S. EPA project manager to select target chemicals for field analysis. These chemicals, usually four to six in number, are selected based on their toxicity, abundance and instrument detection limitations. Chemicals on the Target Compound List (TCL) are selected first because more information about their analysis is known and confirmation of positive results is easily obtained. As a general rule, tentatively identified compounds (TICs) are not selected as target chemicals unless a high priority is placed on their toxicity. For the site in this study, the target chemicals selected include diphenylamine, mercaptobenzothiazole, benzothiazole and aniline. The final selection of these chemicals was based on their toxicity and abundance, even though three of the four target chemicals are TICs.

The initial SSI found high quantities of the target analytes in subsurface soil and waste samples. Surface soil samples from the site were then collected and analyzed by CLP laboratories to determine the extent and degree of contamination. These samples and others, assumed to be of high concentration, were also analysed with the U.S. EPA Region 2 FASP TC/MS. A majority of the samples analysed contained no detectable levels of the target chemicals, although the non-CLP samples did produce some positive hits. None of the CLP samples were found to be positive for target chemicals by CLP or FASP TC/MS analyses. The TC/MS was then transported to the site, which is located within U.S. EPA Region 2, to help determine whether there were measurable quantities of the target chemicals in the dust from the homes at the site. Due to the emergency nature of the program at this site, a decision was made to analyze samples around the clock, thereby enabling the analytical results obtained from the TC/MS to match the collection team's sampling efforts.

Standards and Reagents

The target compounds, diphenylamine, mercaptobenzothiazole, benzothiazole and aniline, were purchased as pure reagents from Aldrich Chemical Co., and 200 ug/mL stock solutions were prepared with HPLC-grade methylene chloride. A mix of the stock solutions was then prepared, and a standard quantitation curve was developed to determine detection limits for these target analytes. The detection limits were found to be as follows: aniline-1.0 mg/L, diphenylamine-0.1 mg/L, benzothiazole-0.1 mg/L, and mercaptobenzothiazole-2.0 mg/L.

An internal standard, base neutral (B/N) mix was prepared from the Supelprime standard consisting of 1,4-dichlorobenzene-d₄, acenaphthene-d₁₀, chrysene-d₁₂, naphthalene-d₈, perylene-d₁₀, and phenanthrene-d₁₀.

INSTRUMENT AND PROJECT QA/QC

The QA/QC applied to this project was derived from the QA/QC requirements for CLP analysis of semi-volatiles. The mass spectrometer was tuned manually using FC43, adjusting the parameters for proper peak shape and ion ratios. DFTPP was then analyzed and the CLP abundance criteria achieved. The internal standard mix was added to every sample, and it was found that the area counts and retention time variability were within that required by the CLP Statement of Work (SOW). Duplicate analyses were performed every 10 samples to ensure result integrity, and blanks were analysed every 12 hrs to confirm system cleanliness. Calibration response and minimum detection limits were established for the target analytes and retention times determined to provide a clear indication of compound presence. The instruments were cleaned and reconditioned as deemed necessary by the performance of the QA/QC samples (duplicates and blanks).

A comprehensive FASP quality assurance program has been instituted for U.S. EPA Region 2 FIT that ensures the integrity and validity of all aspects of the TC/MS and the generated data. The minimum requirements include a full standard operating procedure (SOP), maintenance plan, written documentation for all activities and an initial and ongoing monitoring program that demonstrates the consistency of the generated data. A minimum of 20% of all samples are normally spent for CLP confirmatory analysis. Due to the low sample volume at this site, a decision was made not to utilize CLP verification QA/QC.

Data reduction, validation and reporting procedures are performed by trained personnel after a full review by the FASP manager.

SAMPLE COLLECTION AND PREPARATION

Soil samples were collected from the site using sampling techniques as required by work plan and QA procedures. The sampling technique chosen for the house dust was to collect dust samples obtained by sweeping the kitchen areas of the homes. No further homogenization was performed on the samples prior to analysis. For the house dust samples, the analysis was performed on the actual dust portions of the sweep samples. A portion of each sample was placed in the porous fused quartz sample cup and weighed on an analytical balance; sample quantities ranged from 20 to 140 mg, depending on sample type (soil or dust) and density-the cup was filled with a loosely packed sample. Five

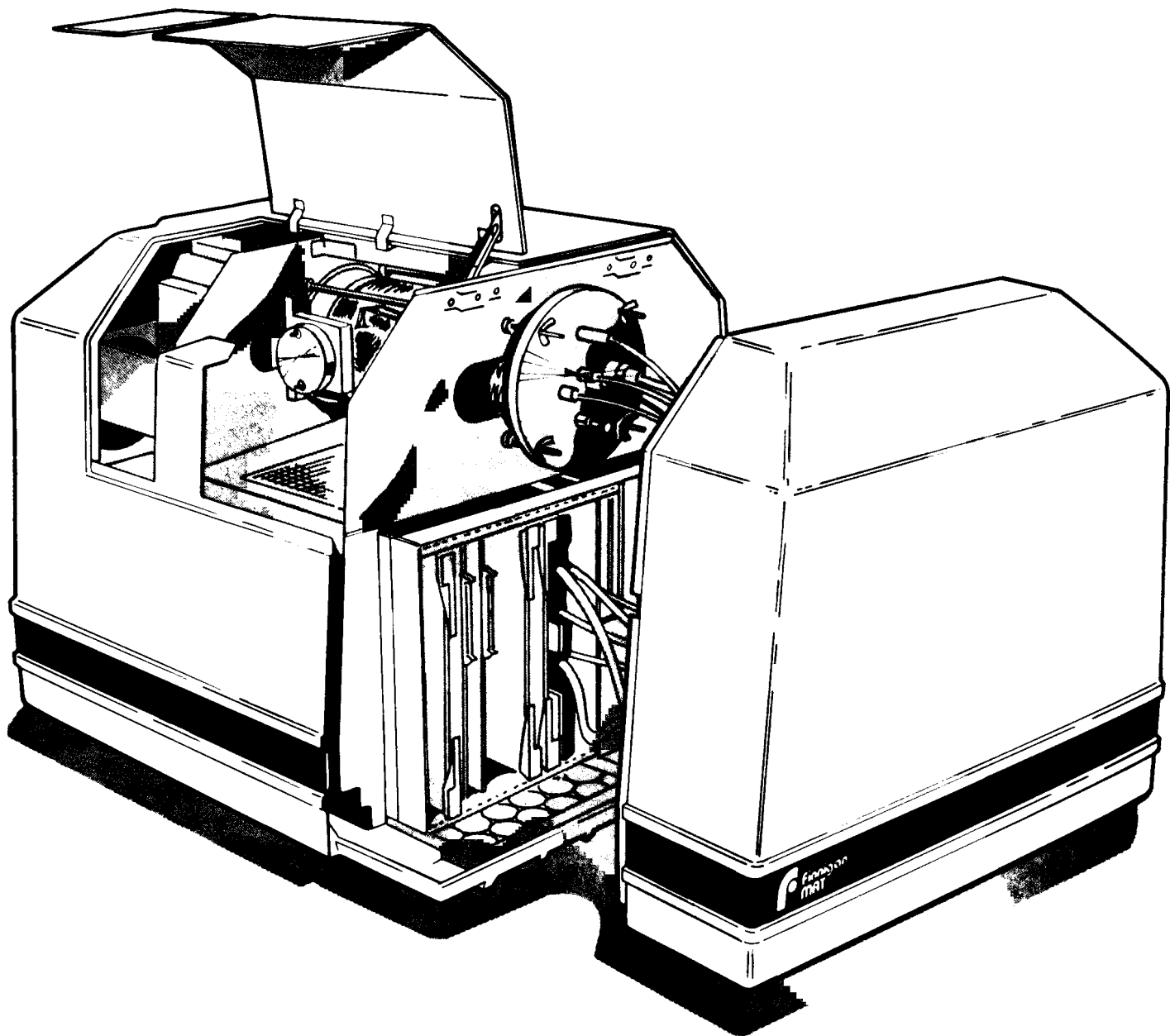


Figure 4
Finnigan MAT INCOS 50 Mass Spectrometer

uL of the base/neutral internal standard mix at a concentration of 200 ug/mL were added to the top of each sample before capping with a porous fused quartz cap.

INSTRUMENT OPERATIONAL CONDITIONS

The capped sample, with internal standard added, was placed in the pyrocell of the TC for heating and analysis. TC/MS operating conditions were as follows:

Throughout the analysis the trap was maintained at 360°C while the splitter was held to 310°C. The pyrocell was heated from 30 to 260°C at a rate of 34°/min while the column was held at 5°C. At the end of the pyrocell LTP cycle, the column was heated from 5 to 285°C at 15°/min. Helium flow through the pyrocell was 30cc/min, but because of a 30:1 split performed on the extracted sample, helium flow through the column into the mass spectrometer was 1cc/min. The capillary column (HP-5 12M x 0.2 MM ID with 0.33-μm film thickness) was run through

a transfer line at 280°C to the mass spectrometer with an ion source temperature of 180°C. The total analysis time, including sample heating, was 37 mins. Figure 5 illustrates the temperature plots for a typical run.

Results and Discussion

This site presented a considerable analytical challenge in the selection of target compounds due to the limitations and requirements of the samples used. In the initial CLP analyses, the TCL compound detected was n-nitrosodiphenylamine with a large number of tentatively identified compounds (TICs). TC/MS analysis of spike soil samples showed that only diphenylamine could be detected within the protocols developed. Current CLP SOW indicates, however, that the n-nitrosodiphenylamine cannot be distinguished from diphenylamine. Diphenylamine was selected as one of the target analytes for this FASP program based on the assumption that negative results were expected and that if the sample did not contain diphenylamine, then n-

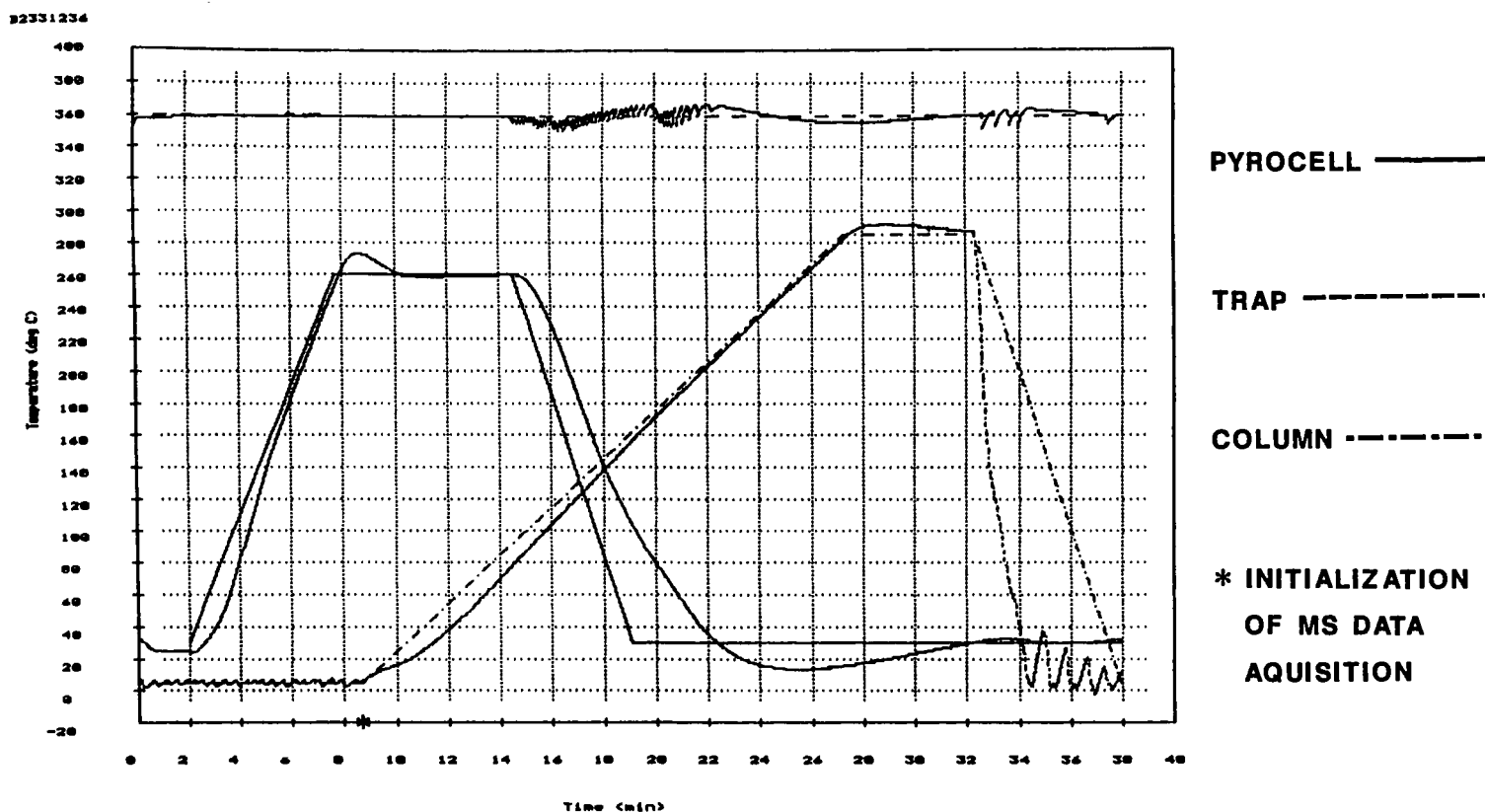


Figure 5
Thermal Chromatograph Temperature
Plot Programmed vs Actual

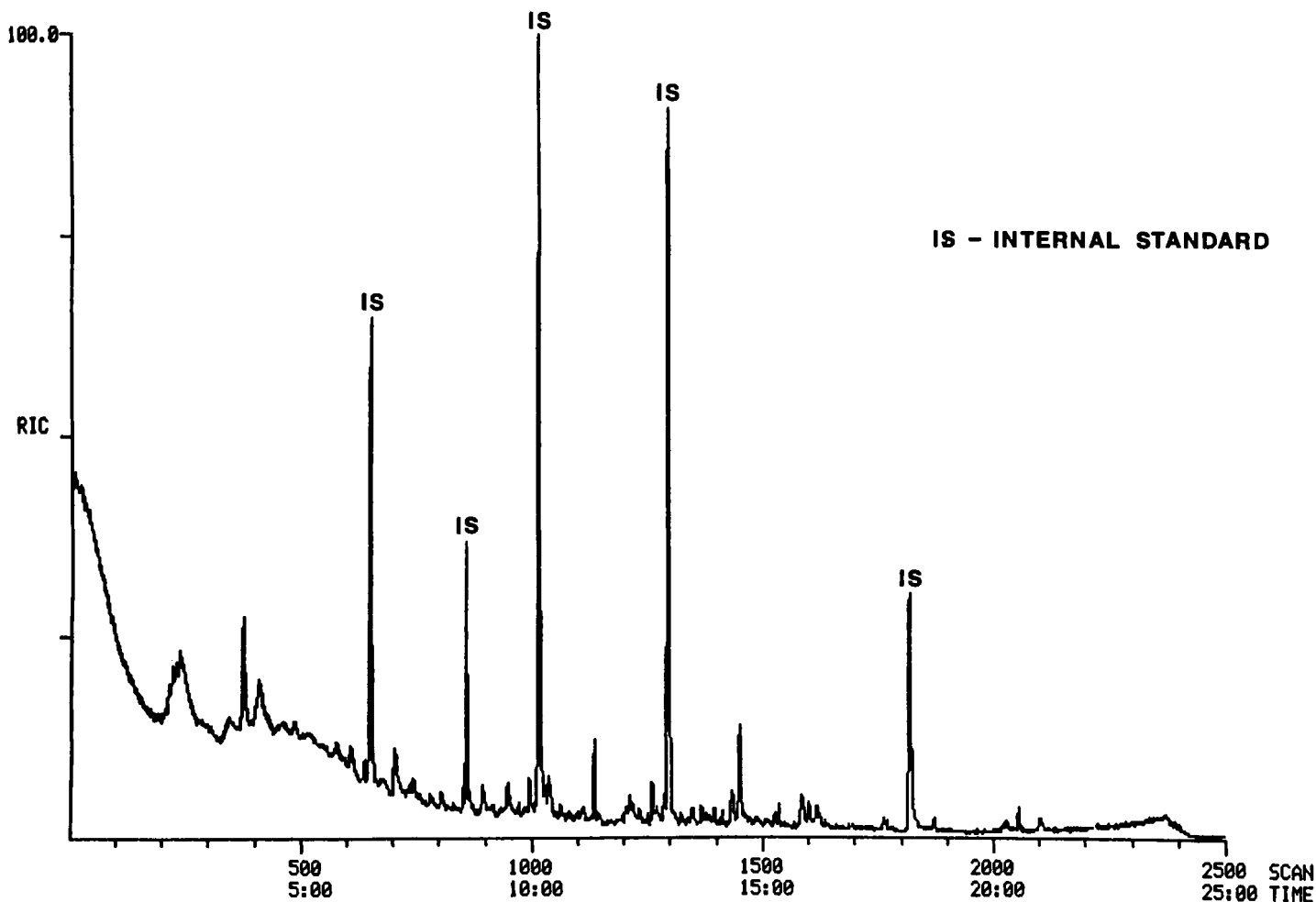
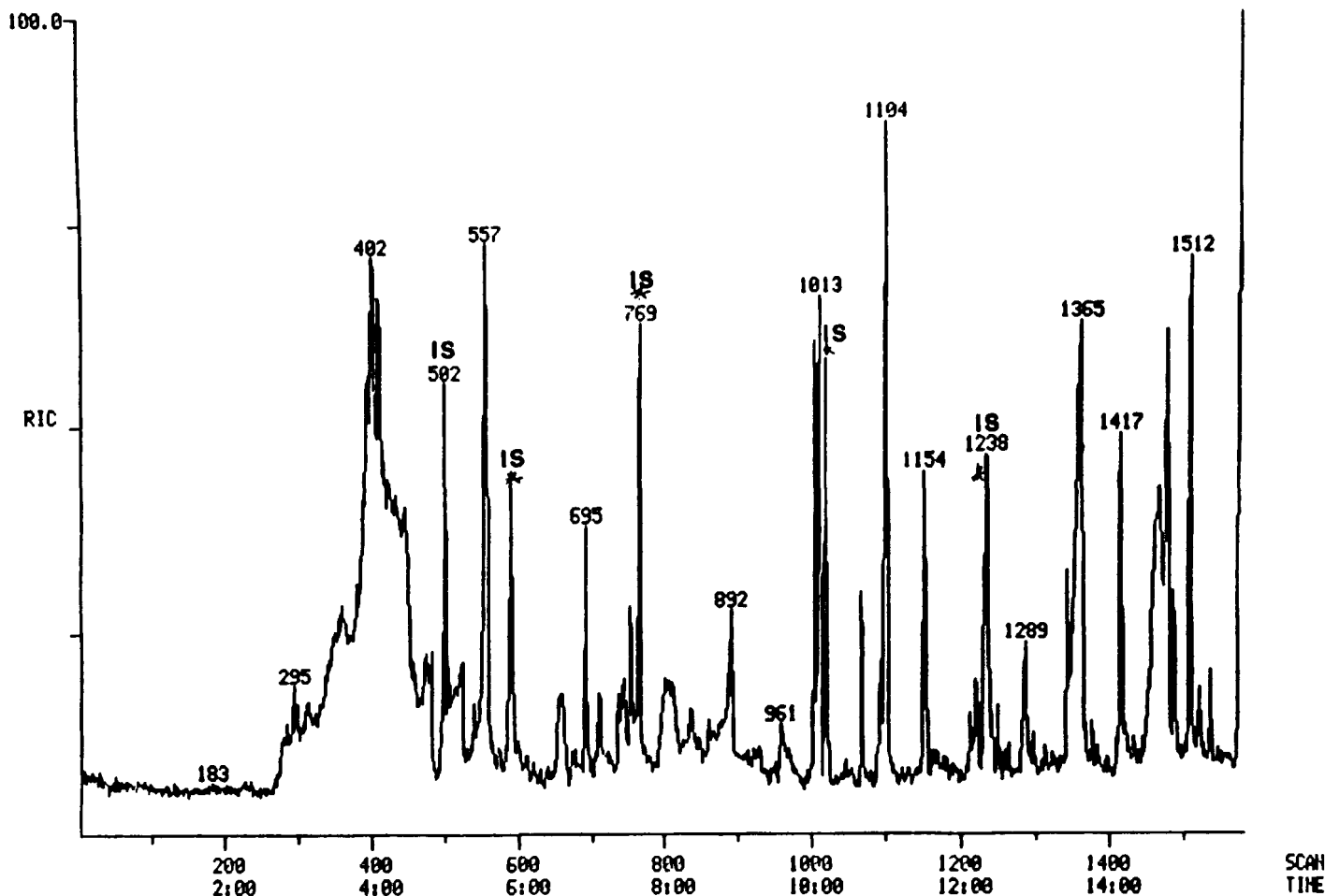


Figure 6
RIC of Soil With Internal Standards



IS - INTERNAL STANDARD

Figure 7
RIC of Household Dust

nitrosodiphenylamine would not be present. Two target analytes, benzothiazole and mercaptobenzothiazole, both sulfur-containing TICs, were selected based on their prevalence in certain site areas and their toxicity. The fourth target analyte, aniline, was selected based on its toxicity.

Figure 6 shows the reconstructed ion chromatogram (RIC) of soil with base/neutral internal standard mix. Figure 7 shows the RIC of a household dust sample. The dust samples exhibited a large number of peaks, most of which were fatty acids, hydrocarbons and other normal household contaminants as determined by library spectral identification. The large quantities of organic material in these dust samples necessitated a change in the experimental design. Whereas in the original design the plan was to analyze ten samples, a random duplicate and a blank, blank analysis was required after three samples just to confirm that the system was clean.

Figure 8 illustrates positive household dust analysis. Figure 9 presents the RIC chromatogram from 800 to 900 scan numbers showing the region where benzothiazole is found; the upper portion of the chromatogram indicates which peaks have mass 135 (benzothiazole) as a base peak. Figure 10 shows the mass spectrum of the peak at scan 841, and Figures 11 and 12 show the library matches confirming the presence of benzothiazole.

Duplicate analyses were performed on all positive samples to confirm the presence of target analytes. The results of all the original positive samples were confirmed, demonstrating the reliability of the original procedure. The only target analyte found in the household dust samples was benzothiazole.

CONCLUSION

The U.S. EPA Region 2 preremedial FASP program has been significantly enhanced with the additional of the TC/MS system for target organics analyses in soil. This unique analytical system provided the field project manager with unambiguous data and rapid turn-around. This instrumentation was utilized in the transportable mode that needed only generator power and a constant temperature environment; the system was fully operational within 1 hr of site arrival and ran continuously for 4 days. The quartz inlet system of the Ruska thermal extractor-gas chromatograph ensured constant temperature control with fast cool-down capabilities. The Finnigan INCOS 50 mass spectrometer equipped with a high-speed pump and all-glass vacuum manifold ensured rapid start-up and very stable operation in the vehicle during the field operations.

By producing mass spectral confirmed data, this interactive FASP program allowed rapid decisions to be made in the field. In our experience, the only minor limitations are residue contamination problems with the thermal extractor trap, especially after analyses of high concentrations of organic materials; operator fatigue, especially on rotating field shifts; and the necessity for a full QA/QC data reduction system.

DISCLAIMER:

Trade names and company names are used for identification only and do not imply endorsement by NUS Corporation or the U.S. EPA.

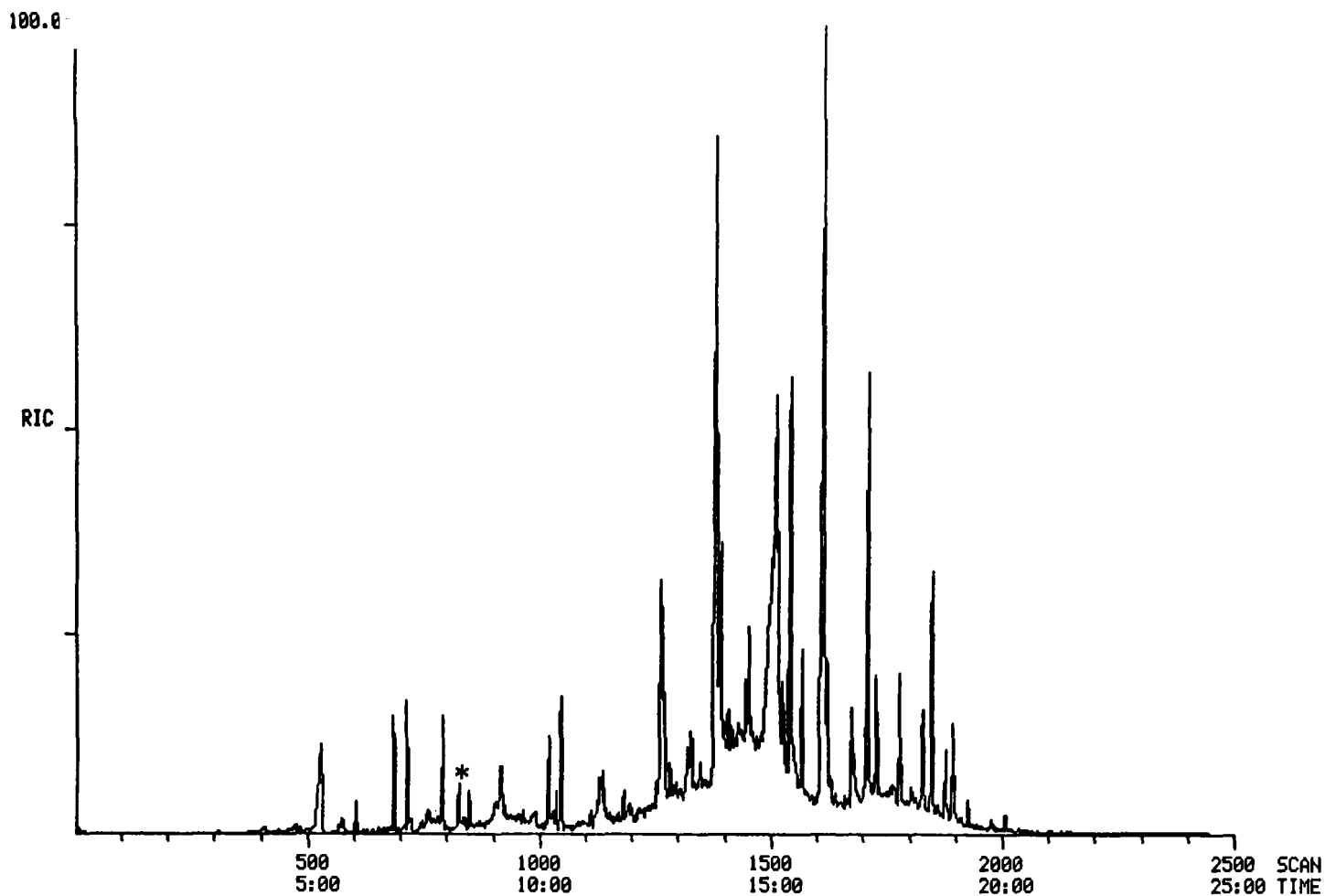


Figure 8
RIC of Household Dust Containing Benzothiazole

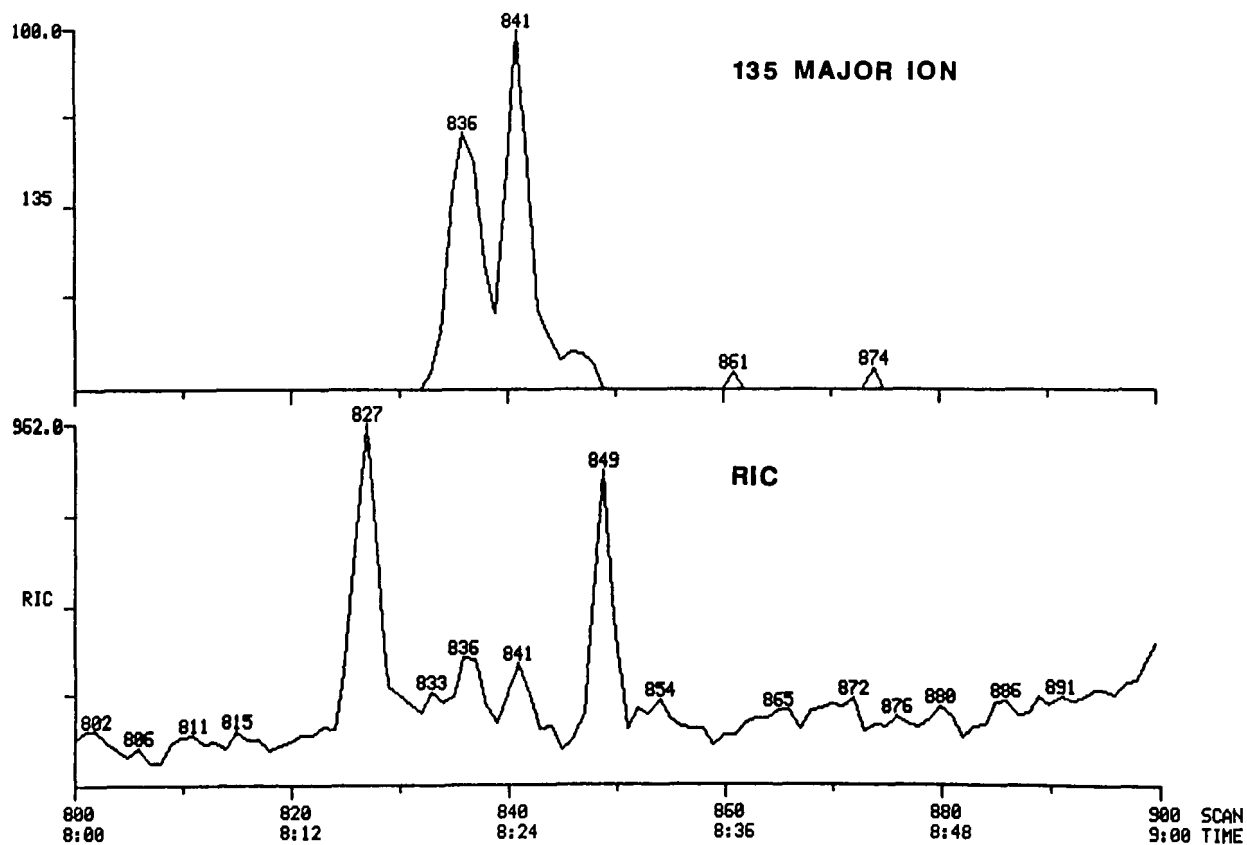


Figure 9
RIC and 135 Major Ion Mass Chromatogram

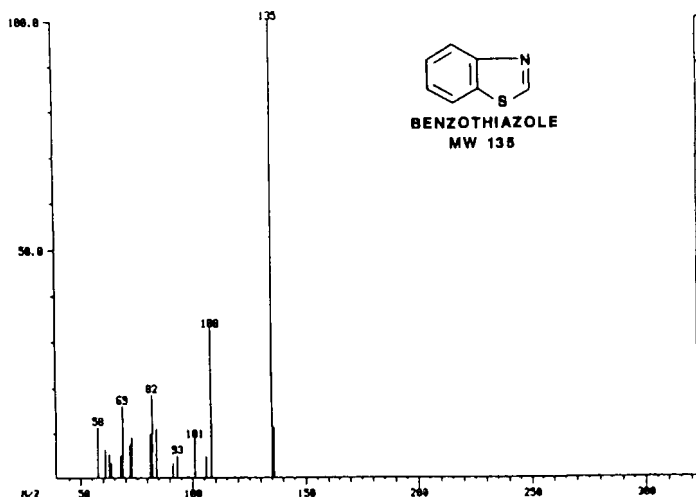


Figure 10
Mass Spectrum of Benzothiazole in Household Dust

REFERENCES

1. U.S. EPA Hazard Ranking System (HRS) for Uncontrolled Hazardous Substance Releases; 40 CFR Part 300, Appendix A of the National Oil and Hazardous Substances Contingency Plan, U.S. EPA, Washington, D.C.
2. Bath, R.J., Minnich, T.R., Naman, R.M., Spear, R.D., Simpson, O., Faust, J., Stedman, D.H., McLaren, S.E., Herget, W.F., and Vaughn, W.M., "Remote Sensing of Air Toxics Using State-of-the-Art Techniques," *Proc. of the EPA/AWMA International Symposium on Measurement of Toxic and Related Air Pollutants*, Raleigh, N.C., May 1989.
3. Grupp, D., Rojek, G., Bath, R.J., Minnich, T.R., Naman, R.M., Brochu, A.J., and Spear, R.D., "The Pre-Remedial Air Toxics Program: A Case Study using Remote Sensing," *Proc. of the EPA/AWMA International Symposium on Measurement of Toxic and Related Air Pollutants*, Raleigh, N.C., May 1989.
4. Minnich, T.R., Bath, R.J., Spear, R.D., Simpson, O.A., Faust, J., Herget, W.F., Stedman, D.H., McLaren, S.E., and Vaughn, W.M., "Remote Sensing of Air Toxics for Pre-Remedial Hazardous Waste Investigations," *Proc. of the 82nd Annual AWMA Meeting and Exposition*, Anaheim, CA, June 1989.
5. Scotto, R.L., Bulich, J., Greenlaw, P., Vaughn, W.M., and Ennis, R., "Remote Sensing Data Quality Objectives and Quality Assurance for a Pre-Remedial Hazardous Waste Site Program," *Proc. of the 82nd Annual AWMA Meeting and Exposition*, Anaheim, CA, June 1989.
6. Grupp, D.J., Everitt, D.A., Bath, R.J., and Spear, R.D., "The use of a Transportable X-ray Fluorescence Spectrometer for On-Site Analysis of Mercury

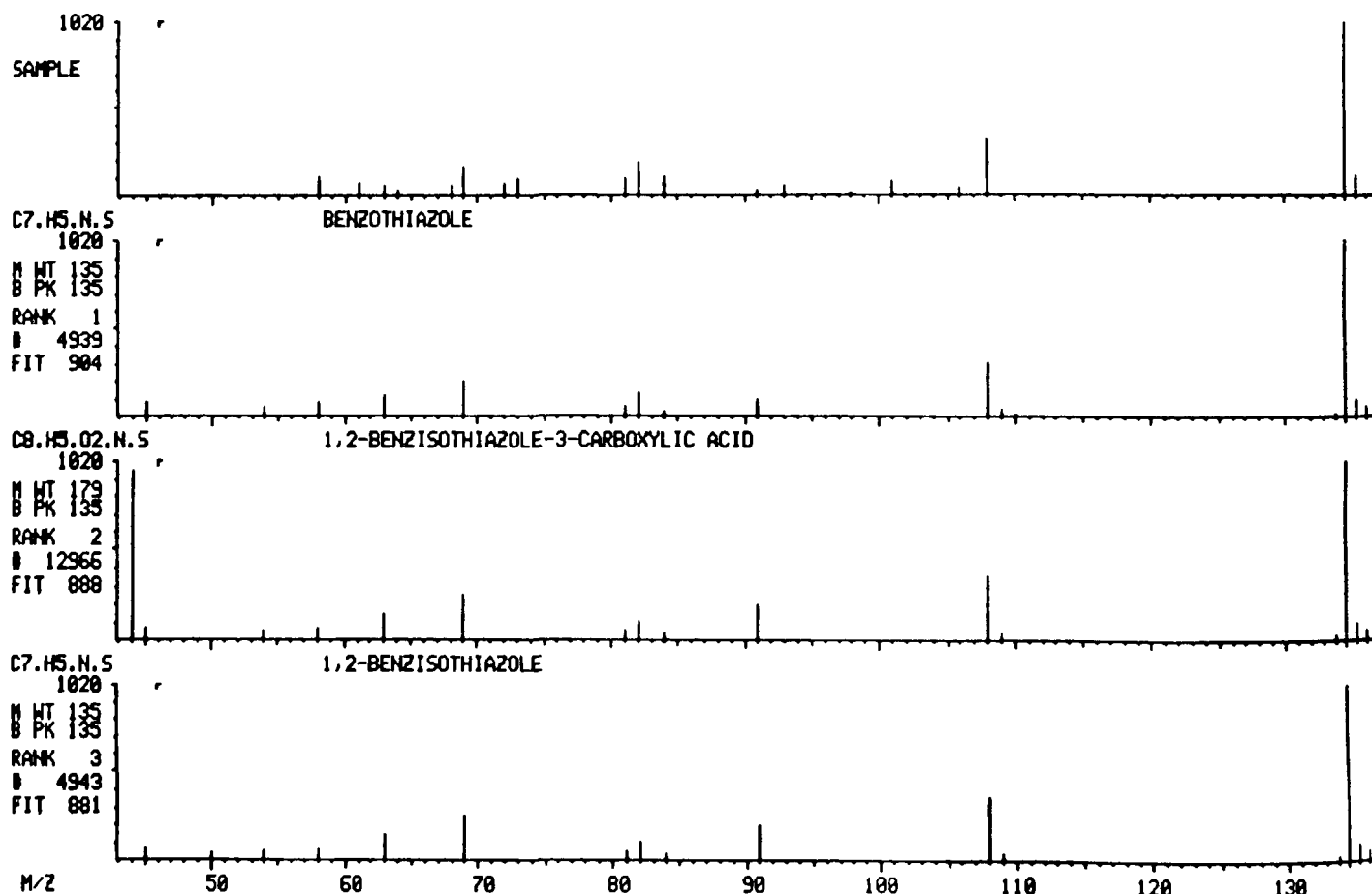


Figure 11
Mass Spectral Library Search of SCAN 841

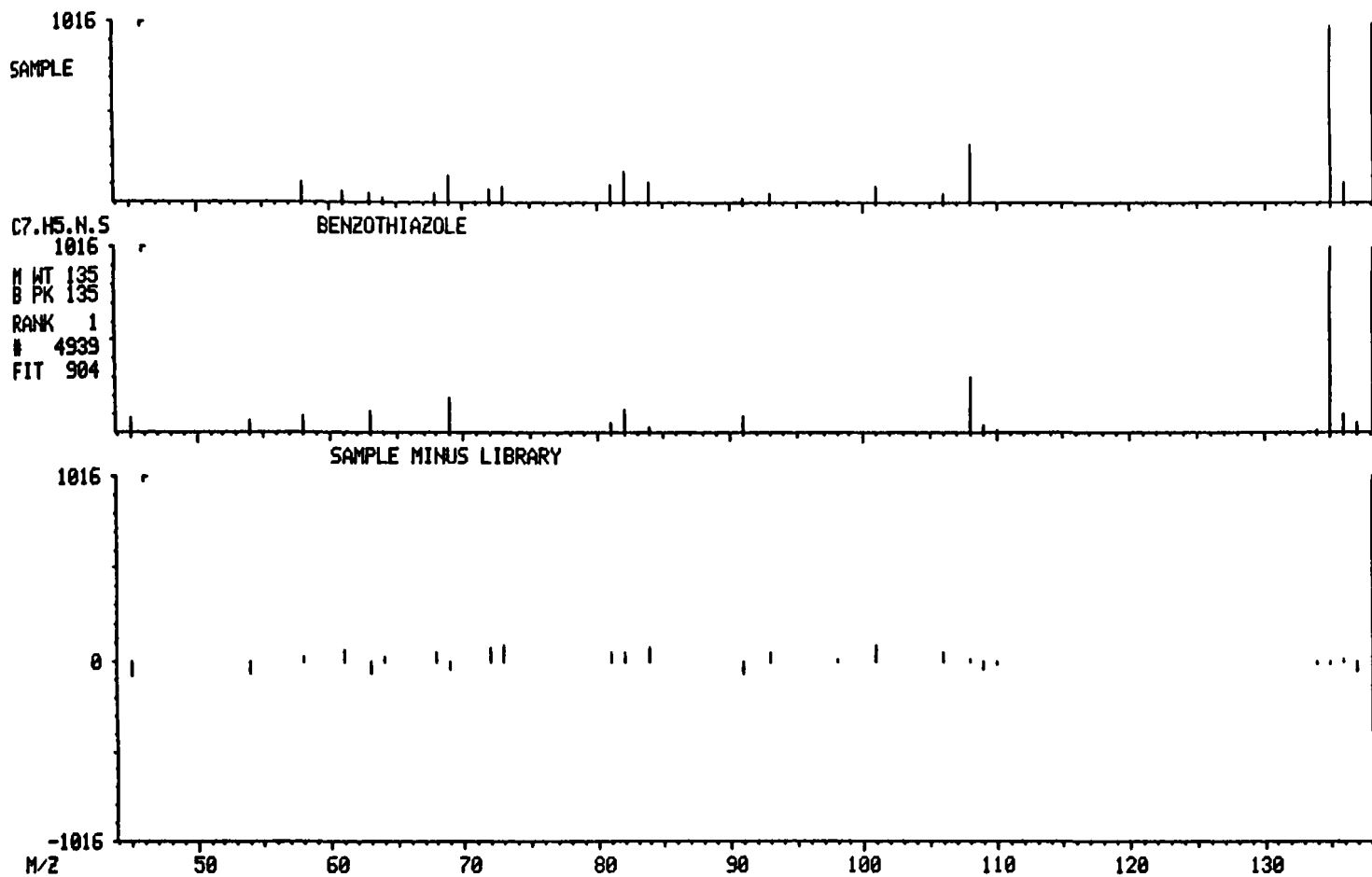


Figure 12
Library Match of Benzothiazole in Sample

- in Soils," *Am. Environ. Lab.* VI, Nov. 1989.
7. Overton, E.B., Henry, C.B., Shane, B.S., Junk, T., Irvin, T.R., Nocerino, J.M., Butler, L.C., Petty, J.D. and Pritchett, T.R., "Application of Thermal Extraction GC/MS Technologies for Rapid Chemical Analysis of Contaminated Environmental Samples." *Fifth Annual Waste Testing and Quality As-*

- urance Symposium Proceedings*, Washington, D.C., July 24-28, 1989.
8. Henry, C.B., Overton E.B. and Sutton C., "Applications of the PYRAN Thermal Extraction GC/MS for the Rapid Characterization and Monitoring of Hazardous Waste Sites." *Proc. of the First International Symposium for Hazardous Waste Site Investigations*, Las Vegas, NV, Oct., 1988.

Performance of GC/MS Analysis Quality Indicators

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ABSTRACT

The United States currently spends over a billion dollars a year to find, characterize and remediate sites contaminated with hazardous chemicals. The primary method of locating contaminated areas is the collection and chemical analysis of environmental samples. The results of these analyses are used to make decisions about site remediation activities that can cost millions of dollars.

The quality of the data used in making these decisions is crucial in the decision-making process. One measure of the quality of the analytical data is the precision and accuracy of the analytical methods. Precision is estimated by analyzing replicate samples, while accuracy is estimated by analyzing matrix spikes.

However, the cost of analyzing environmental samples is high, and other indirect measures of analytical quality are often used. These indirect measures include surrogate spikes and matrix spike/matrix spike duplicates. The indirect measurements attempt to estimate the accuracy and precision of analytical methods for target compounds with measures of accuracy and precision on surrogate compounds.

The Love Canal Habitability Study provided an opportunity to examine the performance of these surrogate measures of analytical performance. During the course of this study, two batches of soil were analyzed repeatedly for the Love Canal indicator chemicals. For these samples, both direct and indirect measures of analytical performance are available.

Both direct and indirect measures of data quality are presented here. The value of current data quality measures of laboratory performance is discussed, and the future course of data quality measures is explored in the context of electronic data transfer.

Comparing the two measures of analytical performance allows the hazardous waste community to evaluate the efficacy of surrogate measures of data quality. A better understanding of the limitations of surrogate performance measures allows remediation decisions to be more defensible.

INTRODUCTION

With the passage of the SARA, the United States embarked on a multi-billion dollar effort to clean up toxic chemical contamination of the environment. This effort involves both the federal Superfund program and industrial programs outside of the Superfund process.

Efforts to clean up the environment begin with the collection of samples and the chemical analysis of the samples to identify and quantify levels of contamination. The analysis of environmental samples has become a \$300 million-a-year business influencing decisions as to appropriate site remediation. Clearly, the quality of the data used to make these decisions is of paramount importance.

The purpose of this discussion is to introduce the regulatory community to one of the most common analytical techniques, used for

analyzing environmental samples, gas chromatography-mass spectroscopy (GC/MS), and the methods used for estimating the precision and accuracy of this method.

The precision and accuracy of concentration estimates are of particular concern in a decision framework and are not as straightforward as might be thought. Four methods are commonly available for estimating the precision and accuracy of GC/MS analyses. Two of these, blind quality control samples and sample replicates, are external estimators created from samples prepared outside of the laboratory. The other two, the addition of surrogate compounds to a sample (surrogate spikes) and the addition of target compounds to selected samples (matrix spikes), are internal estimators from samples prepared within a laboratory.

Ideally, a number of external and internal estimates of precision and accuracy should be available for each study site to allow a comparison of each estimator's performance and a contrast of what the samples represent. However, because of the high cost of chemical analyses, the number of samples analyzed from a site is minimized. This limited number of analyses places greater emphasis on the use of the internal estimators of precision than on the external estimators; little information is available on how the two estimators compare.

The Love Canal Habitability Study, completed in 1988, provided a unique opportunity to compare the usual GC/MS internal quality assurance measurements with the results of replicate analyses of soil samples. Exceptional quality control measures were employed in the Love Canal study, ranging from providing participating laboratories with identical glassware from the same manufacturing lot to developing analysis protocols with unusually strict operating constraints. Many aspects of the chemical analyses were tracked and stored in a data base for later analysis. This data base of analytical results provides a good basis for comparing the internal and external estimators of precision and accuracy.

STUDY BACKGROUND

In the Love Canal study, the concentration levels of eight indicator chemicals found in neighborhoods near the canal were compared with concentration levels of these indicator chemicals found in control areas in Niagara Falls and Buffalo. Although the main purpose of the study was a statistical comparison of the Love Canal neighborhoods with control areas, a number of other investigations were undertaken because of the unique aspects of the study.

One investigation conducted as part of the Love Canal study was to collect two samples of soil from two neighborhoods near the canal. Each sample was homogenized and aliquots of each were sent to each of two laboratories. These aliquots were analyzed in duplicate at 5-day intervals for 65 days over the duration of the sample analysis. This scale of replicate analysis, unusual in environmental studies, allowed a com-

parison of the four measures of precision and accuracy.

The two external measures of precision and accuracy are obtained from the analysis of blind quality control samples or sample replicates. Sample replicates were prepared at Love Canal by extruding soil from the sampling tool (a hollow tube pushed into the soil), quickly mixing it by hand and then placing aliquots of the soil into two or more jars for shipment to the laboratories.

Blind quality control (BQC) samples (samples of soil similar to that found near the Love Canal) were spiked with known amounts of indicator chemical by a U.S. EPA laboratory. These spiked soil samples were placed in sample jars for shipment to the laboratories. The identity of the BQC samples was known to the laboratories, although the spiking concentrations were not. Each laboratory was responsible for analyzing BQC samples at a set frequency during the course of the study.

The two internal measures of precision and accuracy consisted of the analysis of matrix spike samples and the use of surrogate compounds. Matrix spike samples were created by the laboratory by splitting a sample into three aliquots. Known quantities of indicator chemicals were added to two of these aliquots. The third aliquot was analyzed for background concentrations of the indicator compounds. The spiking concentrations of indicator chemicals were standards known to the laboratories. All three samples were analyzed, with the two spiked aliquots becoming known as the matrix spike and matrix spike duplicate.

A surrogate compound is a chemical that is similar to the target compound yet is not normally found in environmental samples. For the Love Canal indicator chemicals that were chlorinated compounds, the surrogates were similar compounds that contained bromine rather than chlorine. These surrogate compounds were added to all samples before the start of the extraction process.

The GC/MS analysis of a soil sample for the Love Canal study consisted of several steps. These steps and the quality control measures associated with them are shown in Figure 1. Analysis consisted of weighing an aliquot of the sample and adding the surrogate compounds. The soil was then mixed with other chemicals that removed compounds not of interest to the study, primarily hydrocarbons. The hydrocarbons were removed to reduce the interference that these compounds create in identifying the target indicator compounds. Solvent was added to the mixture to extract the indicator chemicals and surrogate chemicals from the soil.

The extract obtained was then stored until GC/MS analysis. Before analysis, compounds used as standards for quantification were added to the extract and a small portion of the extract was removed for further concentration. The concentrated aliquot was injected into the GC/MS. Data obtained from the GC/MS for Love Canal consisted of chromatograms, which are the time traces of ion detection intensity, for three ions of each of the target compounds. These chromatograms were used to identify and quantify the target compounds.

The Love Canal samples typically had concentrations below 10 mg/L. At this extremely low concentration it was often difficult for compound identification to pass all quality assurance criteria. It was also very easy for other compounds to mask or otherwise interfere with the identification of the Love Canal indicator compounds. Thus, it was possible for samples with known concentrations of indicator chemicals, such as the BQC samples, to be reported as having nondetectable concentrations of indicator chemicals.

STUDY RESULTS

Because of the complexity of the GC/MS analytical technique, a number of factors influence the precision and accuracy of the method. These include the frequency of calibration of the instrument, the laboratory performing the measurement and the soil matrix being analyzed. Further, each of these factors can have a different influence on each compound being analyzed. Each estimator of either accuracy or precision reflects the influence of confounding factors differently.

Three of the measures discussed (BQC samples, matrix spikes and surrogates) can be used to estimate accuracy. Soil samples do not have a known concentration, so accuracy cannot be calculated for replicate analyses.

Box plots are one method of comparing the different measures of

qualities. Notched box plots are a method of presenting and comparing distributions of values without making assumptions about the form of the distribution. Figure 2 illustrates the attributes of a box plot. Each box plot presents six statistics about a distribution in graphical form. These are:

- The 25th percentile of values, represented by the bottom of the box
- The median or 50th percentile of values, represented by the line within the box
- The 75th percentile of values, represented by the top of the box
- The range of the data value, represented by the lines extending from the ends of the box
- Outlier values, represented by asterisks or circles
- Approximate 95% confidence limits for the median represented by an indentation or notch in the box (If the confidence limits are wider than the box, the box will be folded at the notch, resulting in a somewhat peculiar figure.)

Distributions of values can be compared across categories by examining the notches on each box. When notches do not overlap, the median values are significantly different. When the notches do overlap, there is no significant difference between the medians.

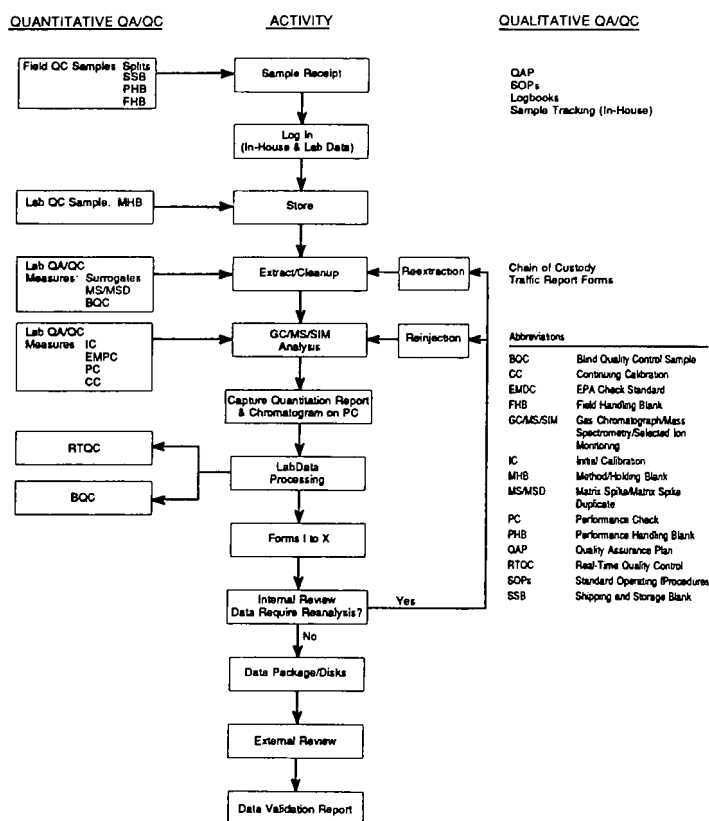


Figure 1
Soil Assessment—Indicator Chemicals Schematic
Representation of the Laboratory QA/QC Program

Accuracy commonly is measured by chemists as percent recovery. This is the estimated concentration of a compound from the analysis, divided by the concentration calculated to have been added to the sample as a percent. Figures 3a through 3c show the distribution of recoveries for each of the eight indicator compounds and three surrogate compounds as notched box plots.

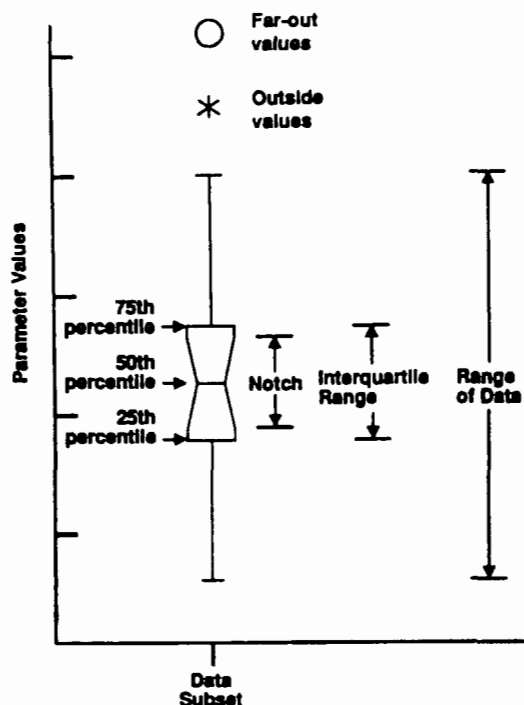


Figure 2
Sample Box Plot

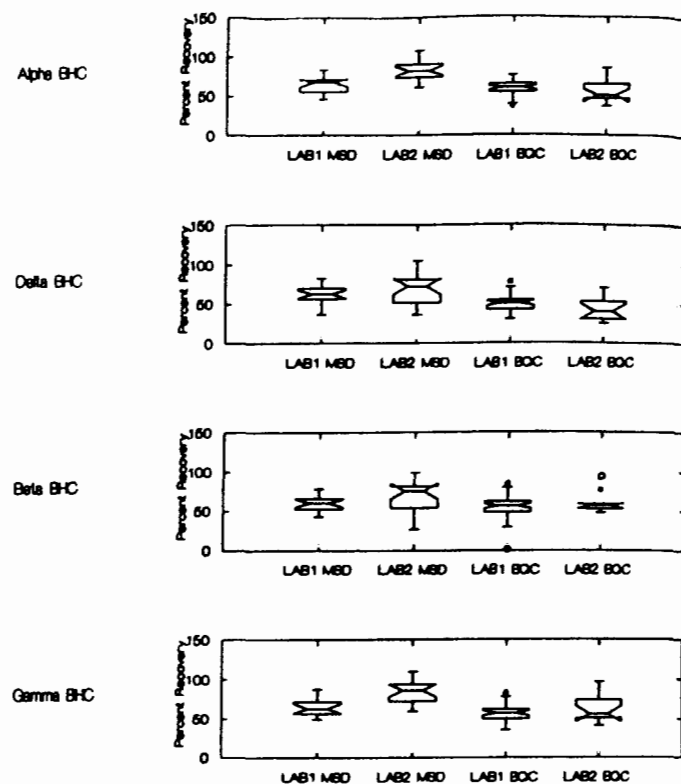


Figure 3b
Distribution of Recoveries for Indicator Compounds

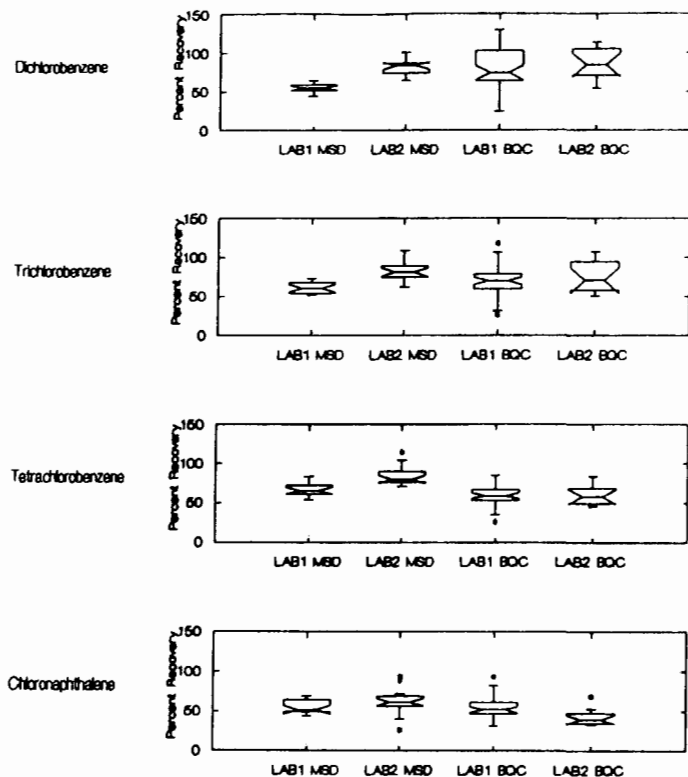


Figure 3a
Distribution of Recoveries for Indicator Compounds

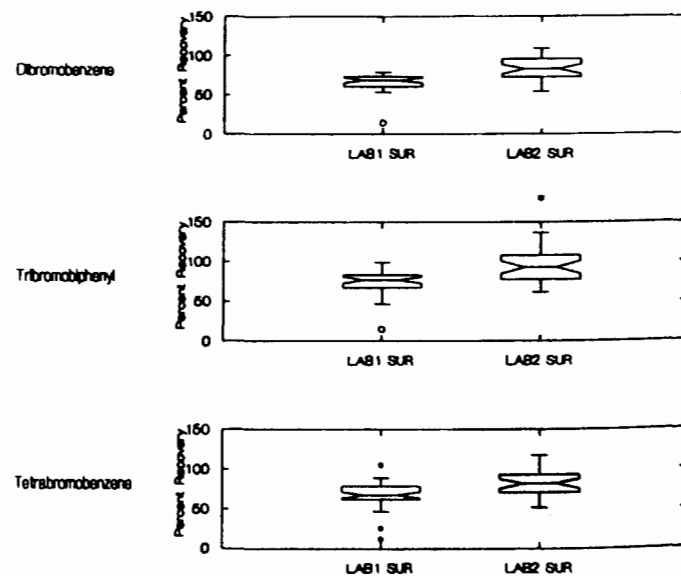


Figure 3c
Distribution of Recoveries for Indicator Compounds

Figure 3a illustrates some of the factors influencing the accuracy of GC/MS measurements. In this graph, the recovery of dichlorobenzene

is broken out into two factors that may influence the recovery: the laboratory doing the analysis and the source of the compound. These two factors combine to create four categories of recovery estimate.

In Figure 3a there is a significant difference between the two laboratories in their ability to recover dichlorobenzene from the matrix spike samples; Laboratory 2 is better than Laboratory 1. This trend is consistent for all compounds spiked in the laboratory (i.e., both matrix spikes and surrogates). However, there is no consistent difference between the two laboratories for the blind quality control samples spiked at the U.S. EPA laboratories.

The inconsistency of these results illustrates some of the subtle problems associated with estimating laboratory performance measurements. There are several plausible explanations as to why such differences exist. Laboratory 2 could have a different technique for adding spiking compounds and then extracting them. This method might differ from that used by Laboratory 1 and allow Laboratory 2 to retrieve newly added compounds more effectively.

Another possibility is the difference in exposure time for compounds added to soil in the laboratory and immediately extracted, and compounds added to soil at a U.S. EPA laboratory and then stored for some time before extraction and analysis. Although Figure 3a shows a more efficient extraction of dichlorobenzene for BQC samples, in general for the other compounds the BQC samples have smaller recoveries than matrix spike samples.

Although the recovery of spiked compounds typically is 50 to 75%, the recovery observed in any one sample has a broader range. The range of recoveries observed is one measure of the precision attainable with the measurement process at a study wide resolution. However, this statistic is not available for the concentrations estimated for replicate samples.

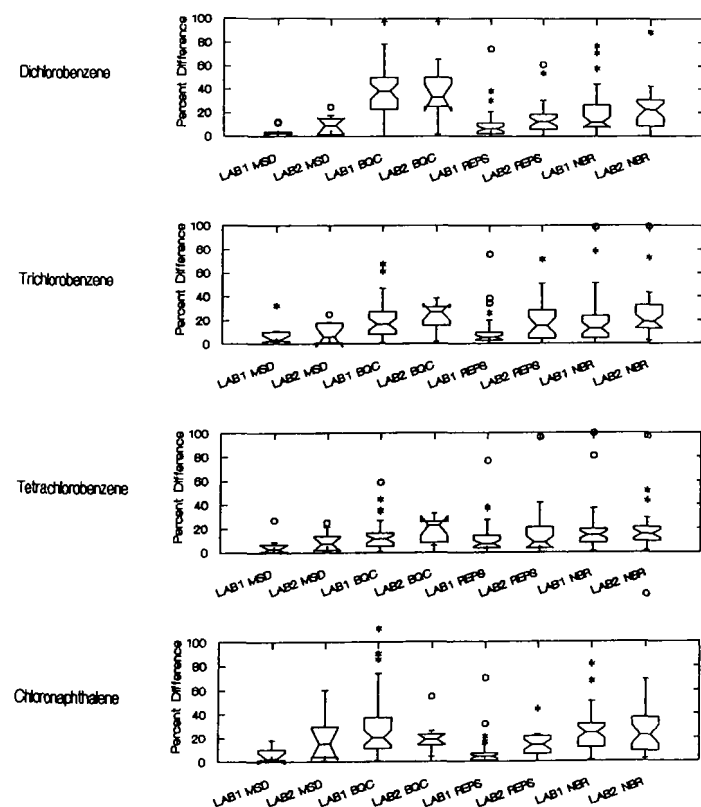


Figure 4a
Estimates of Precision for Indicator Compounds

Figures 4a through 4c show the distribution of a statistic indicating the scale of the estimated concentrations. This is the absolute value of the percent difference between a concentration estimate and its nominal value. The nominal value for matrix spike samples is the mean recovery for the two spiked samples. The nominal value for the BQC

samples is the mean recovery of BQC samples for a laboratory. The nominal value for replicate samples can be either the mean concentration of replicates or the mean concentration of samples from one area analyzed at a laboratory. The first estimates short-term precision (within 1 day); the second a longer term precision over the study.

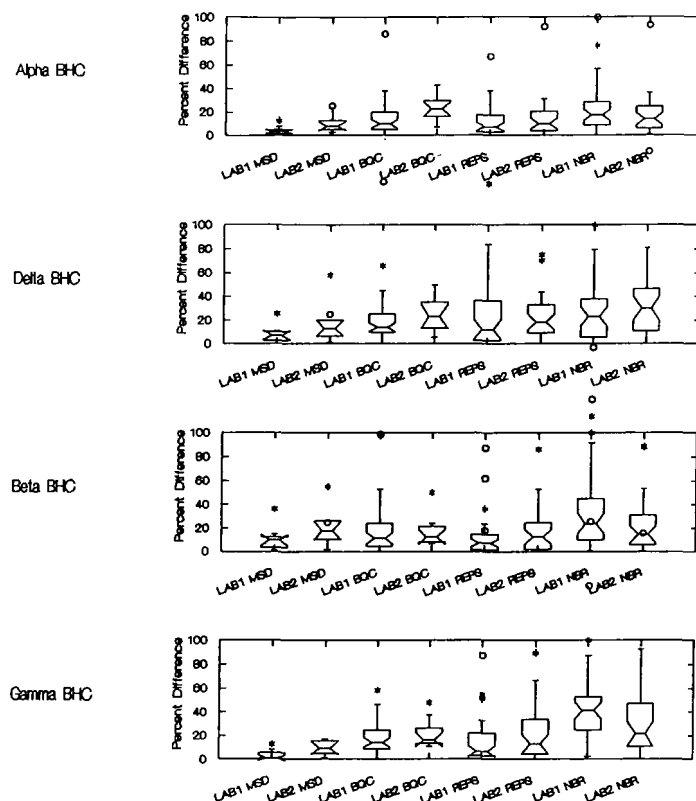


Figure 4b
Estimates of Precision for Indicator Compounds

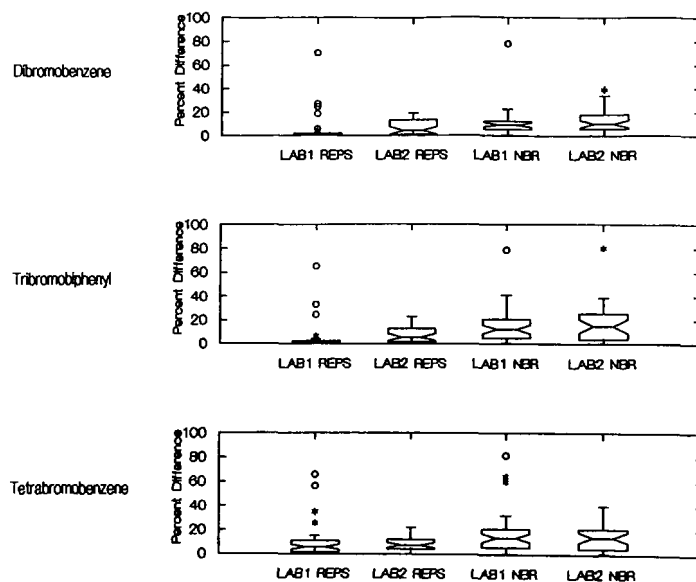


Figure 4c
Estimates of Precision for Indicator Compounds

Figures 4a through 4c show each of these four estimates of precision for both laboratories. Samples labeled "MSD" are the matrix spike samples; those labeled "BQC" are the blind quality control samples; those labeled "REPS" are the replicate samples compared to replicate means; and those labeled "NBR" are The replicate samples compared to neighborhood means.

In general, the NBR and BQC estimates appear to be more variable than the other estimators. This is not surprising, as the baseline for both measures, the mean value over neighborhood for the entire study, is much broader than the other measures.

Typically the reproducibility of measurements is from 10 to 20% for most compounds and measures. However, this can vary from compound to compound depending on the measure used.

Of the four measures of precision and accuracy, only one, the surrogate recoveries, is available for individual samples. A natural question is whether this measure is of sufficient quality to allow concentration estimates for a sample to be recovery corrected. In other words, can the surrogate recoveries be used as an estimate of bias to correct the indicator chemical concentration estimates?

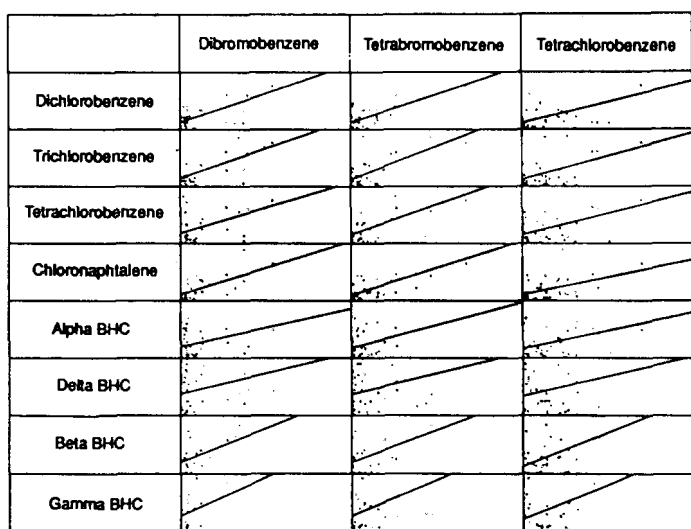


Figure 5a
Comparison Sample Versus Surrogate Precision,
Replicate Sample

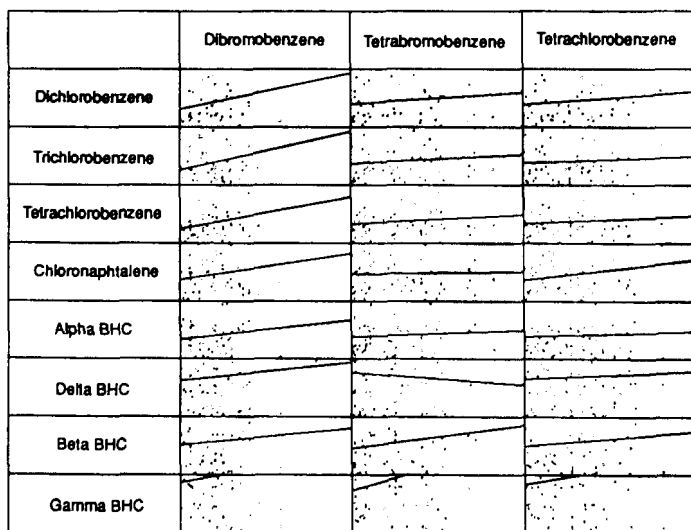


Figure 5b
Comparison Sample Versus Surrogate Precision,
Study Means

One problem with using surrogate compounds to correct for analytical bias is that there is no predefined correspondence between a particular surrogate and an indicator compound. The surrogates were chosen to span the range of elution times for indicator compounds through the gas chromatograph. Figures 5a and 5b show scatter plots of each indicator compound precision against the surrogate compounds precision. Figure 5a shows the precision calculated on the basis of replicate samples extracted on the same data. Precision in Figure 5b is calculated on the basis of the neighborhood means.

In these scatter diagrams, if surrogate precision and indicator chemical precision were perfectly correlated, the data points would align along the diagonal of each plot. A regression line is drawn in each plot to illustrate the actual correlation. As can be seen in the plots, the line intercepts the indicator variable axis, indicating that target compound variability is underestimated by surrogate variability. In general, the regression lines are not parallel with the diagonal, indicating lack of correlation of the two measures of precision.

Figures 6a and 6b are similar to Figure 4 in showing the absolute percent difference from nominal values for different estimators. An additional pair of estimators has been added to this figure, which shows the distribution of absolute percent difference for corrected concentration estimates as compared with the mean value of the replicate. As can be seen, the variability shown by the corrected concentration estimates is similar to that seen in the uncorrected estimates. The precision of the corrected estimates varies by compound from the uncorrected estimates, with some being improved by the correction and others being worsened.

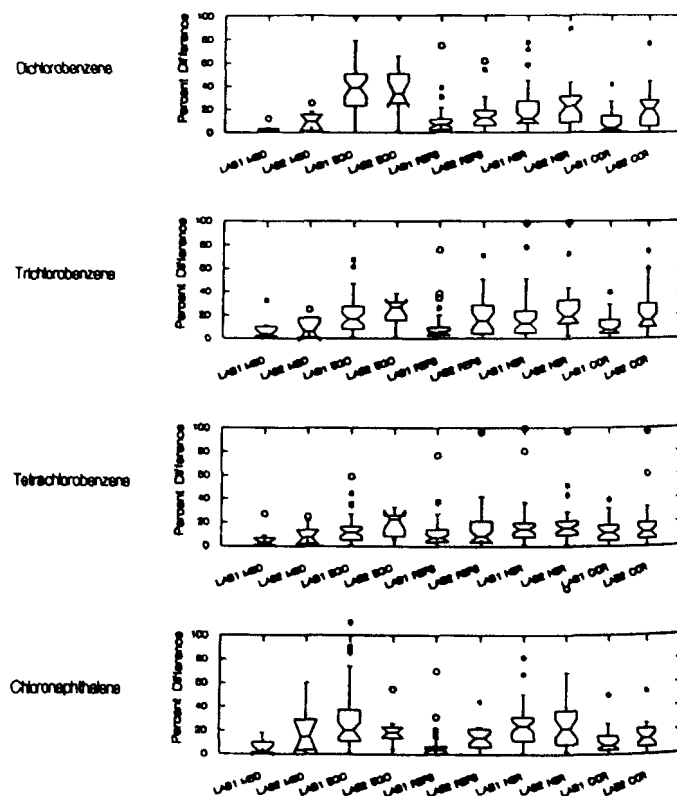


Figure 6a
Estimated Precision for Indicator Compounds Compared with
Surrogate Recovery Corrected Precision

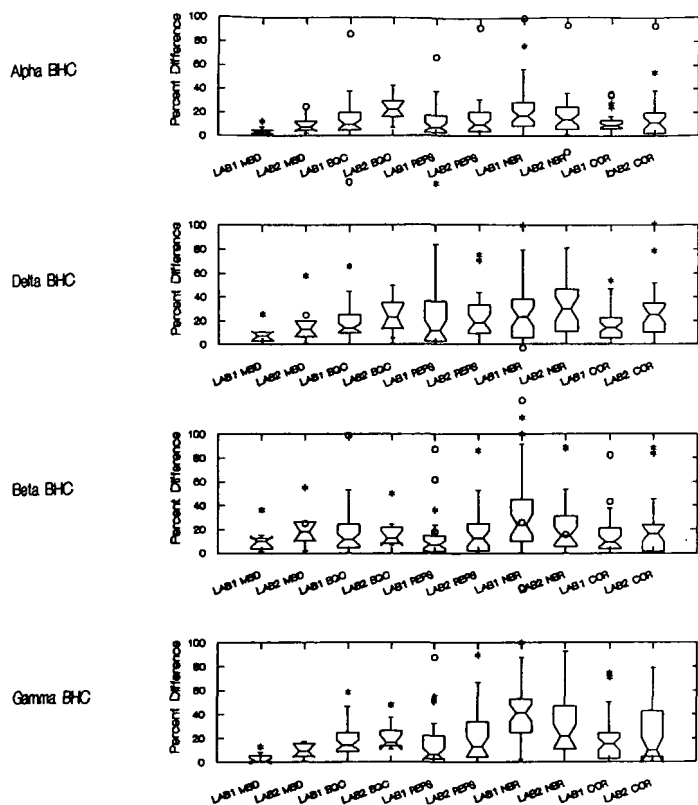


Figure 6b
Estimated Precision for Indicator Compounds Compared with
Surrogate Recovery Corrected Precision

CONCLUSIONS

Good estimators of accuracy and precision are required for an analysis of environmental data as this analysis begins the chain of events that leads to good decisions. Good estimators are needed for good designs, which enable good decisions to be made in an uncertain environment. Reliance on internal laboratory estimates of precision and accuracy through the use of matrix spike and surrogate spike data may overestimate the precision and accuracy achieved by a study. Replicate analyses and the use of high-quality spiked samples prepared by another laboratory are the best measures of precision and accuracy.

Precision should be based on repeated measurements over the course of a study. Precision thus reflects the reproducibility of analyses conducted at different times. This type of comparison is one of the most frequently used in environmental data analyses. The usual split sample replication does not measure all sources of data vulnerabilities.

Finally, correcting concentration estimates from a GC/MS procedure such as surrogate recovery estimates does not appear to improve the precision of the estimates.

Understanding Electrical Leak Location Surveys of Geomembrane Liners and Avoiding Specification Pitfalls

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ABSTRACT

The electrical leak location method developed under contract for the U.S. EPA is now being put to use in many commercial applications, and several contractors are providing electrical leak location services. The commercial surveys conducted to date have been overwhelming successes in that many leaks have been efficiently and accurately located in installations that had been previously tested certified leak-free environment conventional methods. The results of these surveys lead to the speculation that a pre-service electrical leak location survey should be performed on every geomembrane-lined landfill and impoundment before the installation is considered complete and ready for use.

The electrical method detects areas of localized electrical current flow through leaks in the otherwise insulating liner. A voltage source is connected to an electrode in water covering the liner and to a grounded electrode. Leaks are located by searching for the localized areas of relatively high electrical potential in the water caused by current flowing through a leak. The electrical leak location method can be used in liquid impoundments and for a pre-service inspection of solid waste landfills. The testing method will not damage the liner.

As with any new technology, many people in the environmental industry want a better understanding of the principles, capabilities and the proper application of the method. Specifiers of electrical leak location surveys must have this knowledge to specify the most effective and economical surveys. The objective of this paper is to provide important up-to-date information to meet this need.

INTRODUCTION

Geomembrane liners, also known as flexible membrane liners (FMLs), synthetic liners and membrane liners, are sheets of polymeric materials fabricated in a factory and seamed together at the field site to form a continuous liner. Installation can result in punctures or separated seams, causing loss of the liner's physical integrity. Damage also can be accidentally caused by heavy machinery used to place protective bedding material on the liner.

An electrical leak location method was developed and tested under contract for the U.S. EPA. This method has been demonstrated to be the most sensitive, reliable and valid method for locating leaks in geomembrane liners of waste landfills and impoundments. The electrical leak location method is now being widely applied and several contractors are providing electrical leak location services. Several technical references for the electrical leak location method are listed in the Bibliography.

Results of Leak Location Surveys

Southwest Research Institute has surveyed 56 geomembrane-lined storage facilities for leaks using the electrical leak location equipment. The total liner area surveyed was more than 4,400,000 ft². The sizes

of these installations ranged from less than 1000 ft² to more than 500,000 ft² and included both double- and single-lined impoundments and landfills. Almost all of the liners were in new installations. Most of the liners were constructed of high density polyethylene (HDPE), but some were chlorosulfonated polyethylene (CSPE) and polyvinyl chloride (PVC).

Leaks were found at all of the sites except for two sites with small liners. The average density of leaks was approximately one leak per 3200 ft² 13 leaks per acre. Although most of the leaks occurred in field seams, a significant number (more than 15%) were found in the parent material. The high percentage of leaks found in the seams is partly attributed to the fact that some very small seam leaks are found when the seams are surveyed a second time with the leak location probe on the seam.

Typical installations had from four to 12 leaks per acre. Installation and field seaming problems were experienced on the liners with greater than 20 leaks per acre. Several of the liners had more than 50 leaks per acre.

Because some leak location surveys were initiated in response to a known leakage problem, a significantly higher number of leaks might be expected for these installations. However, the number of leaks at the installations with known problems were fewer than installations where the leak location surveys were performed for construction quality assurance purposes. The results of these surveys indicate that a pre-service electrical leak location survey should be performed on every geomembrane-lined landfill and impoundment.

TECHNICAL DISCUSSION

Theory of Operation

Figure 1 shows the basic electrical leak location method for locating leaks in a geomembrane liner. The principles of the electrical leak location method are relatively uncomplicated. A DC voltage is connected to electrodes placed in electrically conductive material above and below the liner. The impressed voltage produces a very low current flow and a relatively uniform electrical potential distribution in the water above the liner in areas with no leaks. If the liner has a leak, water flows through the leak and establishes an electrical current path through the liner. Leaks are located by searching for the localized areas of relatively high electrical potential in the water covering the liner. The increased current density near the leak is indicated as an anomaly in the measured potential. The electrical leak location method can be used in liquid impoundments, as a pre-service inspection of solid waste landfills and to locate leaks in the final cover for landfills or impoundments. This testing method does not damage the liner.

If applied properly, the electrical leak location method is very sensitive. To increase the leak detection reliability to a maximum level, leak

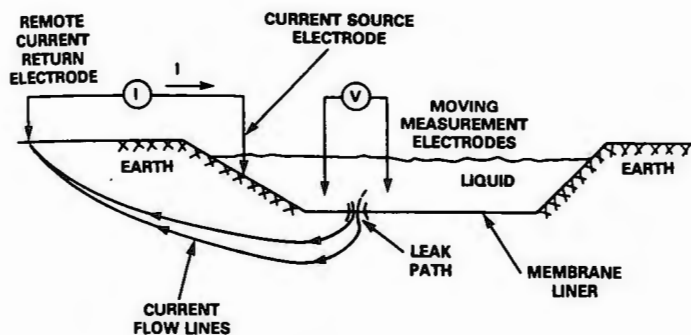


Figure 1
Diagram of the Electrical Leak Location Method

location surveys should be conducted with the maximum practical impressed voltage and detector sensitivity. Some of the leaks that are found are very small and may not leak significantly. Nevertheless, all detected leaks are located and marked for repair. The small leaks can indicate a weak seam that may fail with time or loading. In almost every survey, several larger leaks that require repair are found. The small leaks are repaired at the same time the larger leaks are repaired to increase confidence in the integrity of the liner.

Instrumentation

The manual leak location survey system consists of a lightweight, portable electrical probe and associated instrumentation. This system is for inspection of non-hazardous liquid-filled impoundments and for pre-service inspection of water-filled impoundments and landfills. Figure 2 illustrates the operation of the equipment.



Figure 2.
Manual Leak Location Equipment Consisting of an Electrode Probe and Electronics Unit

Figure 3 shows a typical detector electronics assembly. The battery-powered detector electronics provides an audio tone that varies in proportion to the measured signal so the operator is not required to continuously monitor the meter. Controls are provided to adjust the sensitivity, threshold and audio output level. Test buttons are provided to check the battery voltage and circuit operation. Connectors are provided to connect the detector probe outputs and an earphone for the audio indicator.

A source of DC power is used to impress a voltage across the geomembrane liner. Figure 4 shows an electrical leak location power supply with self-contained safety system. The leak detection sensitivity is proportional to the voltage output of the power supply. Batteries can be used for a safe low voltage power supply, but leak detection sensitivity will be decreased to a level where smaller leaks can not be detected and the leak detection reliability is decreased. For best results and sensitivity, a high voltage electronic power supply is used with a safety circuit. The high voltage power supply has an adjustable output level of up to 320 V DC. The safety circuit provides a measure of protection from accidental contact between earth ground and either power supply output or accidental contact across the power supply output. The safety circuits disconnect the power when a ground fault current is detected, or the output current momentarily increases or decreases due to possible human contact. A bright flashing warning light indicates that the power supply is energized.

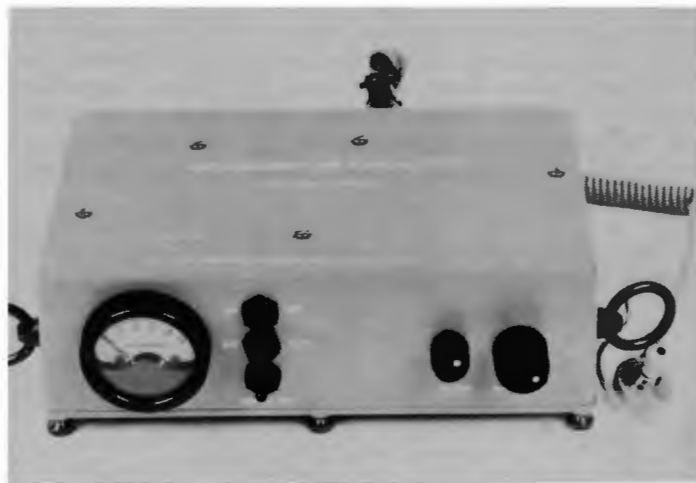


Figure 3
Leak Location Detector Electronics Assembly



Figure 4
Leak Location Power Supply

The detector probe is a long pole with two electrodes. A cable connects the electrodes to the input of the detector electronics. The probe is most conveniently used while wading in the liquid but, with an extension, it can be used from a raft in deeper water applications. Surveys of the side slopes are accomplished using a probe with a long handle

and small wheels to support the electrodes. The side slope area is surveyed by systematically lowering the probe down the slope and then pulling it up the slope.

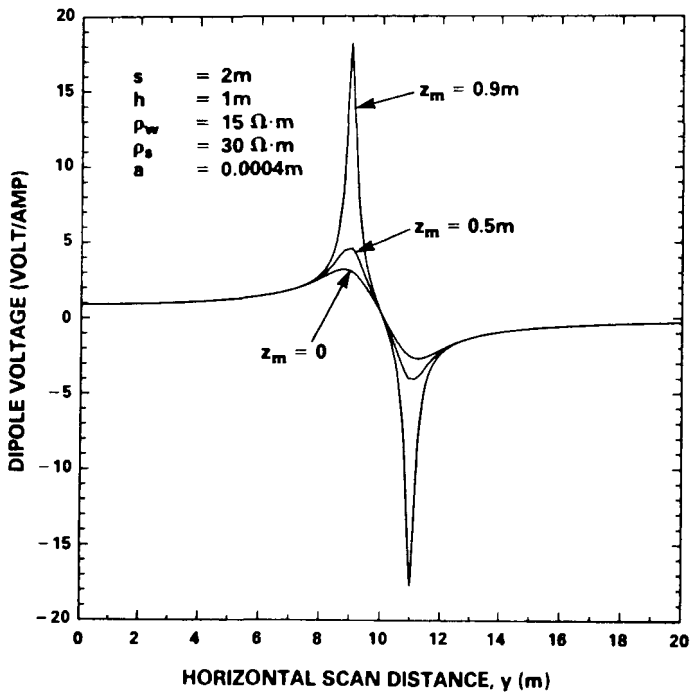
EFFECT OF MEASUREMENT PARAMETERS

Computer Model

A mathematical model was developed to investigate the performance capabilities of the electrical leak location method. The model accommodates various electrical and dimensional parameters for a lined impoundment or landfill. Model studies of the electrical leak location survey technique were conducted to characterize the performance of the method with various electrical parameters of the waste materials, the measurement electrode array geometry, the measurement electrode depths and proximity to the leak and the size and number of leaks.

Anomaly Effects of a Leak

Figure 5 shows a typical family of leak anomaly responses for horizontal detector electrodes that illustrate the effects of various measurement depths. The two peaks in the signal occur when the two electrodes pass within closest proximity of the leak. Figure 6 shows the amplitude of the leak anomaly for three different electrode spacings as the electrodes are scanned at various depths. A substantial improvement in detection sensitivity is obtained when the potential array is scanned closer to the leak. The computed leak responses and field experience affirm the practical importance of performing the survey measurements near the bottom of the impoundment.



Key: s = electrode spacing
h = depth of the water
 ρ_w = liquid resistivity
 ρ_s = underlying soil resistivity
a = leak radius
 z_m = electrode depth
x = offset distance
y = distance along scan line

Figure 5
Plot of the Leak Anomaly Versus Horizontal Electrode Depth

Figure 7 shows the anomaly response of a leak measured with a vertical electrode pair. The leak is located at the position indicated by the maximum response. Multiple leaks can be resolved with less ambiguity when vertical electrodes are used. Again, the computed leak responses point out the practical importance of performing survey measurements near the geomembrane liner.

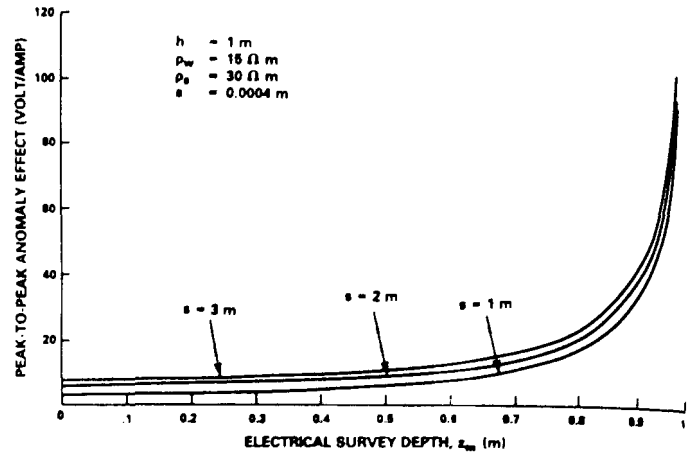


Figure 6
Leak Signal Amplitude Versus Survey Depth

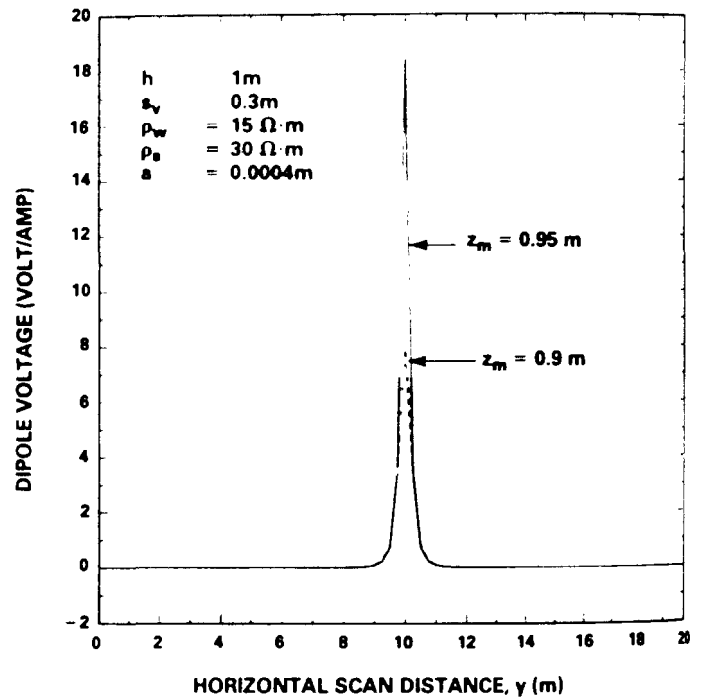


Figure 7
Leak Anomaly Characteristic for Vertical Electrodes

Effect of Measurement Electrode Spacing

In general, the amplitude of the measured leak signal increases as the electrode spacing increases. However, the increase is negligible when the electrode spacing is somewhat larger than the distance to the leak. This principle can be demonstrated by considering the equation for the voltage at some distance from the leak. The simplest mathematical model of a leak is to consider that the leak is a point current source in an infinite half space. If ρ_w is the resistivity of the water, I is the current and the distances from the leak to the two measurement electrodes, the measured voltage difference will be:

$$v = \frac{I\rho_w}{2\pi} \left[\frac{1}{r_1} - \frac{1}{r_2} \right]$$

Figure 8 shows the amplitude of the leak signal versus electrode separation when the electrode closest to the leak is 0.05, 0.1 and 0.2 meters with a current of 5 mamp and a water resistivity of 10 ohm-meters. The graph shows that little is gained by increasing the electrode spacing beyond approximately 0.3 meters.

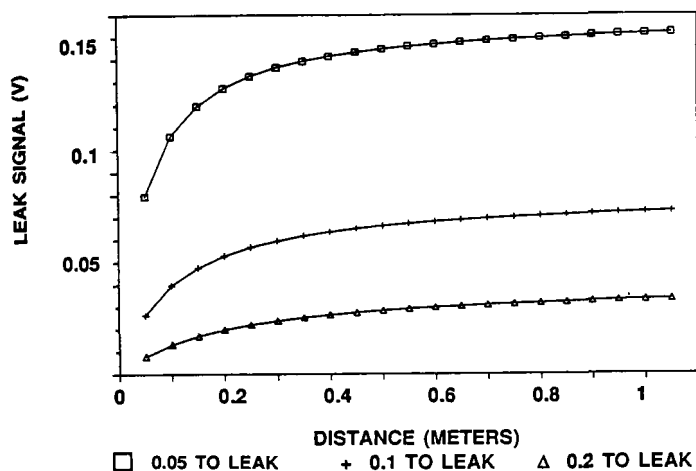


Figure 8
Leak Signal Amplitude Versus Electrode Separation

Effect of Water Resistivity

Figure 9 shows the amplitude of the leak anomaly for different values of water resistivity and water depth with the electrodes suspended mid-way in the water. These curves show that for a given amount of leak current, the leak detectability is increased essentially linearly with the resistivity of the water. The injected current must be increased to offset the effect of lower measured leak anomaly attributed to lower resistivity of the liquid. For constant current injection, the amplitude of the leak anomaly is essentially independent of the resistivity of the material under the liner.

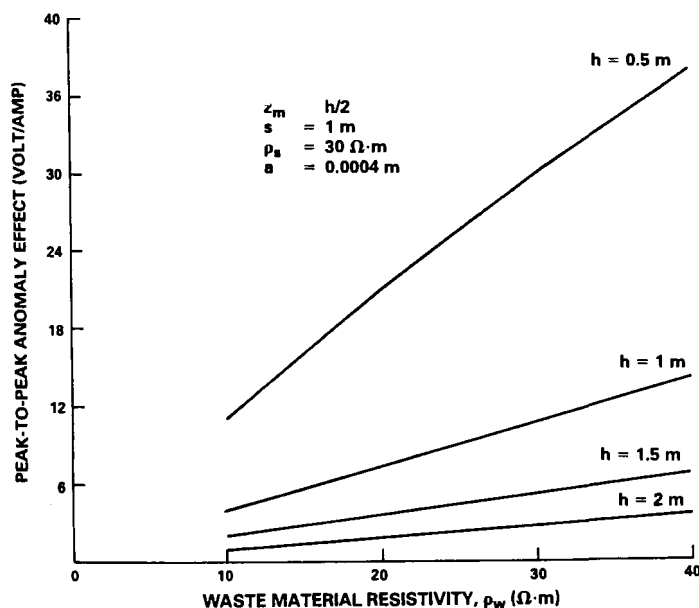


Figure 9
Leak Signal Versus Water Resistivity for Various Water Depths

In practice, a constant voltage power source is used rather than a constant current source. Therefore, as the water resistivity is decreased, more current will flow through the leaks. However, the amount of current

increase does not offset the decrease in signal level.

Effect of Offset Distance from Leak

The maximum allowable spacing between the lateral survey lines depends on the amount of current flowing through the leak and the sensitivity of the leak location equipment. To illustrate this characteristic, Figure 10 shows the amplitude of the leak anomaly for various electrode offset distances from the leak center as a function of the survey height above the liner. The amplitude of the anomaly decays rapidly as the offset distance is increased. These results indicate the importance of scanning the electrodes close to every point on the liner to obtain a high level of leak detection sensitivity.

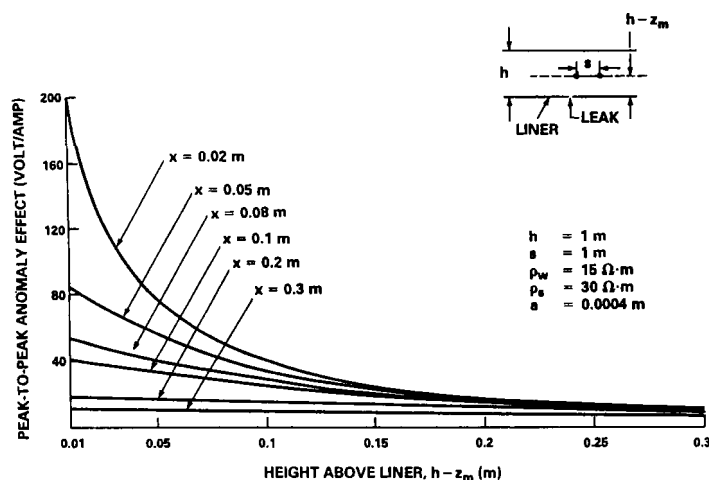


Figure 10
Leak Signal Amplitude Versus Height Above Liner for Various Lateral Offset Distances

Leak Location Accuracy

The leak signal is at a maximum when the leak location electrode is touching the leak. Therefore, leaks are very accurately located by decreasing the sensitivity of the leak location electronics to a level where the point of maximum signal can be observed. The location of the leak can be essentially pinpointed in this way.

Effect of Leak Size

The size of the leak and the conductivity of the water essentially determine the amount of current flowing through the leak for a given impressed voltage. Because the leak signal is proportional to the amount of electrical current flowing through the leak, larger leaks are much easier to detect the smaller leaks. Experimental measurements of leak current versus leak diameter for circular leaks show that the amount of current flowing through the leak is approximately inversely proportional to the diameter of the leak. Other tests have been conducted to show that the shape of the leak has little effect upon the shape of the leak signature.

Effect of Liner Resistivity

Because the liner resistivity is many orders of magnitude greater than the resistivity of the water, the liner resistivity has no effect on the leak detection sensitivity. Laboratory tests have been conducted to show that the change in liner resistivity versus time for exposure to typical levels of acidity, alkalinity and dissolved salt content have negligible effect on the resistivity of the liner material.

Effect of Sediment Layer

The electrical leak location method is less sensitive for locating leaks in geomembrane liners with a sediment layer in the liquid. Physical model tests and field experience indicates the lower sensitivity and that the measurements are not as repeatable with sediment layers present.

The lower sensitivity occurs probably because the electrodes cannot be scanned close to the leak and the liquid shunts the measured potential field to some degree.

Effect of Soil Cover

Figure 11 is a plot of a measured leak anomaly versus depth of soil cover for a geomembrane liner when the electrodes are scanned directly over the leak. The diameter of the leak was 0.3 cm. Although the leak signal decreases rapidly with increasing soil cover thickness, the leak anomaly was easily detected for soil depths up to 0.6m. Figure 12 shows plots of the data with a soil thickness of 0.3m for scan lines offset from the leak. The leak is barely detectable when the electrodes are scanned on a line offset 0.6m from the leak. The signal can be improved by scraping the dry soil off the surface or inserting the electrodes into the more moist underlying soil. Figure 13 shows the decrease in the measured noise for these conditions with a soil thickness of 0.6m.

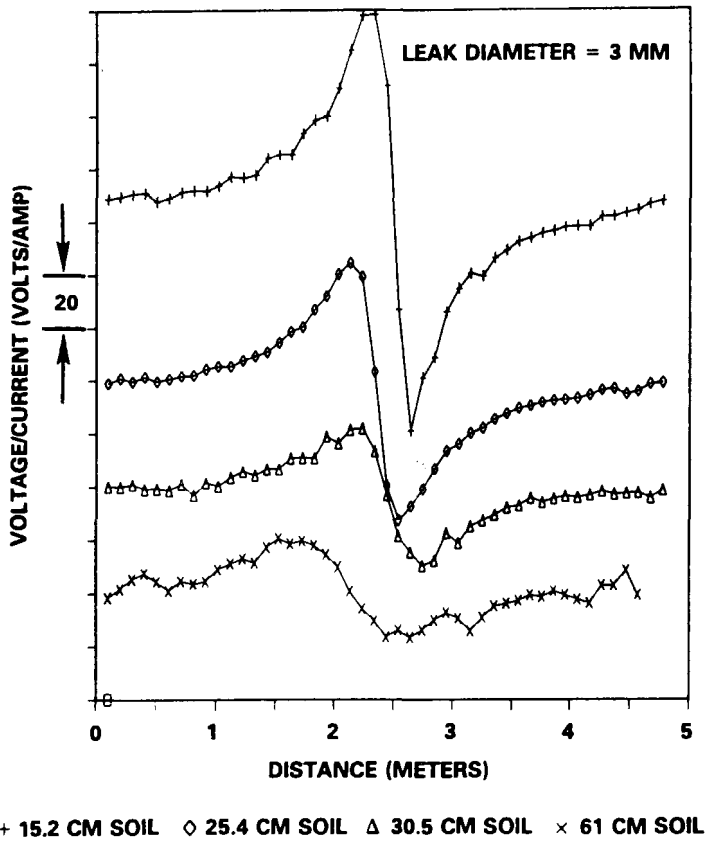


Figure 11
Leak Signals for Various Thicknesses of Soil Cover

TYPES OF SURVEYS AND SURVEY TECHNIQUE

Survey of Bottom of Water-Covered Single Liners or Secondary Liners

When a single liner is in place, the leak location power supply is connected to a source electrode in the water and a grounded electrode. Surveys are conducted along survey lanes established across the impoundment. The most convenient method of operation is to place the lines across the shorter dimension of the impoundment and perpendicular to a straight side. Survey lines are spaced approximately 5m apart. Sufficient accuracy usually is obtained using only a tape measure. Marks are put on the liner above the water line every 5m on the opposite sides of the impoundment. Floating polyethylene ropes or non-conducting survey chains are stretched between opposite marks across the impoundment. As an alternative procedure, the panel seams can be used as the survey lanes. Two or three survey operators can scan the length of a

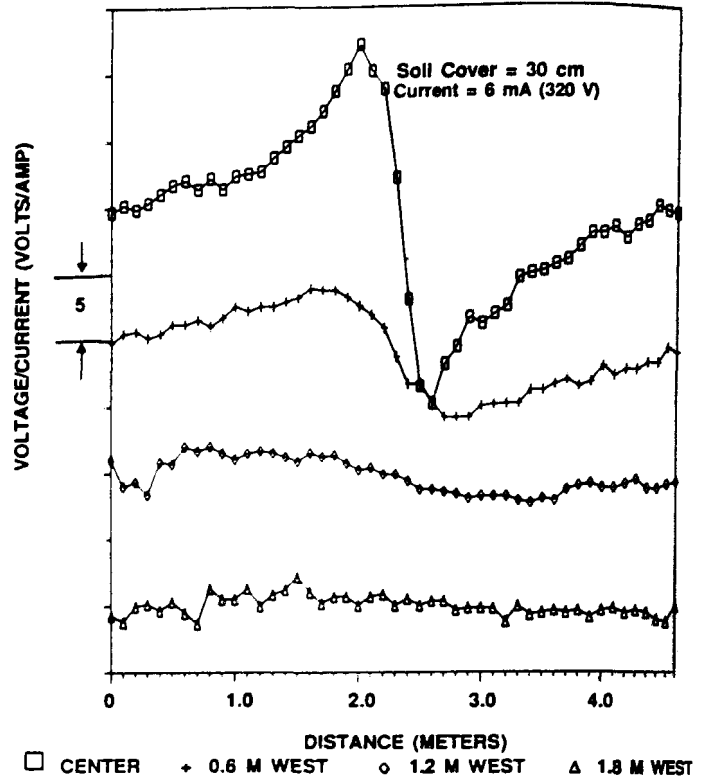


Figure 12
Leak Signals with 0.3m of Soil Cover for Offset Scan Lines

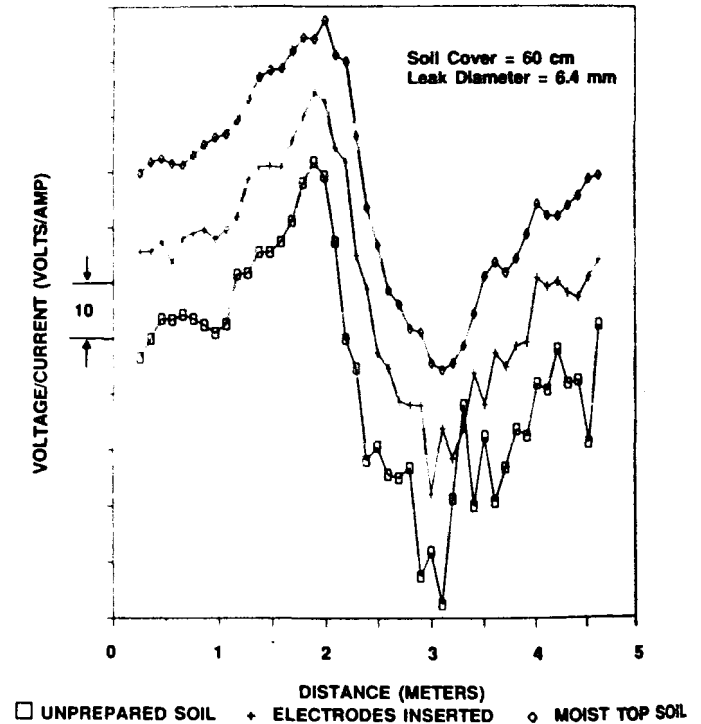


Figure 13
Improvement in Leak Signal Quality When the Soil is Prepared

panel with overlapping coverage by observing or feeling the seams. This alternative procedure is more difficult or impractical to implement with irregular panel layouts.

Horizontal traverse lines are scanned with a coverage of 2.5m on each side of the traverse lines. The probe is scanned along the bottom in

an arc overlapping under the traverse line and past the midpoint of the survey lane. After each arc is swept, the operator moves forward approximately 0.3m and scans a return arc to just beyond the traverse line. The leak detection probe is thus scanned within no more than approximately 0.15m of every submerged point on the liner. The threshold control on the leak location electronics is adjusted frequently to maintain maximum leak detection sensitivity.

Leaks are indicated by a sudden increase in the frequency of the tone in the earphone as the electrode is scanned near the leak. When a leak is detected, the threshold and sensitivity controls are adjusted to obtain a peak on-scale meter reading both laterally and longitudinally when the tip of the probe is scanned. This procedure determines the exact location of the leak. The probe tip is held on the leak while the probe is swung to vertical. The leak is then marked with lead sinkers connected to a small float with a length of string.

The locations of the leaks also are measured relative to a temporary survey grid for a permanent record. Where practical, the location and type of leak also is noted (i.e., on a seam or patch, or in the panel). In addition to covering every square meter of the liner, all liner field seams and patches are double checked.

Survey of Bottom of Water-Covered Primary Liners

By placing the current return electrode in electrical contact with the liquid-saturated drainage layer located between the two liners, the electrical leak location method can be used to locate leaks in the upper liner. The survey procedures for a single liner are then followed. Simple electrical continuity tests between the drainage layer and the earth also can determine the existence of leaks in the bottom liner but not their location.

Survey of Side Slopes

Surveys of water-covered side slopes are accomplished using the probe with a long handle and small wheels to support the electrodes. The side slope area is surveyed by systematically lowering the probe down the slope and then pulling the probe up the slope. The operator moves forward approximately 0.3m between sweeps. Each survey sweep covers an area approximately 0.3m wide down the flooded sidewall. Any leaks found are accurately located, and the locations are referenced to a temporary survey grid established on the berm.

When more than approximately 7m of the side slope are immersed, the manual survey of the side slopes is conducted in stages. The water level is raised or lowered in stages that allow approximately 7m of the immersed side slope to be surveyed at a time. The surveys should provide overlapping coverage between the stages.

The side slopes can be surveyed by raising or lowering the water level in stages either before or after the bottom of the liner is tested. If the side slopes are tested first, from the top down, the cell will be filled with water to the working level prior to the leak location survey. This procedure exposes the liner to loads representative of actual in-service loading. Usually the level of the water can be lowered faster than it can be raised, therefore, the survey can be completed with less standby time as the water level is adjusted.

The advantage of surveying the side slopes after the bottom of the liner is surveyed is that washout or settling of the subgrade under the liner caused by possible large leaks in the bottom of the liner might be avoided if leaks in the bottom are located and repaired prior to full hydrostatic loading. However, there is no assurance that additional leaks will not occur because of the increased hydrostatic loading during the side slope survey. Therefore, additional testing of the bottom of the liner may be required after the side slopes are surveyed.

Survey of Soil-Covered Liners

Often a layer of sand or soil is placed on the liner to serve as a protective layer or drainage layer. Geomembrane liner material is also covered with soil when used for landfill final cover systems. Because of the high probability of damaging the geomembrane liner in the process of emplacing the soil, a leak location survey of the soil-covered geomembrane is a highly effective method of ensuring the integrity of the

liner. The electrical leak location method is the only method capable of locating leaks in a geomembrane covered with protective soil. The method is particularly valid because the liner is tested under load and after the liner has been exposed to possible damage incurred in the process of emplacing the protective soil cover.

The electrical leak location method was modified to make surface soil potential measurements to locate leaks in geomembranes covered by a protective or cap soil layer. The soil is dampened with water to allow good electrical contact and allow the water to percolate through the leaks. Completely flooding the liner is not necessary. Surface potential measurements are made using a portable digital data acquisition system. Surveys are conducted by making potential measurements on closely spaced survey lines. Point-by-point potential readings are made along the survey lines with a fixed measurement electrode separation. The data are downloaded to a computer for storage and plotting. When a suspect area is located, manual measurements are made to further isolate the leak. When the surface of the soil is dry, the dry soil is scraped away so that accurate measurements can be made on the uncovered moist soil.

The data are examined for leak signatures. The characteristic leak signal is a bipolar signal with the initial signal deflecting opposite to the polarity of the current injection electrode. Signals caused by other features such as drainage laterals can be recognized and rejected.

The leak location sensitivity increases as the thickness of the soil decreases. Typically, leaks with a diameter greater than 0.3cm can be located in a geomembrane covered with 0.3m of soil. Testing for leaks with only a portion of the soil cover in place is recommended if the thickness of the soil cover will be greater than approximately 0.3m. Any possible damage to the liner will most likely occur during the installation of the first layer of soil.

The leak location accuracy for surveys conducted with soil cover depends upon several factors including the closeness of the spacing of the point-by-point measurements and the homogeneity of the soil cover. A practical accuracy guideline for leak location surveys with soil cover is approximately one half of the soil thickness. After the soil has been removed, followup measurements can be made to locate the leak within 1.5 cm.

The survey parameters (survey line spacing, spacing of measurements and spacing of measurement electrodes) must be designed for proper coverage and leak detection sensitivity. The design of the surveys must be based on the physics of the electrical leak location method.

Another survey methodology can be successful in some cases, particularly when an electrical leak location was previously conducted with the liner flooded with water and only a few major leaks are suspected. Rather than performing a systematic survey on closely spaced survey lines to locate smaller leaks, the reconnaissance measurements are intended to attempt to isolate a few large leaks in the hope that no smaller leaks are present. The measurement sequence is to locate a leak, remove the soil from over the leak, insulate the leak and then measure the power supply current. This sequence is repeated until the current level decreases to a low level indicating that all of the major leaks are found.

Multi-Channel Leak Location Surveys

Southwest Research Institute has developed a multi-channel leak location system for locating leaks in impoundments with hazardous wastes, for locating leaks in the side slopes of deep impoundments in one stage and for surveying in deep water. The system is particularly cost-effective for large impoundments and landfills. The new system has 12 weighted electrodes suspended from a nonconducting horizontal axle between two large plastic wheels. Twelve data acquisition channels, a serial data telemetry system and a portable computer or multi-channel chart recorder are used to acquire, display and record the leak location data.

The sensor assembly is systematically pulled across the bottom of the impoundment using a power winch. Each survey sweep covers an area approximately 4m wide. If feasible, the sweeps are referenced to liner seams to provide overlapping coverage of the seams as well as complete coverage of the water-covered liner panels. The locations of

the leaks are referenced to a temporary grid system established on the berm of the impoundment.

The leak location data acquisition system has been applied at one large impoundment to survey the 18-m-long side slopes. The sensor and electronics subsystems operated properly and located several leaks. Mechanical modifications are needed to make the assembly more rugged.

Remote-Controlled Leak Location Survey System

A small remotely-controlled boat equipped with potential measurement electrodes and electronics, servo-controlled steering and data telemetry has been developed to locate leaks in hazardous waste impoundments. In one mode, the measured potentials are used with the servo-controlled steering to automatically seek leaks. The system has been constructed and tested in a geomembrane test impoundment. The method is described in U.S. Patent 4,719,407 for Automated Search Apparatus for Locating Leaks in Geomembrane Liners.

SITE PREPARATIONS

Water Covering the Liner

To conduct a leak location survey of the bottom of the liners, a minimum of 0.15m and a maximum of 0.75m (0.6m preferred) of water containing no hazardous or foul substances must cover the liner. Because hydrostatic loading produces mechanical stress in both the seams and the material, leaks may occur only after the liner is subjected to these loads. Therefore, testing the liner after the impoundment has been filled with water is a valid method for determining if leaks will occur under realistic loading conditions.

The depth of the water for the survey (within the specified range) can be determined on a case-by-case basis. Surveying with a shallow water level requires less water and pumping, but limits the hydrostatic loading. The survey covers only the submerged liner area when the cell is filled with water to the depth specified for the survey. Therefore, surveying with shallow water decreases the amount of the side slope that is covered by water and thereby limits the area of survey coverage for the cases where all of the side slopes are not surveyed.

Flooding the Leak Collection Zone

To survey the primary liner of a double liner system, an electrical conduction path through any leaks to the leak collection zone must be established. This process can be accomplished by pumping water in the leak collection system while the primary liner is being filled with water. Water can be pumped into the discharge side of the leak collection system. In some cases, air vents must be provided in the perimeter edges of the primary liner near the top of the berm to allow air trapped between the two liners to be vented. The water also can be pumped into the air vents. The water level in the leak collection zone must be slightly below the level of the water in the primary liner to prevent the primary liner from being lifted.

In some cases when moist sand is used in the leak collection zone, an alternative method can be used to establish the electrical conduction path without flooding the leak collection zone. The reliability of this alternative method depends on the type and moisture content of the sand. The alternative method is to allow the water from the leaks to percolate through the leak collection zone. This method is most effective when the water on top of the liner has been allowed to stand at least 3 days and good electrical contact can be established with the current electrode in the leak collection zone.

Current Electrode in Leak Collection Zone

Provisions should be made to allow the placement of a metal electrode into the leak collection zone of a double liner system. In some cases, a slit is cut in the liner above the water level to allow the insertion of the metal electrode. This slit must be repaired when the leaks are being repaired. In some installations, the electrode can be inserted through a straight plastic pipe that extends down into the leak collection sump.

A third method for providing the electrode is to install a permanent electrode constructed of approximately 0.1m² of thin stainless steel

sheet in the drainage layer near the lowest point of the leak collection system. The corners and edges of the electrode should be rounded to prevent damage to the liner. In addition, the electrode can be wrapped with geotextile or geonet to further protect the liners. An insulated wire (16 AWG to 12 AWG) must be connected between the electrode and a test terminal located at a convenient, accessible site near the impoundment. The connections should be insulated with a suitable coating.

Isolate Electrical Paths Through the Liner

The electrical leak location method locates leaks by detecting electrical conduction paths through leaks in the liner. If feasible, any other electrical conduction paths through or around the liner must be eliminated or insulated. All penetrations, such as fill lines, drain pipes, batten anchors, penetration flanges, footings, pump lines, pump wiring, instrumentation wiring, instrumentation conduits and access ramps making contact with the water in the liner should be insulated from ground or constructed of an insulating material. Electrical paths also can be established through the liquid in plastic pipes if the pipes connect to a grounded metal valve or metal pipe.

Rubber packers can be placed in plastic drain and fill pipes to insure that the fluid in the pipes does not act as an electrical path to ground. In some cases a temporary geomembrane cover can be sealed over pipes and batten anchor bolts. Metal pipes penetrating the liner can be insulated using large plastic garbage bags or caps constructed of insulating foam rubber, geomembrane and plywood.

For the electrical paths to be a factor, the paths must form a conduction path through or around the liner being surveyed. The presence of such electrical conduction paths does not preclude the application of the method. However, if these paths can not be eliminated, isolated or insulated, the paths will be indicated as leaks that may mask the signal from other smaller leaks in their immediate vicinity. In addition, if the conduction paths are substantially lower in resistance than the electrical paths through the leaks, the amount of current flowing through the leaks may be too small to detect small leaks. The design and construction of the impoundment can be reviewed to determine the best methods to eliminate or minimize the effect of these conduction paths on the survey.

Remove Debris

For safety and better leak location reliability, debris such as unnecessary sand bags and non-floating liner material must be cleared from the liner.

Conducting Structures

A leak is indicated as an electrical potential anomaly in an otherwise relatively uniform potential distribution. Conducting structures such as concrete footings, metal supports and sand bags can distort the potential distribution, making leaks more difficult to locate. Small leaks that are substantially covered by structures such as a concrete footing probably cannot be detected. Moderate-size leaks at the perimeter of such structures can usually be detected.

Power Requirements

Electric power of single phase 95 to 125 V AC, 45 to 70 hertz, at approximately 5 amp must be provided at the site for operation of the leak location power supply. The power outlet should be located at the top of the berm.

SAFETY

A potential for injury is present in any work at a construction site. Specific hazards include electrocution, slipping and falling on the geomembrane material, falling in the water, hypothermia and drowning. Job safety is the most important aspect of doing a complete and thorough leak location survey. Proper safety precautions must be followed.

In addition to the standard construction site safety rules, specific safety procedures must be used to safely conduct an electrical leak location survey using a high voltage power supply. The survey operators wading in the water are exposed to an electrocution hazard if they come in contact with a grounded electrical conductor. Precautions must be taken

to avoid this possibility. Some precautions include using only dry electrically-insulating hand lines for entering or exiting the basin and being sure that wire rope, wet rope, metal cables, electrically-conducting poles, electrically-conducting ladders, or any other electrically conducting objects are not available or used for rescue or used to aid personnel in the water.

A safety circuit for the high voltage power supply provides a measure of protection in case of accidental contact of personnel with the high voltage. Because making the power supply inherently safe and making the safety circuit completely reliable are not possible, survey procedures and procedures should be such that personnel can never make electrical contact across the power supply. The safety circuit must absolutely never be tested by human contact. The safety interlocks must not be bypassed to allow operation of the power supply without the flashing red safety strobe.

Other elements of an effective safety plan include proper training of survey personnel, safety briefing for visitors to the site, high-voltage warning signs and employing personal flotation devices for operations near deep water. The water in the impoundment must be non-hazardous if an operator is to be completely immersed. Surveys must never be performed when there is a threat of lightning or under adverse weather conditions such as cold weather, rain, or snow or where the operator has difficulty concentrating on safety.

On some work sites, the survey operators must be qualified to meet OSHA 29 CFR 1910.120 safety requirements. This OSHA regulation requires 40 hr of instruction, on-the-job-training, a medical surveillance program and annual 8 hr training refresher courses.

Operators should be trained in first aid and cardiopulmonary resuscitation. Additional safety procedures must be followed depending on the hazards and conditions present at each site.

SPECIFYING ELECTRICAL LEAK LOCATION SURVEYS

The Appendix is a guide for specifying electrical leak location surveys. The guide offers suggestions for typical surveys as well as assigning responsibilities for preparations for the surveys.

BIBLIOGRAPHY

- Peters, W.R., Shultz, D.W. and Duff, B.M., Electrical Resistivity Techniques for Locating Liner Leaks, *Proc. EPA Eighth Annual Research Symposium Land Disposal, Incineration and Treatment of Hazardous Waste*, Ft. Mitchell, KY, Mar., 1982.
- Peters, W.R., Shultz, D.W. and Duff, B.M., Electrical Resistivity Techniques for Locating Liner Leaks, *Technical Program Abstracts*, Society of Exploration Geophysicists 52nd Annual International Meeting, Dallas, TX, Oct., 1982.
- Shultz, D.W., Duff, B.M. and Peters, W.R., Performance of an Electrical Resistivity Technique for Detecting and Locating Geomembrane Failures, *Proc. International Conference on Geomembranes*, Denver, CO, June, 1984.
- Shultz, D.W., Duff, B.M. and Peters, W.R., *Electrical Resistivity Technique to Assess the Integrity of Geomembrane Liners*, EPA Report No. EPA-600/S2-84-180, U.S. EPA, Cincinnati, OH, Jan., 1985.
- Boryta, D.A. and Nabighian, M.N., "Method for Determining a Leak in a Pond Liner of Electrically Insulating Sheet Material," U.S. Patent No. 4,543,525, Sept. 24, 1985.
- Fountain, L.S. and Shultz, D.W., Liquid Waste Impoundment Leak Detection and Location Using Electrical Techniques, *Proc. SME Annual Meeting*, New Orleans, LA, Mar., 1986, Preprint No. 86-95.
- Converse, M.E. and Shultz, D.W., "Automated Search Apparatus for Locating Leaks in Geomembrane Liners," U.S. Patent No. 4,719,407, Jan. 12, 1988.
- Owen, T.E., "Geomembrane Leak Assessment Shell Shaped Probe," U.S. Patent No. 4,720,669, Jan. 19, 1988.
- Converse, M.E., Glass, K.B. and Owen, T.E., "Directional Potential Analyzer Method and Apparatus for Detecting and Locating Leaks in Geomembrane Liners," U.S. Patent No. 4,725,785, Feb. 16, 1988.
- Darilek, G.T. and Parra, J.O., *The Electrical Leak Location Method for Geomembrane Liners*, U.S. EPA Report No. U.S. EPA/600/S2-88/035, U.S. EPA, Cincinnati, OH, Mar., 1988.
- Darilek, G.T. and Parra, J.O., The Electrical Leak Location Method for Geomembrane Liners, *Proc. U.S. EPA Fourteenth Annual Research Symposium, Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste*, Cincinnati, OH, May, 1988.
- Cooper, J.W., "System for Determining Liquid Flow Rate Through Leaks in Impermeable Membrane Liners," U.S. Patent No. 4,751,467, June 14, 1988.
- Parra, J.O. and Owen, T.E., Model Studies of Electrical Leak Detection Surveys in Geomembrane-Lined Impoundments, *Geophysics*, 53, p. 1453-1458, 1988.
- Parra, J.O., Electrical Response of a Leak in a Geomembrane Liner, *Geophysics*, 53, pp. 1445-1452, 1988.
- Darilek, G.T., Laine, D.L. and Parra, J.O., The Electrical Leak Location Method for Geomembrane Liners-Development and Applications, *Proc. Industrial Fabrics Association International Geosynthetics '89 Conference*, San Diego, CA, Feb., 1989.
- Laine, D.L., Detection and Location of Leaks in Geomembrane Liners Using an Electrical Method: Case Histories, *Superfund '89, HMCRI 10th National Conference and Exhibition*, Washington, DC, November, 1989.

APPENDIX

Specification Guide for the Electrical Leak Location Method For a Geomembrane Leak Location Survey With No Soil Covering the Liner

Introduction

This list of typical specifications is presented with relevant general discussion to explain the preparations required for surveying primary or secondary liners for leaks using the electrical leak location method. Electrical leak location surveys can be contracted for by the owner or operator of the facility, the general contractor, a third-party quality assurance contractor, or the liner installer. To best serve the interests of the facility owner, the electrical leak location surveys should be contracted for by the owner or operator of the facility, or a third-party quality assurance contractor. The following specifications are written for this type of contractual arrangement. Separate specifications are required for the general contractor and for the electrical leak location contractor.

The specifications are for a manual survey of liners with no soil or sand covering the liner. The specifications are intended for guidance and reference only. They are not intended to be all-inclusive, to be necessary in every application, or to recommend any particular practices or procedures. The specifications for each installation should be written specifically for the application, using proper engineering practices and judgement and legal advice and review. Each use of the designations of Company and Contractor should be reviewed and changed as applicable to refer to the owner of the facility, the general contractor, the liner installer, an independent quality assurance consulting firm, or other subcontractor as applicable. Other terms such as landfill, impoundment or pond should be used as appropriate. The specifications are written to be very comprehensive. They should be abbreviated wherever possible. The paragraphs typed bold are provided for explanation and can be omitted from the specification.

Electrical Leak Location Survey Specifications for General Contractor

Electrical Leak Location Survey Under Hydrostatic Load

An electrical leak location survey will be performed by Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78238, (Contact Daren L. Laine, telephone 512-522-3274) or approved equivalent. The survey will be conducted on the bottom and side slopes of both the primary and the secondary geomembrane liners of the basin. Contractor will be responsible for preparing the basin for the survey as described below.

If more than one leak per 2000 ft² of surveyed area is found in either liner, the leak location survey will be limited to one man-day of survey per 20,000 ft² of liner material. The electrical leak location survey will be conducted to better categorize the occurrence of leaks and possible causes of leaks to aid in the specification of corrective measures. The electrical leak location survey will be curtailed until the cause of the leaks is determined and corrective measures are taken by the Contractor. In the case of defective seaming, only patching the leaks will not be a viable corrective action because additional leaks will likely form when basin is put in service. If more than one leak

per 2000 ft² of surveyed area is found in either liner, an electrical leak location survey of the liner will be performed at the expense of the Contractor after the corrective actions are taken and the located leaks are repaired.

The occurrence of greater than approximately one leak per 2000 ft² can indicate defective seaming process or procedures, defective liner material, or ineffective liner material handling or protection measures. In these cases, further electrical leak location surveying are not sensible because the questionable integrity of the installation. In these cases corrective actions must be taken.

Prior experience indicates that detectable leaks are found in some repaired leaks when they are tested using the electrical leak location method. When significantly less than approximately one leak per 2000 ft² of liner is found, rechecking the leaks with the electrical leak location method is usually not necessary if the leak is sealed and then a patch is seamed over the repair. The repair can then be tested using a vacuum box. When more than approximately one leak per 2000 ft² are found, rechecking the seams and patches using the electrical leak location method is warranted. The geomembrane installer is responsible for making the repairs.

Preparing the Basin for Survey

Electrical Paths Through the Liner

Contractor shall electrically insulate electrical conduction paths through the liner. Such conduction paths can be caused by fill pipes, drain pipes, batten anchors, penetration flanges, footings, pump lines, pump wiring, instrumentation wiring, instrumentation conduits and access ramps. Electrical paths can also be established through the liquid in plastic pipes if the pipes connect to a grounded metal valve or metal pipe. Contractor will provide any necessary rubber packers and/or insulated coverings for this purpose. Properly supported temporary geomembrane material sealed over the electrical penetrations can also be used.

The electrical leak location method locates leaks by detecting electrical conduction paths through leaks in the liner. Any other electrical conduction path which also makes a circuit through or around the liner will give the same indication as a leak. The presence of such electrical conduction paths does not preclude the application of the method. However, if these paths can not be eliminated, isolated, or insulated, they will be indicated as leaks and they may mask the signal from other smaller leaks in their immediate vicinity. In addition, if the conduction paths are substantially lower in resistance than the electrical paths through the leaks, the amount of current flowing through the leaks may be too small to allow the detection of small leaks.

Electrode in Leak Collection Zone

Contractor shall make the arrangements for placing a suitable metal electrode in the leak collection zone prior to installing the primary liner. The electrode shall be constructed of approximately 1 ft² of stainless steel sheet. The corners and edges of the electrode must be rounded to prevent damage to the liner. In addition, the electrode shall be imbedded in the sand or wrapped with geotextile or geonet to further protect the liners. An insulated wire (16 AWG to 12 AWG) must be connected between the electrode and a test terminal located at a convenient accessible location near the basin. The connections must be insulated with a suitable coating. The electrode shall be buried at a depth approximately 2 in above the secondary liner near the lowest point of the collection system.

Some alternative methods include cutting a slit in the liner a few feet above the water level to allow the insertion of the metal electrode. The Contractor shall be responsible for having slits cut for inserting the electrode if necessary and repairing the slits. Where necessary and feasible, a rod-shaped electrode can be placed in a leak sampling pipe that extends down into the leak collection sump. However, this last method is usually not as effective as the other methods because of the danger of getting the electrode stuck and the increased resistance of the water in the pipe.

Flooding the Liner

Contractor shall flood the liner to the required depths with water con-

taining no hazardous or foul substances. A source of water will be provided by the Company. Water disposal facilities will be provided by the Company. Contractor will be responsible for pumping or otherwise transferring the water. Contractor will be responsible for damage to the subgrade or berm caused by water leakage and erosion, or hydrostatic loading. Provisions must be provided and procedures shall be followed by the Contractor to minimize the dynamic loading of the liner and possible damage to the liner, leak collection system and/or subgrade caused by the water stream or by a rapid change in the water level. Prior to flooding, Contractor shall clean the basin of debris including scraps of liner material, other construction materials and unneeded sand bags.

The water is needed for the electrical leak location method. The hydrostatic loading of the liner is also desirable for determining if leaks will occur under realistic loading conditions.

The basin shall be filled with the water to the working depth. When more than approximately 20 ft of the side slope is immersed, the manual survey of the side slopes is conducted in stages. The Contractor shall lower the water between each survey stage to allow no more than approximately 20 ft of the immersed side slope to be surveyed at a time. If the water can not be lowered to the level required for the next stage of the survey within 16 hr, Contractor shall pay Company for standby time or additional reduced mobilization costs for the electrical leak location survey contractor.

In some cases where the basin is large, or the discharge rate for the water must be limited, standby time or additional reduced mobilization costs are inevitable and should be planned and contracted for as part of the contract with the electrical leak location contractor. In those cases, the Contractor shall pay Company only for additional standby time or additional mobilization costs due to delays caused by the Contractor in excess of the planned amount.

The side slopes can be surveyed by raising or lowering the water level in stages either before or after the bottom of the liner is surveyed. If the side slopes are surveyed first, from the top down, the basin will be filled with water to the working level prior to the leak location survey. This exposes the liner to loads representative of actual in-service loading. In most cases the level of the water can be lowered faster than it can be raised, therefore, the survey can be completed with less standby time required while the water level is adjusted.

The advantage of surveying the side slopes after the bottom of the liner is surveyed is that washout or settling of the subgrade under the liner caused by leaks in the bottom of the liner might be avoided if leaks in the bottom are located and repaired prior to full hydrostatic loading. However, there is no assurance that additional leaks will not occur because of the increased hydrostatic loading during the side slope survey. Therefore, additional surveying of the bottom of the liner may be required after the side slopes are surveyed.

After the side slopes have been surveyed to the toe of the berm at the most shallow part, the Contractor shall lower the water to the level where the most shallow portion of the bottom of the basin is covered with approximately 6 in of water. When the bottom of the liner slopes more than 30 in, the survey of the bottom shall be conducted in more than one stage. The Contractor shall lower the water between each survey stage to allow the bottom of the basin to be surveyed in no more than 30 in of water. The water level is lowered to the level where the most shallow unsurveyed area is covered with 6 in of water. If the water can not be lowered to the level required for the next stage of the survey within 16 hr, Contractor shall pay Company for standby time or additional reduced mobilization costs for the electrical leak location survey contractor.

Again, for the cases where the basin is large, or the discharge rate for the water must be limited, standby time or additional reduced mobilization costs should be planned and contracted for as part of the contract with the electrical leak location contractor. In those cases, the Contractor shall be liable for paying only for additional standby time or additional mobilization costs due to delays caused by the Contractor in excess of the planned amount.

Flooding the Leak Collection Zone for the Survey of

The Primary Liner

Contractor shall also flood the leak collection zone with water. This can be done by pumping water in the leak collection system while the primary liner is being filled with water. To avoid possible damage, the water level in the leak collection zone must be maintained below the level of the water in the primary liner to prevent the primary liner from being lifted. Water can be pumped into the discharge side of the leak collection system. Air vents must be provided in the perimeter edges of the primary liner near the top of the berm to allow air trapped between the two liners to be vented. The water can also be pumped into the air vents. The Contractor shall be responsible for having slits cut for flooding and air vents, if necessary and repairing the slits.

To survey the primary liner, an electrical conduction path through any leak to the leak collection zone must be established. This task is usually accomplished by flooding the leak collection zone. In some cases when sand is used in the leak collection zone, an alternative method can be used to establish the electrical conduction path. The reliability of this alternative method depends on the type and moisture content of the sand. The alternative method is to allow the water from the leaks to percolate through the leak collection zone. This method is most effective when the sand has residual moisture and the water on top of the liner has been allowed to stand at least three days and good electrical contact can be established with the power supply electrode in the leak collection zone.

The survey of the secondary liner must be conducted prior to installation of the primary liner. However, because the secondary liner is in direct contact with earth ground there is no requirement to flood the subgrade under the liner.

Electrical Power

Contractor will furnish a source of electrical power of 110-120 V AC at 10 amp for the electrical leak location equipment. The power outlet shall be located at the top of the berm.

Safety

Proper safety precautions and safe working practices shall followed. A written safety plan specifically addressing the electrical leak location surveys submitted by the electrical leak location contractor shall be followed. Contractor will also inform the electrical leak location survey subcontractor of the specific safety rules, procedures and hazards at the plant site.

Electrical Leak Location Survey Specifications For Electrical Leak Location Contractor

Electrical Leak Location Survey Under Hydrostatic Load

An electrical leak location survey will be performed by Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78238, (Contact Daren L. Laine, telephone 512-522-3274) or approved equivalent. The survey will be conducted on the bottom and side slopes of both the primary and the secondary geomembrane liners of the basin. Contractor will be responsible for preparing the basin for the survey as described below.

The survey equipment leak detection distance shall be verified prior to the survey. The results of the verification tests shall be used to determine the distance between survey scans. The verification test will be conducted using a simulated leak assembly as shown in Figure 1. The simulated leak consists of a sealed plastic container with an insulated wire penetrating the container through a sealed hole in the container. The insulation at the end of the wire is stripped off for a distance of approximately 1 in. The opposite end of the wire is connected to a grounded electrode or a separate electrode in the leak collection zone. A weight is placed in the container and the container is filled with a sample of water from the basin being tested. A sample of geomembrane liner with the same thickness as the liner being tested is sealed behind a large hole in the lid of the container. A 0.03 in nominal diameter circular leak is placed in the center of the geomembrane sample by penetrating the liner with a heated No. 6 sewing needle (0.030 in nominal diameter) or a sewing pin (0.034 in nominal diameter).

The simulated leak assembly will be placed in the water in the basin

and survey sweeps will be made as the operator approaches the simulated leak. The distance from the leak locator probe to the leak when the leak is just detectable is measured. This is the leak detection distance. Twice this distance will be the maximum distance between survey scans. The power supply electrode can be put at any position in the basin, but the survey must be conducted with the power supply electrode no farther from the leak than the distance when the verification test was conducted.

The leak location sensitivity is proportional to the resistivity of the water used to flood the liner and the power supply voltage. For relatively high resistivity water such as river or lake water, or water from a municipal supply, the simulated leak can be usually be detected at a distance of approximately 18 in. For a saturated brine solution, the simulated leak can usually be detected from a distance of 6 in. Smaller leaks will be detected if the leak location probe electrode happens to pass directly over the leak. Larger leaks can be detected from greater distances. However, these typical leak detection sensitivities can be greatly reduced in some instances and some judgement is necessary for specifying an effective survey for a reasonable cost.

If more than one leak per 2000 ft² of surveyed area is found in either liner, the leak location survey will be limited to one man-day of survey per 20,000 ft² of liner material. The electrical leak location survey will be conducted to better categorize the occurrence of leaks and possible causes of leaks to aid in the specification of corrective measures. The electrical leak location survey will be curtailed until the cause of the leaks is determined and corrective measures are taken by the Contractor. In the case of defective seaming, only patching the leaks will not be a viable corrective action because additional leaks will likely form when basin is put in service. If more than one leak per 2000 ft² of surveyed area is found in either liner, an electrical leak location survey of the liner will be performed at the expense of the Contractor after the corrective actions are taken and the located leaks are repaired.

The occurrence of greater than approximately one leak per 2000 ft² can indicate defective seaming process or procedures, defective liner material or ineffective liner material handling or protection measures. In these cases, further electrical leak location surveying is not sensible because the questionable integrity of the installation. In these cases corrective actions must be taken.

Prior experience indicates that detectable leaks are found in some repaired leaks when they are tested using the electrical leak location method. When significantly less than approximately one leak per 2000 ft² of liner is found, rechecking the leaks with the electrical leak location method is usually not necessary if the leak is sealed and then a patch is seamed over the repair. The repair can then be tested using a vacuum box. When more than approximately one leak per 2000 ft² is found, rechecking the seams and patches using the electrical leak location method is warranted. The geomembrane installer is responsible for making the repairs.

Preparing The Basin For Survey

The Company is responsible for having the basin prepared for the electrical leak location survey. These preparations include: electrically isolating electrical conduction paths; placing a suitable metal electrode in the leak collection zone prior to installing the primary liner; cleaning the basin of debris; flooding the liner to the required depths with water; adjusting the level of the water as necessary; flooding the leak collection zone with water; and furnishing a source of electrical power.

Leak Location Surveys

Electrical Leak Location Survey of Sidewalls of the Secondary and Primary Geomembrane Liners of the Basin

The electrical leak location survey contractor shall conduct a leak location survey of the side slopes of the secondary liner and the primary liner using the electrical leak location method. The side slope area will be surveyed by systematically scanning the side slopes. Procedures shall be followed to assure that the leak detection probe is scanned within the detection distance for every point on the submerged liner. Twice the leak detection distance is the maximum distance between survey

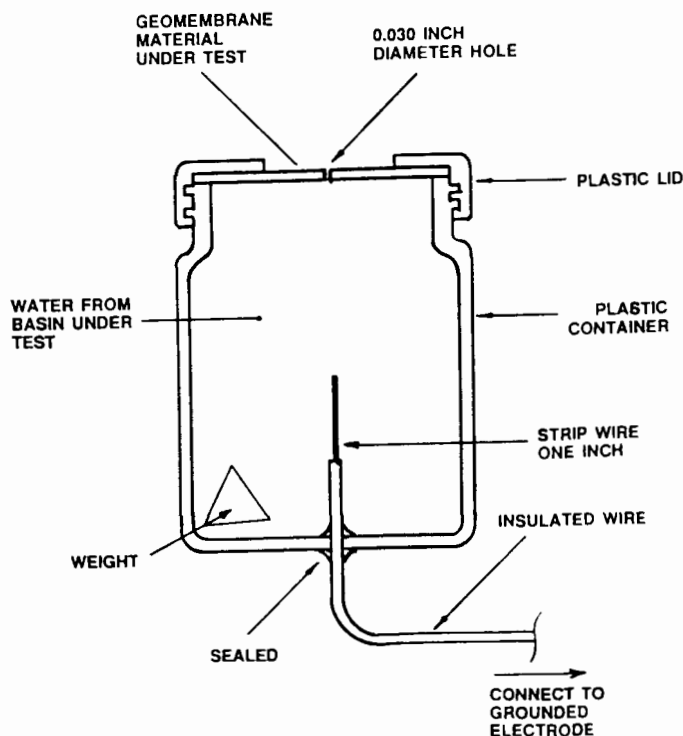


Figure 1
Simulated Leak Assembly

scans. In addition, all of the seams oriented down the side slopes shall be surveyed individually by scanning the leak location probe along the seam.

When more than approximately 20 ft of the side slope is immersed, the water must be lowered in stages to allow the manual survey of the side slopes. Any leaks found will be accurately located and the locations will be referenced to reference marks on liner near the berm of the basin.

Electrical Leak Location Survey of Bottom of the Secondary and Primary Geomembrane Liners Basin

The electrical leak location contractor shall conduct a leak location survey of the bottom of the secondary liner and primary liner using

the electrical leak location method. Procedures shall be followed to assure that the leak detection probe is scanned within the leak detection distance of every submerged point on the liner. In addition, all of the seams shall be surveyed individually by scanning the leak location probe along the seam.

Detected leaks shall be located to within 0.5 in or less and immediately marked with lead sinkers and floats. The location of the leaks shall also be measured relative to reference marks on the berm or side slope of the liner for a permanent record. Where practical, the location and type of leak shall be noted (i.e. on a seam or patch, or in the panel).

Reports, Safety And Other Points

Reports

If requested, the general results of the electrical leak location survey shall be reported to the designated representative of the Company during the daily progress of the field work. A list of the locations of the leaks found shall be submitted to the designated representative of the Company after completion of the field work and before the electrical leak location survey crew leaves the site. A letter report documenting the work, including a brief summary of the survey procedures, results of the survey and problems encountered shall be prepared and submitted within 14 days after completion of the field work.

Safety

Proper safety precautions and safe working practices shall be followed. A written safety plan specifically addressing the electrical leak location surveys shall be submitted to the Company for approval by the electrical leak location contractor prior to the start of the leak location field work. The safety plan shall be followed. Contractor and Company will inform the electrical leak location survey subcontractor of the specific safety rules, procedures and hazards at the plant site.

Confidentiality

Unless agreed to in writing, the name of the facility, the location of the facility, the identity of the Company, Contractor and the geomembrane installer shall be held in strict confidence. Any published results of the survey will include only leak statistics. Information shall not be afforded confidentiality if: such information is publicly available or rightly obtained without restriction by from a third party; or released without restriction by the furnishing party to anyone, including the United States Government.

Some facility owners prefer to avoid publicity concerning their operations. A confidentiality agreement should describe the level of security desired.

Evaluation of Relative Magnitude of Human Exposure by Various Routes in a Community with Multiple PCB-Contaminated Sites

John C. Kissel
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ABSTRACT

Efficient execution of Superfund activities intended to reduce risks to humans posed by toxic wastes requires identification of the most significant routes of exposure in a given location. Estimates are presented of the magnitudes of PCB exposure associated with various pathways in a community with multiple sources of contamination. For many citizens, designated hazardous waste sites are less significant sources of exposure to notorious chemicals than are more familiar surroundings. Integration of hazardous waste management strategies with broader environmental policies is therefore warranted. Examination of the relative magnitudes of exposure attributable to diverse routes also facilitates realistic assessment of the benefits of incremental cleanup actions. Substantial mitigation of risk may occur long before formal completion of site remediation.

INTRODUCTION

Bloomington, Indiana was formerly the location of a capacitor manufacturing and repair facility operated by Westinghouse Electric Corporation. Polychlorinated biphenyls (PCBs) were released from the plant in sewer and air discharges as a result of disposal of retired and defective capacitors. Discarded capacitors were hauled to several dumps and landfills. Copper scavengers opened the capacitors and spilled their contents. In some cases, capacitors were transported to additional locations before or after scavenging. Discharges from the manufacturing facility to a city sewer resulted in contamination of a wastewater treatment plant, and contaminated sludge was unknowingly distributed to citizens as soil conditioner. Westinghouse employees, their families, copper scavengers, sewage treatment plant employees, sludge users, persons who frequented the dumpsites, persons who lived in close proximity to the dumpsites, and the general citizenry have experienced variable levels of exposure.

The U.S. EPA, Westinghouse, the City of Bloomington, Monroe County and the State of Indiana agreed in 1985 to a cleanup strategy involving six sites in or near Bloomington. Four of these sites are NPL. Remedial measures have been taken at all six sites, but at only one is no further action anticipated. Two additional sites are undergoing cleanup outside the terms of the 1985 agreement.

The process of identifying and cleaning sites has become drawn out, politicized and contentious. To evaluate risks and cleanup strategies, it is useful to estimate the relative magnitudes of human exposure to PCBs by various routes in Bloomington. Exposures may be estimated directly from measured environmental concentrations for those routes for which such data are available, or back-calculated from observed body burdens using a pharmacokinetic model. Both methods are utilized here.

Prior to discussing the presence of PCBs in the environment, two qualifications must be stated. First, analytical techniques have evolved

concurrently with concern over PCBs. Consequently, data from disparate sources are not always precisely comparable. Second, commercial PCB preparations are mixtures of compounds with variable physico-chemical and toxicological properties.¹⁻³ Ideally, evaluation of exposure to and risks of PCBs would be approached on a congener-specific basis. Since most historical data are not congener-specific, however, total PCB burden serves as an imperfect surrogate measure. Total PCB trends nevertheless present an illustration of the consequences of widespread utilization and subsequent abandonment of a particular class of poorly degraded, lipophilic chemicals.

BACKGROUND EXPOSURE

Exposures to PCBs in Bloomington are of particular interest to the extent they deviate from exposures typically experienced by the national population. PCBs were used extensively in a variety of products for several decades prior to their removal from commerce in the latter half of the 1970s. As a result, they are widely dispersed in the environment and routinely identified in human tissue and blood. As shown in Figure 1, domestic sales of PCBs peaked in 1970;⁴ sales of PCBs and were ultimately banned in mid 1979. Since PCBs are lipophilic and relatively resistant to degradation, their appearance in the food chain was predictable.

Trends in adult dietary exposures estimated from information gathered in FDA total diet surveys⁵⁻⁸ are presented in Figure 2. Horizontal scales in Figures 1 and 2 are equivalent to facilitate comparison. An estimate of a total dietary exposure of about 90 ng/day in 1985 in Ontario⁹ is in good agreement with the FDA data. Dietary exposure in Osaka, Japan,¹⁰ however, was estimated as greater than 4 ug/day in 1985. Data from the National Human Adipose Tissue Survey (NHATS)¹¹ presented in Figure 3 reveal that virtually all United States residents carried detectable levels of PCBs in the early 1980s. The impact of removing PCBs from routine commerce is reflected in a decline after 1978 in the fraction of the population having greater than 3 ppm in adipose tissue and in the increase in those having levels, although detectable, less than 1 ppm.

Measured blood concentrations¹²⁻¹⁵ of PCBs in general populations or groups not known to have occupational exposure are presented in Figure 4. The suggestion of a peak in blood levels in the mid 1970s and a subsequent decline is consistent with the NHATS data, but the scarcity of pre-1978 blood data precludes a firm conclusion to that effect. Not shown in Figure 4 are (off-scale) blood levels measured in several non-occupationally exposed populations exhibiting unusual rates of fish consumption.¹⁴

The highest point in Figure 4 represents Bloomington sludge users and may be an indication of increased exposure or simply an artifact of the timing of the sampling. An ostensible Bloomington control group

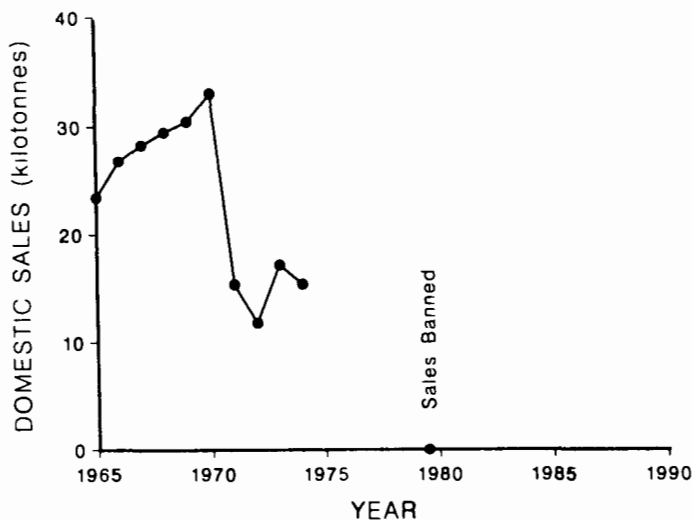


Figure 1.
Annual Sales of PCBs in the United States
(Data from Reference 4).

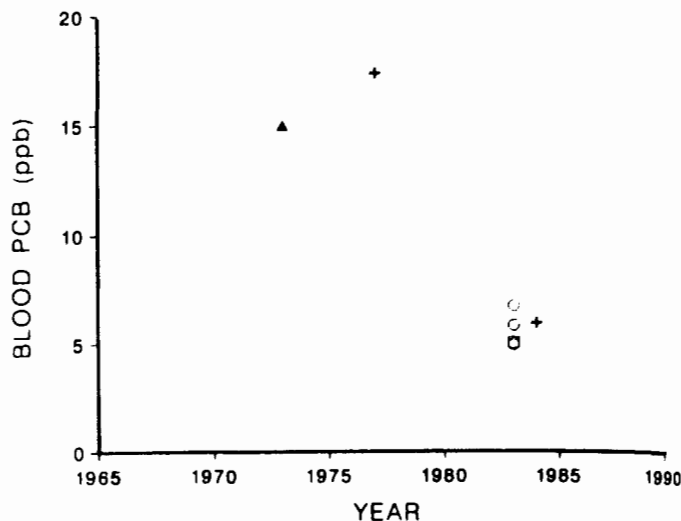


Figure 4.
Reported PCB Levels in Blood in General Populations or
Non-occupationally Exposed Control Groups.

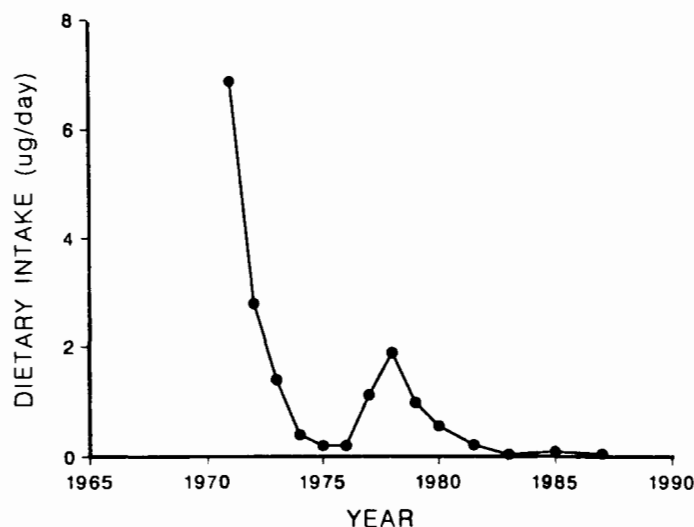


Figure 2.
Estimated Adult (70 kg) Dietary Exposure Based on
FDA Figures (References 5-8).

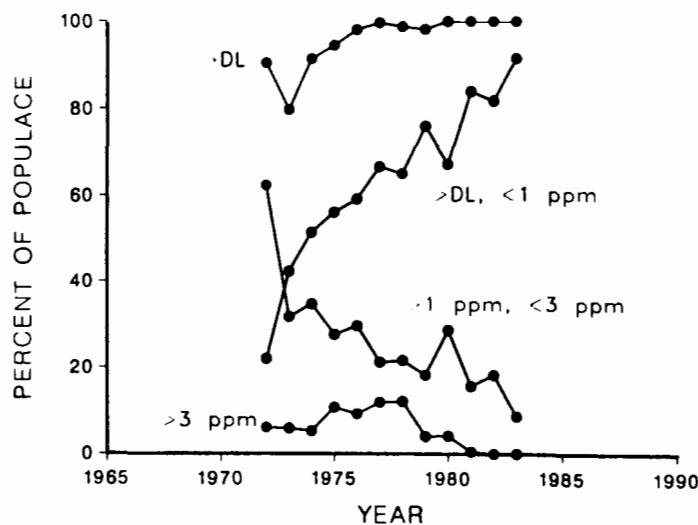


Figure 3.
Distribution of Adipose Tissue PCB Concentrations
in the U.S. Population (Reference 11).
DL Denotes Detection Limit.

All points are Arithmetic Means Except as Noted.
Squares: serum, Reference 13; Diamonds: plasma, Reference 13;
Circles: serum, Reference 14; Triangles: serum medians,
Michigan controls (light fish consumers), Reference 14;
Pluses: serum, Bloomington sludge-users (1977) and
serum geometric mean, Bloomington controls (1984), Reference 15.

found to have higher serum levels than the sludge users¹² contained some health workers who may have been exposed during site inspections¹⁰ and therefore the data for this group are of questionable validity for comparison. The slope between the sludge users and the subsequent (1984) Bloomington controls¹⁵ is similar to that between Michigan controls (light fish eaters) sampled in 1973 and 1980.¹⁴ 1984 Bloomington controls do not appear to have unusual blood levels of PCB. Other subsets of the Bloomington population surveyed in 1984 had blood levels that ranged from apparently slightly elevated to clearly elevated.¹⁵

Persons in classifications entitled game eating closest residence, playing, digging, fish eating, and swimming had geometric mean serum levels 31 to 54% higher than the 5.9 ug/L geometric mean of the controls. Scavengers had a geometric mean slightly over twice that of the controls and the occupationally exposed group (including Westinghouse employees and wastewater treatment plant workers) had a level over four times higher. Only the latter group was statistically distinguishable from the controls at the 5% level, but groups were small. Previously,¹² occupationally-exposed persons were found to have an arithmetic mean serum concentration over four times that of the sludge users, and their family members' mean was about double that of the sludge users. Results from more recent sampling of a larger number of Bloomington residents than were tested in 1984 are not yet available.¹⁶

EXPOSURES CALCULATED FROM KNOWN CONCENTRATIONS

Environmental measurements from which PCB exposures may be calculated directly are available from a variety of sources. Estimates obtained in this manner are presented in Table 1. Commercial food supply exposures were derived from the same sources as Figure 2.

Table 1
Annual Average Daily Adult PCB Exposures Calculated
From Measured Environmental Concentrations.

Exposed individual	Route	Magnitude ($\mu\text{g/day}$)	Data	Ref.
Westinghouse Bloomington employee	workplace air	18-740.	1977	(18)
Lake Michigan sportfisher	fish	39-313.	1973-4	(19)
Bloomington wastewater plant operator	personal air	<36.	1976	(17)
U.S. citizenry	commercial food	6.9	1971	(8)
U.S. citizenry	indoor air	0.65-10.9	1979-84	(20-22)
Nearest Bloomington dumpsite neighbor	outdoor air	<2.7	1983	(24)
Occasional Bloomington dumpsite visitor	outdoor air	<2.3	1983	(24)
U.S. citizenry	commercial food	<0.1	1985	(8)
Bloomington residents near dumpsites	well water	<0.024	1986	(25)
Bloomington citizenry	City water	<0.01	1989	(26)
Bloomington citizenry	outdoor air	<0.008	1986-8	(27)

Workplace air measurements were made by NIOSH¹⁷⁻¹⁸ at a (now closed) municipal wastewater treatment plant and in the Westinghouse plant. The range of inhalation exposures to Westinghouse employees reflects time-weighted average air concentrations associated with the most (capacitor repairman) and least exposed (boilerhouse operator) job classifications investigated.

It was assumed the employees worked 250 8-hr work days/yr and had a 20 m³/day breathing rate. Inhalation exposure for wastewater plant operators was calculated similarly based on an average of personal air samples taken in September of 1976. (Results from a previous set of samples taken in August, 1976, were all below detection, hence the "less than" designation.)

Dietary exposures for Lake Michigan sportfishers (consumers of more than 24 to 26 lb of fish/yr) were taken from the literature¹⁹ and included for comparative purposes. Indoor air exposures to the general public were calculated based on measured average air concentrations of 39 to 653 ng/m³ in homes, schools, laboratories and offices²⁰⁻²² and the assumption that a typical person is indoors 20 hours per day. A more recent study²³ found no PCBs in residential air, but at a detection limit (100 ng/m³) that does not exclude the possibility of agreement with previous results.

Estimated exposure to nearest dumpsite neighbors was based on the highest 24-hr average concentration measured²⁴ at the boundary of the Lemon Lane site (before capping) and an assumption of 4 hr/day of exposure. A somewhat higher boundary concentration was recorded at another site, but measurements made near adjacent homes were lower. Inhalation exposure attributable to occasional dumpsite visitation was based on an assumption of 25 2-hr trips per year and the highest average summertime daytime concentration recorded (also before interim remediation at Lemon Lane) at 180 cm in vertical profile measurements.²⁴

The range of possible activities engaged in by persons visiting the dumpsites is quite broad, and the estimate could be low for a few persons such as copper scavengers who spent significant time near "hot spots" (capacitor piles). Estimated exposure from well water was based on a survey of water quality in wells within 1 mi of major dumpsites²⁵ and a nominal consumption rate of 2 L/day. In most wells tested, PCBs were not detected. A handful of positive values between 2 and 12 ng/L were recorded. Two wells that tested higher were no longer in use for drinking water supply. The city water exposure estimate reflects no detection of PCBs at 5 ng/L in municipal water.²⁶ Outdoor air inha-

lation exposure to the general Bloomington populace was based on the highest annual average concentration obtained from three sites monitored during 1986-1988.²⁷

EXPOSURES BACK-CALCULATED FROM BODY BURDENS

The list of exposures presented in Table 1 clearly is not exhaustive and is limited to those routes for which estimation is easily undertaken. For example, potential dermal exposure from contaminated water or soil or direct contact with PCB oils is not included. In the absence of adequate knowledge of the PCB concentration in a particular medium or of the frequency of the pertinent activity, gross exposure may be back-calculated from measured body burdens given some understanding of the rate at which PCBs are eliminated from the body.

Half-lives of various PCB congeners and commercial mixtures reported in or derived from the literature²⁸⁻³² are presented in Table 2. Apparent half-lives, calculated from sequential data without consideration of continuing exposure, may be much higher than true half lives.

Table 2
Half-lives of PCBs in Humans Reported in or
Calculated^a from the Literature.

Commercial mixture or congener ^b	Half life (yrs)	Sample size	Reference
105	0.56	17	(28)
118	0.82	"	
Kanechlor 300 ^c	5.1	20	(29)
Kanechlor 300 & 500 ^c	>15.	4	
Aroclor 1242 ^d	2.0	5	(30)
Aroclor 1260 ^d	16.9	"	
108/118	0.27-0.82	1	(31)
138	0.88	"	
153	0.93	"	
180	0.34	"	
Aroclor 1242 ^e	2.4-3.1 ^f	58	(32)
Aroclor 1254 ^e	2.6-6.5 ^f	"	

^aAssuming no continuing exposure.

^bUsing numbering system of Ballschmiter and Zell (33).

^cBased on employment history.

^dDistinction not specified.

^eDistinguished as eluting before (1242) or after (1254) DDE.

^fMean values for persons with highest to lowest initial body burdens.

Rates of elimination are least likely to be distorted by background exposure in persons with high existing burdens. Increasing half-lives at lower tissue concentrations of mixtures of compounds such as PCBs may also result from preferential retention of the least rapidly eliminated congeners. Half-lives of specific congeners presented in Table 2 are relatively short. These data may reflect selection of atypical congeners, but the particular congeners evaluated are among those which routinely are found in human samples. The frequency with which they are identified can be explained partly by their occurrence in commercial mixtures, but, nevertheless, if elimination is rapid, ongoing exposure must be high to maintain measurable levels in blood and tissue.

Buhler, et al.,³² suggest that typical exposures to each of the individual congeners they investigated are on the order of 3 to 4 $\mu\text{g/day}$. Given the fractional presence of individual congeners in commercial PCB preparations, this figure is difficult to reconcile with estimates of likely total PCB exposure presented here.

It has been demonstrated that elimination of 2,3,7,8-TCDD from humans can be plausibly simulated using a physiologically based pharmacokinetic (PBPK) model employing assumptions of simple thermodynamically based partitioning and negligible metabolism.³⁴ With input of appropriate physical parameters, this model may be applied to elimination of PCBs. Log octanol water partition coefficients of PCB congeners of interest range from roughly 4 to 7.5.³⁵⁻³⁶ Henry's constants are likely to range from approximately 1 to over 100 Pa m³ mol⁻¹ at physiological temperatures.³⁷⁻³⁸

PBPK model simulations indicate that (70 kg) adult half-lives attributa-

ble to partitioning alone (excretion/exhalation) should vary between roughly 0.5 and 5 yr given these physical properties. Shorter half-lives would result for those congeners that are significantly metabolized. Longer apparent half-lives could be observed in the presence of concurrent exposure. This effect is illustrated in the data of Phillips, et al.,³² cited in Table 2. Aggregate PCB half-lives on the order of 2.5 yr were observed in persons with relatively high body burdens, and longer half-lives were observed in persons with relatively low body burdens. Given an appropriate metabolic rate constant, the PBPK model may be used to compute exposures required to sustain observed body burdens. Selected cases are presented in Table 3. A true half-life of 2.5 yr was assumed.

Some Westinghouse employees had serum PCB levels over 1000 mg/L in 1977.³² The maximum inhalation exposure shown in Table 1 appears sufficient to account for only about 500 mg/L in serum. Dermal exposure is therefore likely to have been very substantial and to have exceeded inhalation exposure to at least some employees. A similar conclusion with respect to another group of PCB workers was reached previously by Lees, et al.,⁴¹ The mean serum PCB level in a group of Westinghouse employees' family members in 1977 was reported as approximately 34 mg/L as compared to the sludge users' 17 mg/L.¹² If the sludge users received negligible non-background exposure, then about half of the family members' body burden could be attributed to unusual exposure. If roughly half of the sludge users' burden was the result of non-background exposures, then about three-quarters of the family members' burden was unusual. Dermal uptake of a lipophilic contaminant from soil has been shown to be plausible elsewhere.⁴² Further application of the PBPK model reveals that likely current exposures to the general population in the United States are not sufficient to maintain existing serum levels and that continuing decline should be anticipated.

Table 3
Annual Average Daily Supplemental Exposures Estimated to be Required to Produce Observed Serum Levels.

Exposed individual	Route	Magnitude (ug/day)
Most exposed Westinghouse employee	dermal	>740.
Family member of Westinghouse employee	dermal, inhalation	25-35.
Sewage sludge user	dermal, inhalation	0-10.

*Assuming aggregate 2.5 year half life.

DISCUSSION

Background exposures to PCBs are declining in the United States. Given the trend in PCB levels in commercial foods, indoor air may now be the primary source of PCB exposure for the bulk of the population. Temporal trends in indoor air concentrations are poorly defined, however, and further research is needed in this area.

Indoor air concentrations measured in the United States in the early 1980s are comparable to outdoor air levels measured in the immediate vicinity of uncontrolled dumpsites in Bloomington at about the same time. Indoor air exposures certainly impact a greater portion of the population.

Results from the Total Exposure Assessment Methodology Study (TEAMS)³⁹ demonstrate that primary exposures to some pollutants of concern, in particular volatile organics, probably occur indoors. This also may be the case for the semi-volatile PCBs. Reorientation of U.S. EPA activities toward a more integrated and consistent assault on environmental problems, as has been suggested by an internal U.S. EPA review panel,⁴⁰ is warranted.

At issue in Bloomington are the adequacy of cleanup efforts underway and the risks presented. Despite the fact that the ultimate cleanup strategy is controversial and a decade or more from completion, the

largest risks listed in Table 1 have been effectively mitigated. Clearly those at greatest risk of harm by PCBs in Bloomington are persons who were employed at Westinghouse during the period PCBs were actively utilized. Cessation of active utilization of PCBs has resulted in a substantial decline in serum PCB levels in such persons^{30,32} and also is likely to have resulted in reduction of exposures to members of their families. Exposures of the latter type are not adequately addressed within the current regulatory framework, a situation that reiterates the need for reorientation of efforts at the U.S. EPA.

Former occupational exposures and any resulting from residual contamination inside the Westinghouse plant fall within the realm of occupational safety and outside the scope of CERCLA cleanup activities. Although PCB body burdens of Westinghouse employees contributed to the perception of a hazardous waste problem in Bloomington, they did not result from waste disposal practice per se and would not be more effectively remedied if CERCLA-related activities in Bloomington were proceeding more smoothly. These exposures have been mitigated by eliminating the activity resulting in waste generation rather than by more effective management of the waste. Occupational exposures to wastewater treatment plant personnel were eliminated by closing the facility (as was previously necessitated by city growth). Simple interim measures (fencing) eliminated routine access to the major dumpsites and associated exposures.

Remaining concerns, in addition to off-site air transport, include transport in groundwater and access to unremediated sites. Transport in groundwater has not yet presented a significant problem in Bloomington, although, in view of local geological characteristics, movement is inevitable barring complete remediation. Groundwater contamination, while very expensive to reverse, generally represents potential rather than immediate risk. The slowness with which groundwater moves prevents natural flushing from being a viable management strategy, but it also provides time for implementation of interim mitigation strategies such as provision of alternative water supplies to persons at risk.

Most of the minor sites in Bloomington at which no remediation is planned are small plots on which contaminated sludge was spread. Attenuation of PCBs by volatilization and perhaps biodegradation appears to be occurring at significant rates.⁴³

The exposure estimates presented in Table 1 may be compared to health criteria. ACGIH lists TLV-TWAs of 0.5 mg/m³ for Aroclor 1254 and 1.0 mg/m³ for Aroclor 1242.⁴⁴ Assuming 250 8-hr work days per year, this figure corresponds to acceptable average annual daily exposures to workers of roughly 2300 and 4600 ug/day, respectively. On the basis of potential carcinogenicity, however, NIOSH recommends a 500 to 1000-fold lower 1 µm³ standard for each Aroclor.⁴⁵

The U.S. EPA recently proposed a drinking water MCL of 0.5 µl for PCBs. This figure corresponds to an approximate acceptable intake of 1 µ/day and, assuming a carcinogenic potency factor of 7.7 mg⁻¹ kg day,⁴⁶ an excess lifetime cancer risk on the order of 10⁻⁴. Interestingly, the City of Bloomington's NPDES permit for the Dillman Road wastewater treatment plant requires effluent PCBs to be less than 0.1 µl, five times lower than the proposed drinking water MCL.

CONCLUSIONS

Perceived sources of significant exposure to pollutants may differ from actual sources. External sources, especially identified hazardous waste sites, are greatly feared. For PCBs (and some other industrial chemicals), more familiar surroundings such as homes and offices appear to present the greatest exposure to the average citizen under current conditions in Bloomington and elsewhere. Policies governing cleanup of hazardous waste sites should therefore be integrated in an overall, multi-media environmental protection strategy.

Much attention is given to the fact that only a small proportion of NPL sites have been declared fully remediated. The bulk of the risk associated with such sites may, however, be eliminated well before cleanup completion. Progress under CERCLA to date is likely to be significantly underestimated if measured by cleanup completions alone.

Understanding of the elimination of PCBs from humans is incomplete and further congener-specific, human-based investigation is needed. Nevertheless, existing United States background PCB exposure

appears insufficient to maintain typical body burdens. Further decline therefore is likely.

REFERENCES

- Safe, S., Bandiera, S., Sawyer, T., Robertson, L., Safe, L., Parkinson, A., Thomas, P., Ryan, D., Reik, L., Levin, W., Denomme, M. and Fujita, T. "PCBs: Structure Function Relationships and Mechanism of Action," *Environ. Health Perspec.*, 60 pp 47-56, 1985.
- Jones, K., "Determination of Polychlorinated Biphenyls in Human Food-stuffs and Tissues: Suggestions for a Selective Congener Analytical Approach," *Sci. Tot. Environ.*, 68 pp 141-159, 1988.
- McFarland, V. and Clarke, J., "Environmental Occurrence, Abundance, and Potential Toxicity of Polychlorinated Biphenyl Congeners: Considerations for a Congener-Specific Analysis," *Environ. Health Perspec.*, 81 pp 225-239, 1989.
- Conway, R., Whitmore, F. and Hansen, W., "Entry of Chemicals into the Environment," Chapter 3 of *Environmental Risk Analysis for Chemicals*, R. Conway, ed., Van Nostrand Reinhold, New York, NY, 1982.
- Gartrell, M., Craun, J., Podrebarac, D. and Gunderson, E., "Pesticides, Selected Elements, and Other Chemicals in Adult Total Diet Samples, October 1978-September 1979," *J. Assoc. Off. Anal. Chem.*, 68(5) PP 862-875, 1985.
- Gartrell, M., Craun, J., Podrebarac, D. and Gunderson, E., "Pesticides, Selected Elements, and Other Chemicals in Adult Total Diet Samples, October 1980-March 1982," *J. Assoc. Off. Anal. Chem.*, 69(1) pp 146-161, 1986.
- Gunderson, E., "FDA Total Diet Study, April 1982-April 1984, Dietary Intakes of Pesticides, Selected Elements and Other Chemicals," *J. Assoc. Off. Anal. Chem.*, 71(6) pp 1200-1209, 1988.
- Gunderson, E., FDA Division of Contaminants Chemistry, Washington, D.C., personal communication, Aug., 1989.
- Davies, K., "Concentrations and Dietary Intake of Selected Organochlorines, Including PCBs, PCDDs and PCDFs in Fresh Food Composites Grown in Ontario, Canada," *Chemosphere.*, 17(2) pp 263-276, 1988.
- Matsumoto, H., Murakami, Y., Kuwabara, K., Tanaka, R. and Kashimoto, T., "Average Daily Intake of Pesticides and Polychlorinated Biphenyls in Total Diet Samples in Osaka, Japan," *Bull. Environ. Cont. Toxicol.*, 38 pp 954-958, 1987.
- U.S. EPA. NHATS Summary Statistics: 7½69 through 9½83 (Unbound), Office of Toxic Substances, Washington, DC, 1986.
- Baker, E., Landrigan, P., Glueck, C., Zack, M., Liddle, J., Burse, V., Houseworth, W. and Needham, L., "Metabolic Consequences of Exposure to Polychlorinated Biphenyls (PCB) in Sewage Sludge," *Am. J. Epid.*, 112(4) pp 553-563, 1980.
- Sahl, J., Crocker, T., Gordon, R. and Faeder, E., "Polychlorinated Biphenyl Concentrations in the Blood Plasma of a Selected Sample of Non-occupationally Exposed Southern California Working Adults," *Sci. Total Environ.*, 46 pp 9-18, 1985.
- Kreiss, K., "Studies on Populations Exposed to Polychlorinated Biphenyls," *Environ. Health Perspec.*, 60 pp 193-199, 1985.
- Stehr-Green, P., Ross, D., Liddle, J., Welty, E. and Steele, G., "A Pilot-Study of Serum Polychlorinated Biphenyl Levels in Persons at High Risk of Exposure in Residential and Occupational Environments," *Arch. Environ. Health*, 41(4) pp 240-244, 1986.
- Steele, G., Indiana State Board of Health, Indianapolis. Personal communication, Aug., 1989.
- NIOSH, Health Hazard Evaluation Determination: Westinghouse Electric Corporation, Bloomington, Indiana. Report No. 76-52-386, Cincinnati, OH, 1977.
- NIOSH, Health Hazard Evaluation and Technical Assistance: Winston Thomas Sewage Treatment Plant, Bloomington, Indiana. Report No. TA 76-84, Cincinnati, OH, 1977.
- Cordle, F., Locke, R. and Springer, J., "Determination of Risk in Regulating Polychlorinated Biphenyls (PCBs) A Case Study," Chapter 10 of *Toxicological Risk Assessment: Volume II General criteria and Case Studies*, D. Clayson, D. Krewski and I. Munro, eds., CRC Press, Boca Raton, FL, 1985.
- McLeod, K., "Polychlorinated Biphenyls in Indoor Air," *Environ. Sci. Tech.*, 15(8) pp 926-928, 1981.
- Murphy, T., Formanski, L., Brownawell, B. and Meyer, J. "Polychlorinated Biphenyl Emissions to the Atmosphere in the Great Lakes Region. Municipal Landfills and Incinerators," *Environ. Sci. Tech.*, 19(10) pp 942-946, 1985.
- Oatman, L. and Roy, R., "Surface and Indoor Air Levels of Polychlorinated Biphenyls in Public Buildings," *Bull. Environ. Contam. Toxicol.*, 37 pp 461-466, 1986.
- Lewis, R., Bond, A., Johnson, D. and Hsu, J. "Measurement of Atmospheric Concentrations of Common Household Pesticides: A Pilot Study," *Environ. Monitor. Assess.*, 10:59-73, 1988.
- Lewis, R., B. Martin, D. Sgontz, and J. Howes. "Measurement of Fugitive Atmospheric Emissions of Polychlorinated Biphenyls from Hazardous Waste Landfills," *Environ. Sci. Tech.*, 19(10) pp 986-991, 1985.
- Hites, R., D. Liebl, W. Jones, and M. Troyer. *Collection and Analysis of Drinking Water Well Samples for PCB Content*, SPEA, Indiana University, 1986.
- City of Bloomington Utilities. Monthly staff reports. Bloomington, IN, 1989.
- Hermanson, M. and Hites, R., "Long-term Measurements of Atmospheric Polychlorinated Biphenyls in the Vicinity of Superfund Dumps," *Environ. Sci. Tech.*, (In press).
- Chen, P., Luo, M., Wong, C. and Chen, C., "Comparative Rates of Elimination of Some Individual Polychlorinated Biphenyls from the Blood of PCB-Poisoned Patients in Taiwan," *Fd. Chem. Toxic.*, 20 pp 417-425, 1982.
- Hara, I., "Health Status and PCBs in Blood of Workers Exposed to PCBs and of Their Children," *Environ. Health Perspec.*, 59 pp 85-90, 1985.
- Steele, G., "Estimates of the Biologic Half-Life of Polychlorinated Biphenyls in Human Serum," *New Eng. J. Med.*, 314(14) pp 926-927, 1986.
- Buhler, F., Schmid, P. and Schlatter, CH., "Kinetics of PCB Elimination in Man," *Chemosphere.*, 17(9) pp 1717-1726, 1988.
- Phillips, D., Smith, A., Burse, V., Steele, G., Needham, L. and Hannon, W., "Half-Life of Polychlorinated Biphenyls in Occupationally Exposed Workers," Submitted to *Arch. Environ. Health*.
- Ballschmiter, K. and Zell, M., "Analysis of Polychlorinated Biphenyls (PCB) by Glass Capillary Gas Chromatography," *Fresenius Z. Anal. Chem.*, 302 pp 20-31, 1980.
- Kissel, J. and Robarge, G., "Assessing the Elimination of 2,3,7,8-TCDD from Humans with a Physiologically Based Pharmacokinetic Model," *Chemosphere.*, 17(10) pp 2017-2027, 1988.
- Miller, M., Wasik, S., Huang, G., Shlu, W. and Mackay, D. "Relationships between Octanol-Water Partition Coefficient and Aqueous Solubility," *Environ. Sci. Tech.*, 19(6) pp 522-529, 1985.
- Hawker, D. and Connell, D., "Octanol-Water Partition Coefficients of Polychlorinated Biphenyl Congeners," *Environ. Sci. Tech.*, 22(4) pp 382-387, 1988.
- Burkhard, L., Armstrong, D. and Andren, A., "Henry's Law Constants for the Polychlorinated Biphenyls," *Environ. Sci. Tech.*, 19(7) pp 590-596, 1985.
- Dunnivant, F., Coates, J. and Elzerman, A., "Experimentally Determined Henry's Law Constants for 17 Polychlorinated Biphenyl Congeners," *Environ. Sci. Tech.*, 22(4) pp 448-453, 1988.
- U.S. EPA, *The Total Exposure Assessment Methodology (TEAM) Study: Summary and Analysis; Volume 1*, EPA/600/6-87/002a, Office of Research and Development, Washington, DC, 1987.
- U.S. EPA. *Unfinished Business: A Comparative Assessment of Environmental Problems*. Office of Policy Analysis. Washington, DC, 1987.
- Lees, P., Corn, M. and Breyse, P., "Evidence for Dermal Absorption as the Major Route of Body Entry During Exposure of Transformer Maintenance and Repairmen to PCBs," *Am. Ind. Hyg. Assoc. J.*, 48(3) pp 257-264, 1987.
- Kissel, J. and McAvoy, D., "Reevaluation of the Dermal Bioavailability of 2,3,7,8-TCDD in Soil," *Haz. Waste Haz. Mat.*, (In press).
- Kissel, J., Bedan, M., Austin, P. and Hermanson, M., "Assessment of Long Term Loss of PCBs from Soil Amended with Contaminated Sewage Sludge," accepted for presentation, 62nd annual Water Pollution Control Federation conference, San Francisco, CA, 1989.
- ACGIH, *Threshold Limit Values and Biological Exposure Indices for 1987-1988*, Cincinnati, OH, 1987.
- NIOSH, *Pocket Guide to Chemical Hazards*. U.S. Government Printing Office, Washington, DC, 1985.
- U.S. EPA, "Drinking Water Criteria Document for Polychlorinated Biphenyls," ECAO-CIN-414, Final, Cincinnati, OH, April 1988.

Interim Methodology for Performing Petitioned Health Assessments

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ABSTRACT

The Agency for Toxic Substances and Disease Registry may, under CERCLA, as amended, and RCRA, as amended, perform a Health Assessment for a facility or release in response to a petition. Such petition may be offered by individuals (private citizens) or licensed physicians who supply information that individuals have been exposed to hazardous substances. In response to this mandate, ATSDR has developed an interim methodology for performing Petitioned Health Assessments. This paper describes the methodology developed by ATSDR for performing an assessment and will include ATSDR interim procedures and current data on the status of Petitioned Health Assessments.

INTRODUCTION

The Agency for Toxic Substances and Disease Registry (ATSDR) is authorized under CERCLA, as amended by SARA, to perform various Health Assessments. Specifically, the Agency may "perform a Health Assessment for releases or facilities where individual persons or licensed physicians provide information that individuals have been exposed to a hazardous substance, for which the probable source of such exposure is a release. In addition to other methods (formal and informal) of providing such information, such individual persons or licensed physicians may submit a petition to the Administrator of ATSDR providing such information and requesting a Health Assessment."

In addition to CERCLA, RCRA, as amended, has a provision under the Exposure Information and Health Assessment section stating that "any member of the public may submit evidence of releases of or exposure to hazardous constituents from a facility, or as to the risk or health effects associated with such releases or exposure, to the Administrator of ATSDR." Petitions or evidence submitted as defined by the above acts (i.e., CERCLA and RCRA) are considered Petitioned Health Assessments. Because these laws, as they pertain to Petitioned Health Assessments, are broadly defined, it was necessary for ATSDR to develop an interim methodology for dealing with Petitioned Health Assessments.

ATSDR recognizes that decisions to perform a Health Assessment should be based on public health concerns. Determining public health concerns is an "interpretive" process and such concerns cannot always be identified from the information received with a petition. Gathering additional information, analyzing it and thereby identifying the health concerns is equivalent to performing the Petitioned Health Assessment. Furthermore, as specified above in the CERCLA and RCRA legislation, threats to the public, other than those posed by chemical releases or facilities, although they may be related to Petitioned Health Assessments, may not be the responsibility of ATSDR.

Once a public health concern has been established, even though ATSDR would like to respond to the needs of the public with a Health

Assessment, performing a Health Assessment on each and every incident may not be in the best interest of the public. Other, more appropriate, authorities might better address public health concerns that do not relate to releases or facilities.

Furthermore, since the CERCLA legislation states that "if [such] a petition is submitted and the Administrator of ATSDR does not initiate a Health Assessment, the Administrator of ATSDR shall provide a written explanation of why a Health Assessment is not appropriate." Hence, formal procedures for accepting or rejecting petitions are imperative. The following discussion will outline the interim methodology that was developed within the ATSDR Office of Health Assessment (OHA) for addressing Petitioned Health Assessments.

INTERIM METHODOLOGY

Gathering Preliminary Information and Acknowledging Petitioner

Within a reasonable time period after receiving a petition (i.e., a target of 10 working days), all appropriate ATSDR personnel provide any first-hand information they might have on the facility or release. If a Health Assessment has not been performed on a release or facility (see below), an acknowledgement letter will be written responding to the specific information provided by the petitioner(s) and incorporating any additional information provided by ATSDR personnel.

If ATSDR has already performed a Health Assessment, the acknowledgement letter will reflect this and will include a copy of the document. Furthermore, the acknowledgement letter will state that unless the petitioner has additional information not considered in the already completed Health Assessment, ATSDR will not pursue the petition any further. If the petitioner sends new information in response to the ATSDR acknowledgement letter, the request will be considered as a new petition and dealt with as such.

Collecting Background Information

Once a petition has been acknowledged, background information must be collected so that ATSDR can determine whether to accept or reject the petition. As a first step in this interim process, the appropriate ATSDR Regional Representative develops contacts and collects background information on the alleged release or facility. At a minimum, the Regional Representative contacts:

- The Petitioned Health Assessment contact designated by the U.S. EPA headquarters
- The most appropriate U.S. EPA personnel with knowledge or potential knowledge of the site or release
- The most appropriate representatives of state health and environmental agencies
- The most appropriate local health and environmental agencies
- The petitioner(s)

ATSDR uses the information gathered by the Regional Representative to apply the first interim decision criteria [i.e., Interim Mode A Decision Criteria (see below)]. In addition to gathering information and developing contacts, the Regional Representative also obtains a recommendation from each agency on whether the petition should be accepted (see Mode A Decision Criteria, below). The information gathered in this step is not intended as a basis for the Health Assessment but only to provide information for accepting or rejecting the petition.

Applying the Interim Mode A Decision Criteria

A committee (i.e., Screening Committee), consisting of applicable ATSDR management personnel, reviews the information gathered by the Regional Representative and applies the following Interim Mode A Decision Criteria:

- A-1. Has a Health Assessment or its equivalent already been performed relative to the site, release or population?
 - if yes, forward the Health Assessment to the petitioner, stating that ATSDR will take no further action unless the petitioner has information not considered in the report or its equivalent;
 - if no, proceed with the evaluation;
- A-2. Can a source or release of contaminants alleged by the petition to exist be identified?
 - if yes, proceed with the evaluation;
 - if no, reject for this reason;
- A-3. Can a target population exposed or potentially exposed in the past, present or future alleged by the petition to exist be identified?
 - if yes, proceed with the evaluation;
 - if no, reject the petition for this reason;
- A-4. Do any of the government agencies recommend that ATSDR accept the petition?
 - if yes (one or more), proceed with the evaluation;
 - if no (all), and reasons appear credible to OHA, reject the petition for these reasons; in some cases OHA may still proceed with an evaluation if it believes that there are public health issues that have not yet been adequately addressed.

If a petition is rejected for any of the above reasons, then a letter will be sent to the petitioner stating the reasons for this rejection (see below-Mode B Decision Criteria).

Assigning Site to Scoping Team, Site-Visitation, Data Collection, and Preparation of Site Summary Report

Once a decision has been made to proceed with the petition, a member(s) of an appointed evaluation team (i.e., Scoping Team) visits the site and meets with knowledgeable federal, state and local officials and the ATSDR Regional Representative. In addition, the Scoping Team member(s) contacts those individuals previously designated by the Regional Representative and any other individuals knowledgeable about the site that were not available for personal communication during the site trip. Background information and monitoring data, site-visit information and any other information or monitoring data collected by the Scoping Team member(s) are evaluated and used to complete an ATSDR Site Summary Form.

Presenting Preliminary Information to the Screening Committee

When the information gathered during the site-visit trip has been consolidated and the site-visit report and ATSDR Site Summary Form have been completed, the information is presented at a Screening Committee meeting for preliminary feedback. The purpose of this meeting is to insure that all involved parties have a thorough understanding of the petition, the release and the implications of the release before the OHA Scoping Team member(s) meet with the petitioner(s).

Meeting with Petitioners and Preparing Trip Report

After preliminary presentation to the Screening Committee, the appropriate OHA staff travel with the ATSDR Regional Representative to meet with the petitioner(s). The trip report prepared after this meeting

becomes part of the official record, and any new information or health concerns brought to the Agency's attention by the petitioner(s) is considered when the petition is reviewed under the Interim Mode B Decision Criteria (see below).

Formal Presentation to Screening Committee and Applying Interim Mode B Decision Criteria

The Scoping Team member(s) assigned to evaluate the petition presents the findings and all related information to the Screening Committee. The Screening Committee will apply the Mode B Decision Criteria (below) to determine whether the petition is accepted or rejected.

Mode B Decision Criteria:

- B-1. Have individuals been exposed to a hazardous substance for which the probable source of such exposure is a release?
- B-2. Are the location, concentration and toxicity of the hazardous substances involved significant?
- B-3. Is there potential for further human exposure?
- B-4. What is the strength of recommendations from other government agencies?
- B-5. Is the incident applicable to CERCLA or RCRA or to other more appropriate environmental statutes (can the public best be served by a more appropriate government agency)?
- B-6. Are ATSDR resources available and what other ATSDR priorities have bearing, such as its responsibilities to conduct other Health Assessments and health effects studies?

The Above Mode B Decision Criteria require the use of professional judgment to evaluate the criteria's bearing on the ultimate decision to accept or reject the petition. After applying these criteria and reaching a decision to accept or reject the petition, ATSDR drafts a response letter to inform the petitioner(s) of the decision, the reasons for the decision (if appropriate) and the nature of any followup action(s) (if appropriate).

Preparing Draft Health Assessment

If the petition is accepted by applying the Interim Mode B Decision Criteria, it is then assigned to an appropriate multi-disciplinary Health Assessment team to develop a Draft Health Assessment. A copy of this Draft Health Assessment is provided for comment to the U.S. EPA, State and others in accordance with ATSDR policy.

Preparing Final Draft Health Assessment

Comments on the Draft Health Assessment received from the U.S. EPA, the State and others are considered, and the document is revised as necessary to prepare the Final Draft Health Assessment. Once the Final Draft Health Assessment is completed, a public meeting is conducted to discuss the findings.

Public and Petitioner Comment on Final Draft Health Assessment

The Final Draft Health Assessment is released for public and petitioner comment.

Responding to Comment, Preparing and Distributing (final) Health Assessment and "closing" the Petition File

All comments on the Final Draft Health Assessment received from the public and petitioners is considered and the document is revised as necessary to prepare the (final) Health Assessment. The Health Assessment is then distributed according to ATSDR policy. It also is sent to the petitioner with a letter of transmittal closing the petition file (unless ATSDR is undertaking some followup health action, e.g., proceeding with a followup Health Assessment or a health study, registry, surveillance activity, etc.).

STATUS OF PETITIONED HEALTH ASSESSMENTS

At the time this manuscript was prepared, ATSDR had received 62 requests for Petitioned Health Assessments from private citizens, public

officials, physicians, lawyers and others (Table 1). Approximately 50% of the requests were received from private citizens. Although physicians are specifically mentioned in the CERCLA regulations, only two of the 62 requests have come from physicians; however, both physicians were also public officials. Either very few private physicians are aware of the petition process or they may have elected to have their patients (private citizens) file the petition requests.

Table 1
Profile of Health Assessment Petitioners

Type of Petitioner	Number of Requests	Percentage
Private Citizen	30	49
Public Official	15	24
Physician ¹	2	3
Lawyer	13	24
Other ²	2	3
Total	62	100

¹Both physicians that petitioned ATSDR were also public officials.

²Tribal Council and military officer.

Requests have been received for sites on the NPL, for RCRA sites and for "other" sites and facilities (Table 2). The site designation of "other" consisted mostly of active and inactive commercial or industrial facilities (Table 3). As shown in Table 3, some petitions received by ATSDR do not precisely fall into the category of a release or facility, as described in CERCLA and RCRA. A profile, by U.S. EPA Region, of the petitions received is shown in Table 4.

Table 2
Profile of Petitioned Health Assessments by Site Type

Type	Number of Requests ¹	Percentage
National Priorities List (NPL)	21	31
Resource, Conservation, and Recovery Act (RCRA)	11	16
Other	36	53

Notes:

¹Includes multiple site listings for a single petition received by ATSDR.

Table 3
Profile of Non-NPL/RCRA Petitioned Health Assessments By Site Type

Type of Site	Number of Requests
Commercial/Manufacturing Facilities	14
Landfills/Abandoned Disposal Areas	7
Multiple Source Sites	5
Contaminated Municipal/Private Water Supplies	2
Military Base	1
Federal Penitentiary	1
Municipal Incinerator	1
Mining Waste	1
Smoke from Burning of Timber	1
Agricultural Pesticide Release	1
Sewage Contamination of Waterways	1
Pesticide Test Ponds	1
Total	36

At the time this manuscript was prepared, 60 of the 62 petitions received by ATSDR were being processed in one of the phases of the

Table 4
Profile of Petitions by EPA Region

Region	Number of Requests	Rank by Number of Requests
1	5	6/7
2	9	3
3	8	4
4	15	1
5	11	2
6	5	6/7
7	2	8
8	0	10
9	6	5
10	1	9
Total	62	

interim methodology for performing Petitioned Health Assessments. A delineation of the status of the petitions is shown in Table 5. Forty-four of the 62 petitions received have had the evaluation process (i.e., scoping) completed and that 30 Health Assessments currently have been completed or are in progress.

Table 5
Status of Petitioned Health Assessments

Status Category	Number of Requests
Rejected	14
Assigned (HA in progress)	22
Scoping (in progress)	17
Withdrawn by Petitioner	1
HA Completed	8
Total	62

HA= Health Assessment.

Scoping= Evaluating petition request.

CONCLUSIONS

ATSDR, in response to the broadly defined CERCLA and RCRA legislation, has developed an interim methodology for performing Petitioned Health Assessments. This interim methodology includes a procedure using two-mode decision criteria for accepting or rejecting Petitioned Health Assessment requests. Because ATSDR has based the decision criteria primarily on human health concerns, ATSDR believes that these procedures are sound from both a legal and, most importantly, a public health perspective.

Some of the petitions received by ATSDR do not appear to be the responsibility of ATSDR, as implied in the CERCLA and RCRA legislation, nor would the public health concerns raised by these petitioners be best served by ATSDR. ATSDR believes that the interim decision criteria developed to accept or reject these types of requests will best serve the public interest and ATSDR needs. Wherever applicable, ATSDR will refer a petition to the appropriate federal, state and local authorities for follow-up actions to protect public health.

With the experience ATSDR gains through the use of this interim methodology for performing Petitioned Health Assessments and with public comments that will be received when these criteria are published in the *Federal Register*, ATSDR may modify this methodology in the future to best serve the public interest and ATSDR needs. It is readily apparent, however, that public health concerns will remain the primary basis for all ATSDR decisions whether to perform Health Assessments or other appropriate actions at petitioned sites or facilities.

Medical Surveillance/Biological Monitoring Cleanup at the Rocky Mountain Arsenal

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ABSTRACT

The problems facing the industrial hygienist/safety professionals at hazardous waste sites during cleanup are numerous.

Those responsible for the safety and health of site personnel must learn how to make combined use of environmental and medical surveillance data in order to provide adequate protection. Selecting qualified medical monitoring facilities is mandatory. This process includes accredited laboratory facilities with appropriate QA/QC programs.

The AIHA/ACGIH Hazardous Waste Committee and its Medical Surveillance Subcommittee have been working with OSHA toward creating a generic standard for medical surveillance. Such a standard will give all hazardous waste contractors a starting point. Site-specific variations can then be added by the site health and safety officer with assistance from a board-certified occupational/environmental medicine physician. The AIHA/ACGIH committee and its subcommittee have created a set of criteria to assist the hazardous waste remedial action contractors in their selection of appropriate medical facilities to do their employee medical examinations.

The Rocky Mountain Arsenal cleanup at Basin F is a good example of a properly operated medical surveillance and environmental monitoring system.

The remedial action contractor built a state-of-the-art decontamination facility capable of handling up to 120 people in 30 min. The site workers of Rocky Mountain Arsenal faced the problems of heat stress in 90 to 97° F. summer weather as well as frost-bite in sub-zero winter weather without any serious casualties. The contractor learned how to keep workers alive and well and still get the job done and make money.

During the early days of Superfund site identification and characterization, the occupational/environmental medicine physician was monitoring young, health-conscious scientists. As the remedial action phase got under way, an entirely different group of people came under medical surveillance. They ranged in age from 18 to 65 and their life styles in general were in sharp contrast to the scientist group. The findings on their medical examinations were quite different. These findings present additional decision-making problems for the hazardous waste contractor.

There is need for continuous interaction between the contractor management and the medical monitoring facility. One must meet all of the requirements of OSHA and the U.S. EPA and still comply with the Privacy Act relative to confidentiality of medical information. One must also deal with the mandate of EEOC in terms of non-discrimination in hiring practices.

Medical surveillance of all persons entering upon a Superfund site is required by law under OSHA. If it is well done, it can be of great benefit to all concerned. If it is poorly done, it can create a host of potentially expensive problems.

Introduction

The history of the Rocky Mountain Arsenal begins in 1942. It was established by the U.S. Department of the Army as a manufacturing facility for the production of chemical and incendiary munitions. During World War II, chemical intermediate munitions, toxic products and incendiary munitions were manufactured and assembled by the U.S. Army. From 1945 to 1950, stocks of Levinstein mustard were distilled, mustard-filled shells were demilitarized and mortar rounds filled with smoke and high explosives were test fired. Various obsolete ordnance were also destroyed by detonation or burning during this period.

In the early 1950s, RMA was selected to produce the chemical nerve agent GB (Sarin) under U.S. Army operations. The North Plants manufacturing facility was completed in 1953 and was used to produce agents until 1957. Munitions-filling operations continued until late 1969. Primary activities between 1969 and 1984 involved the demilitarization of chemical warfare materials.

Concurrent with military activities, industrial chemicals were manufactured at RMA by several lessees from 1947 to 1982. The products included chlorinated benzenes, naphthalene, chlorine, fused caustic, insecticides (DDT, Aldrin, Dieldrin and Endrin), herbicides, nematocides, adhesives, anti-icers and lubricating greases.

In May of 1974, di-isopropylmethyl phosphonate and dicyclopentadiene were detected in the surface water at the northern boundary of the arsenal. Later that year, the Colorado Department of Health (CDH) detected the same chemical in a well north of the arsenal and issued three administrative orders against Shell and/or the Army in April of 1975. Thus began the litigation history of the RMA.

One must remember that in 1942 Denver was a very small town and the arsenal site was far from civilization. I also doubt that any of the planners at that time ever dreamed that the arsenal would some day be surrounded by a large urban area. I seriously doubt that any consideration was given to groundwater and its possible contamination by arsenal activities. The country was engaged in a global war and it was "full speed ahead" with little consideration for the environment.

The Rocky Mountain Arsenal encompasses approximately 17,000 ac of land in Adams County, Colorado. Much of it looks very benign. There are many species of wildlife roaming the arsenal including herds of deer, thousands of prairie dogs and rabbits. Game birds abound and the lakes and ponds are full of fish. Bald eagles have built a nest on arsenal property.

The full extent of the contamination of soil and groundwater at the arsenal is not known. It may never be known. The lists of chemicals fill many pages and are not considered complete. The environmental problems created by the arsenal have created much political activity and the public has demanded action.

SITE CHARACTERIZATION MEDICAL MONITORING

The initial stages of cleanup began with site characterization. My organization has been involved in the medical monitoring for the past 9 years. We have supplied medical surveillance and biological monitoring to a number of the contractors. In this initial phase of cleanup activity, the majority of the personnel working on the Rocky Mountain site were scientists and technicians.

The Activities at this stage of the investigation included drilling test wells, taking soil and water samples and doing air monitoring. Some of the locations in which they were working called for level B protection. This means the use of impervious clothing in multiple layers including gloves and boots with liners and helmet with supplied air (either back pack with tanks or airline hose from a compressor). I have been suited up for level B and have been out on-site carrying equipment and doing physical work in direct sunlight with outside ambient temperatures in the 70's (°F). Within 20 min. I began to feel the heat load. I could only imagine how I would feel if the outside ambient temperatures were in the high 90's (°F). I was wearing a back pack with compressed air tank and was put through the experience of a tank change. I recall that it took me 20 min. to get dressed with the help of two people from the decontamination unit.

I went through this exercise because I feel that it is important for the examining physician at hazardous waste projects to experience exactly what the workers on the project will experience. It gave me a much broader perspective and enabled me to do a better job for the contractor personnel.

As each contractor began work in 1980, I sat down with the industrial hygiene and health and safety personnel and reviewed the available environmental data. Based on this discussion, we jointly developed a protocol for medical monitoring. We knew that we were dealing with organic solvents and a variety of chlorinated hydrocarbon pesticides. These chemicals are known liver toxins and some are kidney toxins. Some are leukemogens and others can cause aplastic anemia. The organophosphate pesticides depress the cholinesterase.

All of the baseline physical examinations included: personal and family medical history, occupational history, hobbies, recreational activities, use of tobacco, alcohol and medicines; hands-on physical examination; chest x-ray; lung function testing; resting ecg or treadmill ecg (for level A & B protection); complete blood count; biochemical profile; vision screening; audiometric testing; complete urine analysis; cholinesterase; methemoglobin; heavy metals. Where indicated, pesticide screens of various kinds were added. All personnel were screened for drug use as a safety precaution.

Having developed the medical monitoring protocol, the next important step was to select laboratories that had good QA/QC programs. We chose a local reference laboratory that was certified by the Centers for Disease Control. This laboratory participated in two external quality control programs. We then found a toxicology laboratory that also demonstrated proper QA/QC by participating in multiple external programs. Our trace metals laboratory participates in four national and two international QA/QC programs and does 40% QC in house. We feel very comfortable with the results from these laboratories.

Chest x-rays (PA and lateral views) are interpreted by a Board Certified radiologist. Pulmonary function tests are done on equipment that is calibrated daily. The tests are conducted by a technician who has taken a NIOSH-approved course in spirometry and passed the certification examination. The ecg's are all interpreted by cardiologists. The audiometric testing is done on equipment that meets the requirements of the OSHA standard on hearing conservation.

After the baseline examination, employees are monitored on a periodic basis. The interval is usually once a year, but in some situations may be more frequent. They also are examined at the end of a project or when leaving employment. If there has been a spill or toxic release, an interim examination usually is conducted.

In the initial phase of the arsenal cleanup, we were examining groups of scientists and technicians engaged in site identification and characterization. These were almost all young people (aged 20 to 35), in excellent health and in a good state of physical fitness. Many were com-

petitive athletes. Most were non-smokers and had good dietary habits. Very few were overweight. Most of them consumed little or no alcohol. We did not find any drug users.

CLEANUP PROGRAM MEDICAL MONITORING

When the remedial action contractors came for the next phase of the cleanup, we found ourselves evaluating an entirely different group of people. They ranged from 18 to 65 years of age. Quite a number were overweight. Most were in a fair to poor state of physical fitness. Many were cigarette smokers and heavy users of alcohol. We found a few drug users. Many had very poor eating habits. Many had elevated serum lipids (cholesterol and/or triglycerides).

A major remedial action effort took place in 1988-1989 at a location known as Basin-F. This area was considered one of the most highly contaminated areas at the RMA. The cleanup plan was drawn up by the contractor. This plan of course, included a site health and safety plan which was reviewed by the industrial hygiene group and the medical monitoring group. The medical surveillance protocol was created and adopted. This project was unique in that the labor force was union organized. The "hot zone" was identified and was surrounded by a buffer zone with a perimeter fence. All personnel working inside the fence were put in level B protection during the initial phase of the cleanup.

A team of 22 field health and safety personnel was selected and hired by the contractor. This team included three EMT's (emergency medical technicians) and seven air monitoring and meteorology technicians. All of these people were trained by the contractor for this project. The air monitoring personnel selected seven locations for monitoring stations at the perimeter. High volume samplers were used with continuous real-time computerized monitoring. Wind velocity and direction also were measured.

The contractor designed and built a state-of-the-art decontamination facility. This facility was equipped with the latest in decontamination equipment. It was staffed by a supervisor and seven technicians. It was stocked with large supplies of all of the required protective clothing and respiratory protective gear. It was capable of handling up to 120 people in 10 min. It also housed the on-site laundry. It was set up to handle male and female personnel (there were some female heavy equipment operators and laborers).

During the summer months, all field personnel were monitored for heat stress. Hourly WBGT monitoring was done in the support zone. The work/rest regimen was based on these readings. As the ambient temperatures went up, the work periods were shortened and the rest periods were lengthened. During 90 to 100°F weather, the work day began at 4:00 a.m. and the project was shut down by 10:00 a.m. Under these conditions, the labor force would work for 20 min. and rest for 40 min. Some of the work was done on the night shift to avoid the heat.

During the rest periods, personnel were pulled out of the "hot zone" into the decontamination trailer which was maintained at 60°F. The EMT's checked vital signs (heart rate, respiration, blood pressure and body core temperature). The body core temperature was measured by using a tympanic thermometer. Field medical monitoring was the first line of defense against heat stress.

At the peak of activity, there were 60 to 70 people in the Basin all of the time. Approximately half of these were heavy equipment operators and half were laborers. The heavy equipment operators were in air-conditioned cabs and therefore had less solar load than the laborers. The heavy equipment operators were all on supplied air from racks of tanks on their vehicles. It became necessary in the hot weather to ice the air tanks and the hoses. Even with all of these measures, the ambient temperature inside the cabs got into the mid 80's (°F). Some of the laborers used back packs with small 45 min. tanks of compressed air. Others dragged airline hoses around that supplied air from large tanks or compressors.

When it came to putting down the black vinyl liner for the waste pile containment, the contract had to be re-written to allow this work to be done at night. During the day, thermometers 3 ft. above the liner registered 140°F. At the beginning of the hot weather, I was asked, as the medical consultant, to go out to the work site and give a lecture on heat stress to the managers and supervisors. This lecture was

accomplished by utilizing the charts and slides on heat stroke and heat stress prepared by ACGIH. The contractor then took the posters and prepared from the cartoons a booklet that was given to all personnel in the field.

OVA's (organic vapor analyzers) and HNU equipment were used for field environmental monitoring. Organic chemical in the ambient air were measured to monitor pesticide levels. Ammonia, hydrogen sulfide and fugitive dust also were measured. Neither ammonia nor hydrogen sulfide was detected. All of the above measurements were done with real-time monitoring. The fugitive dust action limit was set at 1 mg/m³. Action limits set for chemicals were fractions of PELs and TLV's.

During the winter months, insulated coveralls were worn under the protective clothing. The impermeable suits provided protection against the wind chill. Hard hats were fitted with insulated liners. Insulated boot liners were provided and cotton gloves were worn inside the neoprene gloves. There was a warm up regimen of 15 min/hr of work when ambient temperatures were at 0°F. During the warm up period, the EMT's checked fingers, toes and ears for evidence of frostbite. Body core temperature was measured to be sure that employees were not going into hypothermia.

As the clean-up progressed, the basin was downgraded to level C personal protective equipment, based environmental monitoring data. However, when the OVA reading for toluene (as an example) exceeded 1 ppm, the area would be upgraded to level B and field personnel would go back on supplied air. Every precaution was taken to prevent exposure of field personnel to toxic chemical hazards. During the entire project, there was daily communication between the site health and safety officer and the medical consultant.

CONCLUSIONS

During the peak phase of activity there were 130 people on-site in-

cluding support personnel outside the perimeter fence. All of these support personnel, including security guards and office workers, were included in the medical monitoring program. The contractor was not taking any chances with the health and safety of his personnel. Some of the motivation, of course, was not only medical but also legal. All employees including regular employees staying on with the company were provided with exit medical examinations as they left the project. Analysis of the health and safety data did not reveal any evidence of serious exposure to toxics. There were no heat stroke or frost-bite casualties.

The contractors and their management and field personnel are to be congratulated for carrying out a project of this scope and magnitude with no serious health casualties.

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REFERENCES

1. Proctor, N.H., Hughes, J.P. and Fischman, M.L., *Chemical Hazards of the Workplace*, 2nd Ed., J.B. Lippincott Co., Philadelphia, PA, 1988.
2. Kneip, T.J. and Crable, J.V., *Methods for Biological Monitoring*, American Public Health Assoc., Washington, DC, 1988.
3. Williams, P.L. and Burson, J.L., *Industrial Toxicology*, Van Nostrand Reinhold Co, New York, NY, 1985.
4. Baselt, R.C., *Disposition of Toxic Drugs and Chemicals in Man*, 2nd Ed., Biomedical Publications, Davis, CA, 1982.

Quantitative Public Health Risk Assessment at a Low Level Contaminant Superfund Site

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ABSTRACT

A study of the potential public health risk was undertaken at the Chisman Creek Superfund Site. This site is located in south east York County, Virginia, and consists of four fly ash disposal areas, three man-made ponds and a freshwater tributary stream that drains into Chisman Creek and the Chisman Creek estuary. Fly ash was generated from a fuel mixture of bituminous coal and petroleum coke and was disposed at the site from 1957 to 1974. The site was placed on the NPL in 1983.

Contaminants associated with the site are nickel, arsenic, vanadium, lead and zinc. Potential pathways of exposure reviewed included soil and surface water. A public health risk assessment was calculated for chronic intake of carcinogenic and non-carcinogenic contaminants. Ingestion of contaminants was calculated for members of the general population, including sensitive persons. These calculated exposure values were used to determine the risk associated with this site. Using the derived data and published information, risks estimated for the local population were determined. These risk assessment values were determined not to "exceed" the U.S. EPA's 10⁻⁴ to 10⁻⁷ level of carcinogenic risk or unity for the non-carcinogen hazard index. Derived health assessment information was used as one variable in determining the necessary remediation criteria.

This paper discusses problems encountered in determining exposure factors and incremental risks at a site containing low levels of trace metals. The results of this study indicate that risk interpretation must be conducted with caution at low level metal sites. The dietary importance and risk relationship of trace metals also is noted. Since the mechanisms of actions for the trace metals studied are different, no combined effects were calculated. Numerical values for carcinogenic potencies and acceptable intake concentrations for chronic exposure were obtained from the U.S. EPA *Superfund Public Health Evaluation Manual*. Other factors influencing risk are discussed as related to the exposed population. The importance of sensitive individuals in the population is noted. Regulatory evaluation, assumption factors for a sensitive population and risk assessment as a remediation criteria are discussed.

INTRODUCTION

Numerous federal and state laws have recently been enacted requiring investigation and remediation of sites contaminated with hazardous substances including organic, inorganic, pesticide, radionuclide and other wastes¹. The primary factor responsible for site selection, remedy selection and cleanup levels has been the site's actual or potential impact affecting human health and the environment, often collectively called a public health hazard. Several highly publicized incidents resulting in threat or harm to the public and environment originally triggered enactment of the initial Superfund legislation (CERCLA) and the re-

authorization legislation (SARA). As a result of these Superfund laws, environmental engineers have developed new techniques to control, transport, excavate, stabilize, incinerate, biodegrade and encapsulate materials considered to be hazardous. Although these technologies can successfully control and remediate hazardous material at sites, information about the public health hazards posed by the sites often was lacking. To evaluate public health risks, methodology was modified and/or formulated to quantify risks associated with hazardous waste sites. These public health epidemiological and statistical methods used data derived from the fields of toxicology, physiology, industrial hygiene, biology, chemistry and meteorology. This interdisciplinary approach resulted in a "new" discipline called risk assessment. With the development of any "new subject," a degree of maturity and growth is necessary to establish a theoretical and practical basis. This paper will provide a case example of risk methodology and interpretation used to assist in the determination of cleanup standards for a low-level Superfund site.

Regulatory Considerations

Since risk assessment is in its early stages of scientific and regulatory evolution, few, if any, governmental agencies have established procedural policy to conduct, evaluate, interpret and review this technique. However, the (U.S. EPA) published five proposed guidelines (carcinogenicity, mutagenicity, developmental toxicity, chemical mixtures and exposure) to help risk assessors establish standards for conducting risk assessment². Although these guidelines are not regulations, they do provide a framework in which cleanup risk assessment criteria can be addressed. In fact, other agencies (e.g., the EPA, Nuclear Regulatory Commission) have used similar methodological approaches to establish standards³. As the field of risk assessment develops, better refinement of techniques will allow more governmental agencies to use these procedures to establish regulatory standards and cleanup criteria.

Routes of Exposure

The routes or pathways of exposure in humans from hazardous waste site activities include dermal, ingestion and inhalation. Traditionally, the primary occupational route was inhalation. However, this pathway's importance is diminished in non-occupational populations. In the general population, the route and potential exposure can dramatically vary from one individual to another. Therefore, numerous scenarios must be evaluated to determine maximum risk. In almost all cases, the worst practical scenario must be considered when determining the final risk. This risk assessment process may include a synergism of compounds, routes and number of exposure events.

Site Background Information

The Chisman Creek Superfund Site is located in southeast York

County, Virginia, approximately 1 mi north of Grafton⁵. The site consists of four fly ash disposal areas, three man-made ponds, a freshwater tributary stream that drains the site and flows into Chisman Creek and the Chisman Creek estuary. The site has been divided into two operable units by the U.S. EPA. Operable Unit 1 consists of the four fly ash disposal areas (designated Pits A, B, C and D) and areal groundwater. Operable Unit 2 consists of three ponds (designated A, B and C), the freshwater stream and the Chisman Creek estuary. This paper addresses the risks associated with operable Unit 2 only.

The site contains fly ash generated from a fuel mixture of bituminous coal and petroleum coke. The fly ash was produced at Virginia Electric and Power Company's (Virginia Power) Yorktown Power Station and was disposed of at the site by R. L. Brandt and Sons, Inc., a local contractor, from 1957 to 1974. The site was placed on the NPL in 1983.

Previous investigations of the Chisman Creek site include studies by the Virginia Department of Health and the Virginia Water Control Board in 1980 and 1981 and by the Virginia Institute of Marine Science in 1983. The RI and FS for Operable Unit 1 were performed by the U.S. EPA's contractor, CH₂M Hill, in November, 1985 and August, 1986, respectively. The ROD for Operable Unit 1 was issued by the U.S. EPA in September, 1986. Virginia Power agreed to perform the Operable Unit 1 remediation, and remedial construction was completed in December, 1988.

The U.S. Fish and Wildlife Service (FWS) conducted the RI for operable Unit 2. The draft RI report was issued in April, 1987, and the final RI report was issued in December, 1987. GAI Consultants, Inc. (GAI), a contractor to Virginia Power, conducted the FS for Operable Unit 2 by agreement with the U.S. EPA. Virginia Power agreed to perform the Operable Unit 2 remediation, and remedial construction was completed in December, 1988.

Long-term operation and maintenance activities currently are being performed on the site by Virginia Power. Additionally, Virginia Power and the County of York have entered into an agreement to operate the site as a public park. Softball and soccer fields along with nature areas have been developed and public use of these facilities is scheduled for mid-1990.

Methods

Risk assessments were calculated for the chronic intake of carcinogenic and non-carcinogenic trace elements. No combined effects were included in the risk assessment calculations since the mechanism of actions for these metals studied are different. Numerical values for carcinogenic and non-carcinogenic potencies and acceptable intakes for chronic exposure were obtained from the U.S. EPA *Superfund Public Health Evaluation Manual (SPHEM)*⁶.

Chemical concentrations were determined as described in the Chisman Creek Superfund Site Feasibility Study for Operable Unit 2⁵. Contaminated elements evaluated in this study are nickel, arsenic, vanadium, lead and zinc. The highest concentration of each contaminant was used for the risk evaluation. Assessment pathways evaluated were ingestion of sediment (soil) and surface water. All ingestion was considered to be accidental and does not represent a daily consumption intake. Intake values for water and sediment are 100 mL (non-carcinogens) and 1000 mL (carcinogens) per day and 10 g per day, respectively. Intestinal absorption was considered 100% for all compounds. For carcinogenic calculations, a lifetime was 70 yr, body weight was 35 kg and exposure duration was 450 days over one's lifetime. For non-carcinogenic calculations, a body weight of 10 kg was used.

Risk assessment calculations for the carcinogenic elements, nickel and arsenic, are identical to those described in the *Superfund Public Health Evaluation Manual*⁶ and the "Chisman Creek Superfund Site Feasibility Study for Operable Unit 2"⁵. The Hazard Index Value (HI) for non-carcinogenic elements, nickel, vanadium, lead and zinc, were determined using identical methods as described in the *Superfund Public Health Evaluation Manual*⁶. All values were considered for chronic exposure. The Acceptable Intake Concentrations for chronic exposure (AIC) for vanadium, nickel, lead and zinc were obtained from the *Superfund Public Health Evaluation Manual*⁶ or the Health Effects Assessment Documents for Arsenic⁷ or Nickel and Nickel

compounds⁸. The Chronic Daily Intake values (CDI) were calculated by dividing the ingestion concentration by the body weight.

RESULTS

The highest concentrations of carcinogenic elements are shown in Table 1. These values are reported for Ponds A, B, C and the stream water and sediment. Ingestion was determined from the concentrations in Table 1 and is represented using in the value of mg/day (Table 2). The risk assessment based on a lifetime exposure from ingestion of water or sediment is shown in Tables 3 and 4. These values represent additional cases of cancer over a lifetime. The carcinogenic potency values for nickel and arsenic are 0.84 mg/kg-day and 15 mg/kg-day, respectively.

Non-carcinogenic water and sediment concentrations are shown in Table 5. Ingestion concentration for water and sediment per day are shown in Tables 6 and 7, respectively. The hazard index values for vanadium, nickel, lead and in zinc sediment are shown in Table 8. Values equal to 1.0 are defined as unity. All methodology is identical to the *Superfund Public Health Evaluation Manual* (6) and the "Chisman Creek Superfund Site Feasibility Study for Operable Unit 2"⁵.

Table 1
Highest Concentrations Detected of Nickel and Arsenic in Water and Sediment for Carcinogenic Evaluation

Water Concentration (ppb)				
	Pond A	Pond B	Pond C	Stream
Nickel	27	27	27	83
Arsenic	10	10	10	145
Sediment Concentration (ppm)				
	Pond A	Pond B	Pond C	Stream
Nickel	749	79	29	107
Arsenic	28	128	15	17

Table 2
Ingestion of Nickel and Arsenic from Water and Sediment (mg/day) for Carcinogenic Evaluation

Water Concentration				
	Pond A	Pond B	Pond C	Stream
Nickel	0.027	0.027	0.027	0.083
Arsenic	0.010	0.010	0.010	0.145
Sediment Concentration				
	Pond A	Pond B	Pond C	Stream
Nickel	7.49	0.79	0.29	1.07
Arsenic	0.28	1.28	0.15	0.17

Table 3
Risk Estimate for the Ingestion of Water from the Ponds and Streams as Additional Cancer Cases Over a Lifetime Period

	Pond A	Pond B	Pond C	Stream
Nickel	3.1×10^{-13}	3.1×10^{-13}	3.1×10^{-13}	2.9×10^{-12}
Arsenic	7.5×10^{-13}	7.5×10^{-13}	7.5×10^{-13}	1.6×10^{-10}

Table 4
Risk Estimate for the Ingestion of Sediment for the Ponds and Streams as Additional Cancer Cases Over a Lifetime Period

	Pond A	Pond B	Pond C	Stream
Nickel	2.4×10^{-8}	2.6×10^{-10}	3.5×10^{-11}	4.8×10^{-10}
Arsenic	5.9×10^{-10}	1.2×10^{-8}	1.7×10^{-10}	2.1×10^{-10}

Table 5
Water and Sediment Concentrations for the Non-Carcinogenic Evaluation

Water Concentration (ppb)				
	Pond A	Pond B	Pond C	Stream
Nickel	27	27	27	83
Vanadium	80	19	19	70
Lead	5	5	5	970
Zinc	4.6	4.2	18	83

Sediment Concentration (ppm)				
	Pond A	Pond B	Pond C	Stream
Nickel	749	79	29	107
Vanadium	1,670	141	48	541
Lead	28	17	13	62
Zinc	202	38	67	217

Table 6
Ingestion of Water for Non-Carcinogenic Evaluation (mg/day)

	Pond A	Pond B	Pond C	Stream
Nickel	0.027	0.027	0.027	0.083
Vanadium	0.080	0.019	0.019	0.097
Lead	0.005	0.005	0.005	0.070
Zinc	0.005	0.004	0.018	0.008

Table 7
Ingestion of Sediment for Non-Carcinogenic Evaluation (mg/day)

	Pond A	Pond B	Pond C	Stream
Nickel	0.749	0.079	0.029	0.011
Vanadium	1.670	0.141	0.048	0.054
Lead	0.280	0.017	0.013	0.062
Zinc	0.020	0.038	0.067	0.022

Table 8
Hazard Index Values for Non-Carcinogenic Elements

Chemical	CDI (mg/kg/day or mg/l/day)	AIC (mg/kg/day or mg/l/day)	HI
Pond A			
Vanadium Water	0.0008	2.0×10^{-2}	0.04
Sediment	0.0167	2.0×10^{-2}	0.84
Nickel Water	0.0003	1.0×10^{-2}	0.03
Sediment	0.0075	1.0×10^{-2}	0.74
Lead Water	0.0001	1.4×10^{-3}	0.04
Sediment	0.0003	1.4×10^{-3}	0.20
Zinc Water	0.0001	2.10×10^{-1}	0.0002
Sediment	0.0020	2.10×10^{-1}	0.01
Pond B			
Vanadium Water	0.0002	2.0×10^{-2}	0.01
Sediment	0.0013	2.0×10^{-2}	0.07
Nickel Water	0.0003	1.0×10^{-2}	0.03
Sediment	0.0079	1.0×10^{-2}	0.08
Lead Water	0.0001	1.4×10^{-3}	0.04
Sediment	0.0002	1.4×10^{-3}	0.12
Zinc Water	0.0001	2.10×10^{-1}	0.0002
Sediment	0.0004	2.10×10^{-1}	0.002
Vanadium Water	0.0002	2.0×10^{-2}	0.01
Sediment	0.0005	2.0×10^{-2}	0.02
Nickel Water	0.0003	1.0×10^{-2}	0.03
Sediment	0.0003	1.0×10^{-2}	0.03
Lead Water	0.0001	1.4×10^{-3}	0.04
Sediment	0.0001	1.4×10^{-3}	0.09
Zinc Water	0.0002	2.10×10^{-1}	0.001
Sediment	0.0007	2.10×10^{-1}	0.003
Stream			
Vanadium Water	0.0097	2.0×10^{-2}	0.49
Sediment	0.0054	2.0×10^{-2}	0.03
Nickel Water	0.0008	1.0×10^{-2}	0.08
Sediment	0.0011	1.0×10^{-2}	0.11
Lead Water	0.0001	1.4×10^{-3}	0.04
Sediment	0.0006	1.4×10^{-3}	0.44
Zinc Water	0.0008	2.10×10^{-1}	0.004
Sediment	0.0022	2.10×10^{-1}	0.01

DISCUSSION

Health Effects

The concentration values for carcinogenic elements, nickel and arsenic, and non-carcinogenic elements, vanadium, nickel, lead and zinc, are represented in Tables 1 and 5. These values are below concentrations associated with heavy metal diseases^{7,8,9}. Nickel is considered both a carcinogenic and a non-carcinogenic hazard by U.S. EPA in the SPHEM⁶. However, primary association for nickel as a carcinogenic element is through occupational inhalation^{8,9} resulting in elevated nasal and lung cancer. A different, and more important, cancer etiology is reported for arsenic. Arsenic has been associated with skin cancer

in humans drinking contaminated water⁷. Unlike nickel, this association represents a valid concern as related to the public health.

The non-carcinogenic elements have only been associated with disease in elevated concentrations on a chronic exposure basis or accidental acute episodes. Since the element concentrations of interest are well below acute toxicological dose thresholds, no acute non-carcinogenic hazard index values were calculated. However, recent concerns over lead have raised the issue of whether low concentrations may be harmful to sensitive members of the population¹⁰. The sensitive groups most often considered are pregnant women and young children. It is likely, as with asbestos, that a no observable dose threshold exists with lead. However, as with numerous trace elements, it is possible that low con-

centrations are biochemically necessary for normal metabolism. A detailed discussion of health effects and biology of the elements associated with this site can be found in references 5, 7, 8 and 9.

Exposure Constants

Values of intake are represented in mg/day for both carcinogenic and non-carcinogenic elements (Tables 2, 6 and 7). These values were then divided by the body weight (35 or 10 kg). The low weight values were used to introduce a highly conservative estimate in the final calculations. There fore, population members having weights greater than those used in the calculations exhibit an even larger factor of conservatism. This process allows risk assessment policies to provide a high degree of protection to all population members without opting for the "traditional" average risk estimates¹¹. Use of these values can provide standard guidelines for risk assessment at low level sites without unrealistic conservatism.

A similar factor was applied to the intake values of water and sediment. Although these values are large for accidental ingestion in the adult population, this exposure may be realistic for children who, for example, engage in frequent pica ingestion. Most of these conservative assumptions are balanced by a more liberal exposure time of 450 days. Providing the values used in this investigations⁶s risk assessment calculations allows other scientists to better judge methodology rather than use uncertainty factors¹². Until more accepted intake values are determined for sensitive populations, risk assessors should utilize conservative factors to address and satisfy the public's expectation of a high degree of public protection.

Risk Assessment

Values for additional cancers were determined using the highest reported water and sediment concentrations (Table 3 and 4). No calculated risk value approaches the 1.0×10^{-7} additional cancer risk. The highest risk value reported was 2.4×10^{-8} . With risk values so low, it is impractical to consider synergistic or additive effects of exposure. If these assumptions were to be incorporated into the risk estimate, simple addition or multiplication may be a valid mechanism for risk synergy. Thus, a theoretical mechanism for estimating the synergistic effect is to multiply the largest risk values of each compound. Inclusion of factors beyond simple multiplication for compounds effecting different organ systems is unrealistic.

Hazard index (HI) values were all below unity (Table 8). In fact, some HI values were below the significant place calculations. With the exception of vanadium in the sediment of Pond A, no HI value approached unity. The *Superfund Public Health Evaluation Manual*¹⁶ states: "It is emphasized that the hazard index is not a mathematical prediction of incidence or severity of effects. It is simply a numerical index to help identify potential exposure problems. Results for multiple chemicals should not be interpreted too strongly. If some of the indicator chemicals do not have adequate toxicity information, thus preventing their inclusion in the hazard index, the hazard index may not be reflective of actual hazards at the site. Consideration of chemicals that do not have toxicity values could significantly increase the hazard index to levels of concern. Professional judgement is required to determine how to interpret the hazard index for a particular site."

The addition of HI values within and between groups may provide some insight to potential risks. These risks may be future classified when a cumulative value is determined by addition from the same source. These risk characteristics, called cumulative values, are defined as follows:

- <1- no hazard or risk
- 1 to 2-incrementally elevated or an acceptable risk
- 3 to 5-moderate concern for the sensitive population
- 5 to 10-moderate concern for the general population
- >10-a concern requiring a planned action
- >13-immediate concern for the public

Although these cumulative values are arbitrary and have not been validated in actual population studies, they do provide a range in which to judge a qualitative HI value risk. However, as with any non-threshold

estimate, judgment based on animal and epidemiological studies must be considered when making a final determination. This judgmental process becomes even more evident when evaluating Superfund sites that contain low levels of contaminants.

Neither the carcinogenic or non-carcinogenic risks at the Chisman Creek site are at levels of concern as related to the public's safety. Although some consider lead to be a no-threshold element, most other elements have dietary importance. Incorporation of an element's essential dietary requirements usually is not considered in risk assessment. However, increased levels of some compounds (e.g., selenium) may be beneficial¹³.

Risk Assessment for Evaluating Action Alternatives

Since engineering design methods provide no evidence or guidance in regard to health effects, the resultant remedial construction usually is unrelated to risk assessment judgments. However, combining the engineering design with desired health risks provides a useful selection mechanism. The action alternatives should be based first on the ability to achieve the desired risk. This risk must incorporate the surrounding natural background concentrations, the exposure pathways and acceptable level of toxicants. At low level sites the aesthetic values, public pressures and cleanup costs usually are stronger considerations than elevated public health risks. However, systematic and site-specific risk determinations provide valuable information for the selection of remedial actions and the level of cleanup and hazards associated with the actual remedial construction.

CONCLUSION

This investigation provides additional guidance for determining action alternatives at low level hazardous waste sites. When carcinogenic risk assessments are below 10^{-7} and non-carcinogenic additive values are below a cumulative value of 2.0, the importance of future site development and costs become of greater importance. The selection of a remedy, the level of cleanup and cost of cleanup should be directly related to the cumulative non-carcinogenic risk and carcinogenic risk assessments.

REFERENCES

1. Hazardous Sites Cleanup Act of Pennsylvania. Act 1988-108.
2. Hayes, D. J. and MacKerron, C. B., "Superfund II: A New Mandate." *The Bureau of National Affairs Special Report*, 1987.
3. Preuss, R. W., Ehrlich, A. M. and Garrahan K. G., "U.S. EPA Guidelines for Risk Assessment." *Proc. Seventh National Conference on Management of Uncontrolled Hazardous Waste Sites*. HMCRI, Silver Spring, MD 1986.
4. U.S. EPA. *National Emission Hazard for Hazardous Air Pollutants: Regulation of Radionuclides*, 40 CFR 61 (Federal Register Volume 54; page 9612), 1989.
5. Virginia Electric and Power Company. "Chisman Creek Superfund Site. Feasibility Study for Operable Permit 2, Glen Allen, Virginia," 1988.
6. U.S. EPA. *Superfund Public Health Evaluation Manual*. EPA/540/1-86/060, Washington, DC Oct. 1986.
7. U.S. EPA. *Health Effects Assessment Document for Arsenic*. Publication Nos. PB 86-134319, Cincinnati, OH.
8. U.S. EPA. *Health Effects Assessment Document for Nickel and Nickel Compounds*. Publication Nos. PB 86-232212, Research Triangle Park, NC.
9. Rom, W. N., *Environmental and Occupational Medicine*. Little, Brown and Company, Boston, MA 1983.
10. Needleman, H. L. and Belling, D., "Commentary: Recent Developments," *Environ. Res.* 46, pp 190-191, 1988.
11. Hubbard, A. E., Hubbard, R. J., George, J. A. and Hagel W. A., Quantitative Risk Assessment as the Basis for Definition of Extent of Remedial Action at the Leestown Pesticide Superfund Site, *Proc. Seventh National Conference on Management of Uncontrolled Hazardous Waste Sites on Uncontrolled Hazardous Waste Sites*, HMCRI, Silver Spring, MD, 1986, pp 186-192.
12. Hirschhorn, J. S. Oldenburg, K. U. and Doran D., "Using Risk Concepts in Superfund." *Proc. of the Eighth National Conference, Superfund 1987*, HMCRI, Silver Spring, MD, 1987, page 166-168.
13. Lange, J. H., Talbott, E. O., Baffone, K. M., Weyel, D. A., Soboslay, E. G., Koros, A. M. C. and Sykora, J. L., "Selenium Cancer Activities of Selenium." *Medical Hypothesis*, pp 443-447, 1987.

Quantitative Uncertainty Analysis in Exposure and Dose-Response Assessments in Public Health Risk Assessments Using Monte Carlo Techniques

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ABSTRACT

Most health risk assessments for Superfund sites combine a series of high, upperbound or worst-case *assumptions* to derive a point estimate of risk that is conservative, i.e., protective of public health. By setting the bias high enough to dominate the uncertainty in each step, such a risk assessment considers scenarios that will rarely, if ever, happen. In addition, the results from such a risk assessment have an unknown amount of conservatism built into them. This paper presents a method for uncertainty analysis using Crystal Ball™ for Monte Carlo simulations. The program combines thousands of realizations for the probability density functions of each input variable yielding a final probability distribution rather than a single number.

INTRODUCTION

Following guidance published by the U.S. EPA, most health risk assessments for hazardous waste sites concatenate a series of high, upperbound, or worst-case assumptions to derive a point estimate of risk that is conservative, i.e., protective of public health.^{22, 23} The U.S. EPA is well aware that risk assessments need to include uncertainty analyses and sensitivity analyses in every project. Through guidance documents,^{22, 23} handbooks²¹ and research reports,^{1, 25} the Agency requires uncertainty analyses in Superfund investigations and has investigated algebraic and computational methods to meet those requirements. Unfortunately, the methods proposed to day have been too cumbersome to accomplish the objective, so most risk assessments prepared today include only a qualitative discussion of uncertainties.

Monte Carlo Methods

Monte Carlo simulations yield numerical estimates of uncertainties.^{18, 20} Until the recent arrival of powerful desktop workstations, Monte Carlo simulations were too computationally expensive to have practical application in public health risk assessments. Now, as workstations become readily available, it is appropriate to find efficient ways to extend risk assessment methods to estimate point values as well as distributions of health risk.^{2, 3}

In the world of Monte Carlo techniques, most or all input variables become random variables with known or estimated probability density functions (called PDFs). [Equivalently, an input variable can be specified by a cumulative distribution function (CDF)]. Within this framework, one or more variables can take on ranges of values with known probabilities. For example, one could specify that an adult's weight is distributed as a normal random variable with a mean of 70 kg and a standard deviation of 10 kg. In this world view, constants, like pi (approximately 3.14159), remain fixed values.

Until recently, all Monte Carlo simulations were done using custom software.^{4, 10, 15} With the arrival of new forecasting software that works

with a spreadsheet, e.g., Crystal Ball™¹⁷ and @Risk™¹⁹ Monte Carlo calculations now can be designed and implemented as easily as spreadsheet calculations.

RISK ESTIMATION USING CRYSTAL BALL™

For a Monte Carlo simulation for steady-state or equilibrium conditions, the analyst uses ordinary algebra to describe the governing equations for source strength, flow and fate of the contaminants, exposures and toxicities—all to make a point estimate of the human health risk in the Risk Characterization step of the risk assessment.

To illustrate the Monte Carlo method with a simplified example, Exhibit 1 shows a spreadsheet for estimating the health risks to adults weighing 70 kg who are exposed to eight carcinogenic and eight non-carcinogenic polycyclic aromatic hydrocarbons (PAHs) over a 70-yr lifetime via the single pathway of chronic inadvertent ingestion of soil containing 100 mg/kg of each compound. The spreadsheet uses these formulae to calculate: (1) the estimated Incremental Lifetime Risk and (2) the estimated Hazard Index from the exposure:

$$ILR = \frac{\text{Conc} \cdot \text{Ing} \cdot \text{BAF} \cdot \text{CPF}}{\text{BW} \cdot 1.E+6} \quad (1)$$

$$HI = \frac{\text{Conc} \cdot \text{Ing} \cdot \text{BAF}}{\text{BW} \cdot \text{RfD} \cdot 1.E+6} \quad (2)$$

where:

ILR = Incremental Lifetime Risk of Cancer from Exposure
(0 ≤ probability ≤ 1)

HI = Hazard Index from Exposure
(0 ≤ fraction)

Conc = Concentration of the Compound in the Soil
(mg/kg)

Ing = Mass of Contaminated Soil Ingested per Day
(mg/d)

BAF = BioAvailability Factor (relative to water)
(0 ≤ fraction ≤ 1)

CPF = Cancer Potency Factor of the Compound
(inverse mg/(kg•d))

RfD = Reference Dose for the Compound
(mg/(kg•d))

BW = Body Weight
(kg)

1.E + 6 = factor to make units commensurable

Using reference doses (RfDs) and relative cancer potency factors recently developed,^{11, 14} using the assumption that each person inadvertently ingests 100 mg/d of the contaminated soil and using the assumption that the relative bioavailability of the PAHs from the soils is 0.5, the spreadsheet calculates that a person has a estimated Incremental Lifetime Risk of cancer of 2.2-03 (probability point estimate) and an estimated Hazard Index of 2.4E-01 from this single exposure pathway. These point estimates are interpreted as protective of public health. Without information on synergisms or antagonisms, the overall Risk and Hazard Index are estimated by summing the values for each compound across all pathways. Following a short qualitative discussion of uncertainties inherent in the different variables, most risk assessments would stop with these point estimates.

The Monte Carlo method continues with several additional steps, all keyed into the existing spreadsheet. First, the analyst determines (continuous or discrete) probability density functions¹² to describe each variable included in the uncertainty analysis. In this step, the analyst must also determine if any correlations exist among the input variables and make appropriate calculations if they do. Second, using software such as Crystal Ball™ the analyst makes a large number (say, 2,000 to 5,000) of “realizations” of the model. Third, the analyst views the results to establish: (1) the range of results, (2) the shape of the distribution of results and (3) appropriate statistical summaries of the results, such as the arithmetic average, the median and various quantiles^{5, 6}.

In terms of the spreadsheet in Table 1, the Monte Carlo technique approximates the PDF for the final estimate after assigning PDFs to some or all of these input variables: (1) the body weight, (2) the volume of soil inadvertently ingested each day, (3) the relative bioavailability of the PAH from the soil and/or (4) the CPFs and RfDs. Because the input variables enter the formulae by multiplication and division (and subsequent summation), and because some or all of the input variables may not have normal distributions, the PDF for the final estimate is, in general, nonGaussian in shape.

SPECIFICATION OF DISTRIBUTIONS FOR THE INPUT VARIABLES

To illustrate the method, we have estimated the PDFs for the Incremental Lifetime Risk and Hazard Index for several scenarios using these assumptions: First, the weight of an adult is normally distributed with a mean of 70 kg and a standard deviation of 10 kg.²⁴ Second, the amount of soil that an adult inadvertently ingests each day is lognormally distributed with a log mean of 3 units and a log standard deviation of 1 unit. In keeping with LaGoy,⁶ this PDF sets the mean ingestion at 33 mg/day and sets the 93 percentile of ingestion at 100 mg/day. Third, based on professional judgment, the relative bioavailability is represented by a triangular distribution with vertices at 0.2, 0.5 and 0.6. Fourth, the CPFs and RfDs are independently distributed as lognormal variates, as discussed in the appendix.

By assumption, each of these distributions is statistically independent of the others. Each of these assumptions is reasonable (or not unreasonable) in view of the current knowledge and belief. We do not offer detailed justifications for each of the assumption here because

PAH	Conc in Soil (mg/kg)	ICF Published Oral RfD (mg/kg•d)	Unit Normal (rv)	Random Variate Oral RfD (mg/kg•d)	EPA Published Oral CPF (mg/kg•d)-1	ICF Relative Potency (ratio)	Unit Normal (rv)	(Random Variate) Oral CPF (mg/kg•d)-1	Estimated Bioavailable ADD (life) (mg/kg•d)	Estimated Hazard Index (frac)	Estimated Incremental Lifetime Risk (frac)
.....
PAH Compounds Considered Potentially Carcinogenic											
benzo(a)pyrene	100	1.0E-02	0.0	1.0E-02	1.15E+01	1.00E+00	0.0	1.15E+01	7.14E-05	7.1E-03	8.2E-04
benzo(a)anthracene	100	1.0E-02	0.0	1.0E-02		1.45E-01	0.0	1.67E+00	7.14E-05	7.1E-03	1.2E-04
benzo(b)fluoranthene	100	1.0E-02	0.0	1.0E-02		1.40E-01	0.0	1.61E+00	7.14E-05	7.1E-03	1.2E-04
benzo(k)fluoranthene	100	1.0E-02	0.0	1.0E-02		6.60E-02	0.0	7.59E-01	7.14E-05	7.1E-03	5.4E-05
indeno(1,2,3-cd)pyrene	100	1.0E-02	0.0	1.0E-02		2.32E-01	0.0	2.67E+00	7.14E-05	7.1E-03	1.9E-04
chrysene	100	1.0E-02	0.0	1.0E-02		4.40E-03	0.0	5.06E-02	7.14E-05	7.1E-03	3.6E-06
dibenzo(a,h)anthracene	100	1.0E-02	0.0	1.0E-02		1.11E+00	0.0	1.28E+01	7.14E-05	7.1E-03	9.1E-04
benzo(ghi)perylene	100	1.0E-02	0.0	1.0E-02		2.20E-02	0.0	2.53E-01	7.14E-05	7.1E-03	1.8E-05
PAH Compounds Not Considered Potentially Carcinogenic											
naphthalene	100	5.0E-03	0.0	5.0E-03					7.14E-05	1.4E-02	
fluorene	100	5.0E-03	0.0	5.0E-03					7.14E-05	1.4E-02	
anthracene	100	5.6E-04	0.0	5.6E-04					7.14E-05	1.3E-01	
phenanthrene	100	7.0E-03	0.0	7.0E-03					7.14E-05	1.0E-02	
fluoranthene	100	2.0E-02	0.0	2.0E-02					7.14E-05	3.6E-03	
pyrene	100	1.5E-02	0.0	1.5E-02					7.14E-05	4.8E-03	
acenaphthylene	100	1.0E-02	0.0	1.0E-02					7.14E-05	7.1E-03	
acenaphthene	100	2.0E-01	0.0	2.0E-01					7.14E-05	3.6E-04	
									
										Sums -->>	2.4E-01 2.2E-03
Assumptions:											
	Adult Weight (kg)	Soil Ingestion (mg/d)	Bioavail (ratio)	Toggle NC (0 1)				Toggle C (0 1)			
			
	70.0	100.0	0.5	0.0				0.0			

Table 1
Sample Spreadsheet for Estimating Health
Effects from Ingesting Soil Contaminated
with PAHs

our primary focus is to demonstrate a new computational framework. At this time, we investigate the effects of these assumptions without further justification. However, we have additional research underway to refine, support and document the assumptions.

RESULTS

Printed from Crystal Ball™, Figure 1 shows the histogram of estimated risk with the assumptions that body weight, soil ingestion and bioavailability are represented by the PDFs in the previous section and that the CPFs and RfDs are point values. Similarly, Figure 2 shows the histogram of estimated risk with the assumptions that body weight, soil ingestion, bioavailability, CPFs, and RfDs are all random variates described by the PDFs in the previous section.

Forecast: Sum of Risk

Summary: Confidence Level is 1.00e+2% based on Entire Range
Confidence Range is from $-\infty$ to $+\infty$
Display Range is from 0.00e+0 to 1.00e-2
Entire Range is from 1.16e-5 to 1.31e-2
After 3e+3 Trials, the Std. Error of the Mean is 1.72e-5

Statistics:	Display Range	Entire Range
Trials	3e+3	3e+3
Percent of Other	9.99e+1	1.00e+2
Mean	6.85e-4	6.93e-4
Median	3.97e-4	(unavailable)
Mode	8.33e-5	(unavailable)
Standard Deviation	8.95e-4	9.43e-4
Variance	8.00e-7	8.89e-7
Skewness	3.91e+0	(unavailable)
Kurtosis	2.49e+1	(unavailable)
Range Width	1.00e-2	1.30e-2
Range Minimum	0.00e+0	1.16e-5
Range Maximum	1.00e-2	1.31e-2
Mean Std. Error	1.63e-5	1.72e-5

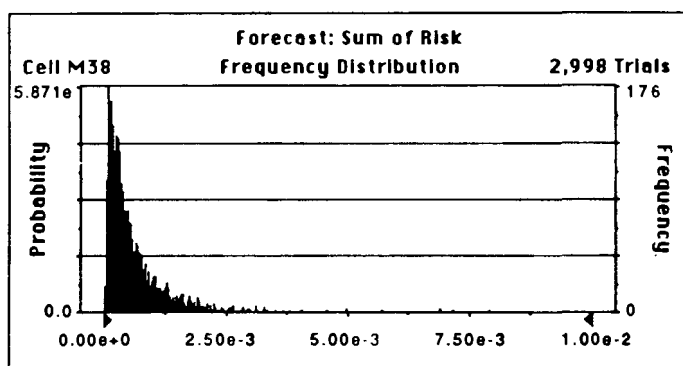


Figure 1

Histogram for Estimated Incremental Lifetime Cancer Risk with Three Exposure Variables as Random Variates

These two graphs show the results of several thousand simulations to quantify the uncertainties. For the type of health risk calculations investigated here, Monte Carlo simulations with inputs described by random variables yield strongly nonGaussian distributions for estimated health risk. As the number of random inputs increases, the histogram for the health risk becomes increasingly nonGaussian and the relative standard deviation increases.

Table 2 presents statistics for the deterministic case and five probabilistic cases, demonstrating the effects of turning one input at a time into a random variable. For example, the 95-percentile estimate of the overall cancer risk in the last numerical column is 6.75E-04, less than the conservative point estimate of 2.20E-03 in the deterministic case in the first numerical column.

Based on theoretical considerations, on the practical experience and on the simulations reported here, we find that the greatest uncertainty in the shape and location of the PDF for estimated human health risk comes from the uncertainties in the shapes and positions of the PDFs for toxicities.

Forecast: Sum of Risk

Summary: Confidence Level is 1.00e+2% based on Entire Range
Confidence Range is from $-\infty$ to $+\infty$
Display Range is from 0.00e+0 to 1.00e-2
Entire Range is from 7.76e-7 to 4.87e-3
After 5e+3 Trials, the Std. Error of the Mean is 4.38e-6

Statistics	Display Range	Entire Range
Trials	5e+3	5e+3
Percent of Other	1.00e+2	1.00e+2
Mean	1.83e-4	1.83e-4
Median	8.84e-5	8.84e-5
Mode	1.87e-5	1.87e-5
Standard Deviation	3.10e-4	3.10e-4
Variance	9.60e-8	9.60e-8
Skewness	5.43e+0	5.43e+0
Kurtosis	4.83e+1	4.83e+1
Range Width	1.00e-2	4.87e-3
Range Minimum	0.00e+0	7.76e-7
Range Maximum	1.00e-2	4.87e-3
Mean Std. Error	4.38e-6	4.38e-6

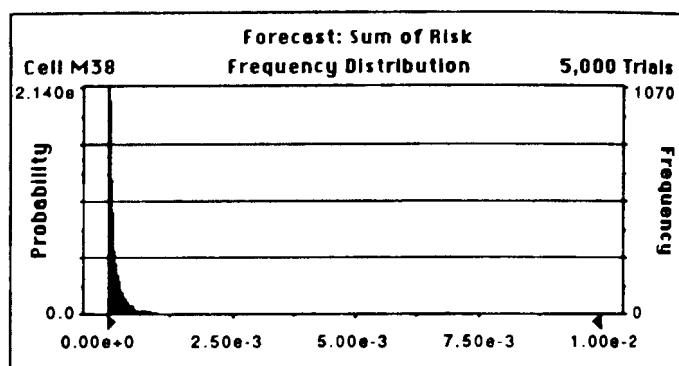


Figure 2

Histogram for Estimated Incremental Lifetime Cancer Risk with Three Exposure Variables and Two Toxicities as Random Variates

Table 2
Summary of Scenarios for Cancer Risk from Ingesting Contaminated Soil

Weight	70	100	100	100	100	100
Soil Ingestion	100	100	100	100	100	100
BioAvailability	0.8	0.8	0.8	0.8	0.8	0.8
CPF's	Based	Based	Based	Based	Based	Based
RfD's	Based	Based	Based	Based	Based	Based
Statistics						
max	2.20E-03	4.08E-03	1.05E-02	1.31E-02	6.82E-03	4.87E-03
95p	2.20E-03	2.83E-03	2.83E-03	2.18E-03	1.88E-03	6.75E-04
75p	2.20E-03	2.47E-03	2.47E-03	1.98E-03	1.68E-03	1.88E-04
50p	2.20E-03	2.25E-03	2.25E-03	1.88E-03	1.68E-03	1.88E-04
25p	2.20E-03	2.03E-03	2.03E-03	1.94E-03	1.88E-03	1.88E-04
1p	2.20E-03	1.81E-03	1.81E-03	1.91E-03	1.88E-03	1.88E-04
min	2.20E-03	1.80E-03	1.80E-03	1.16E-03	1.88E-03	1.88E-04
average	2.20E-03	2.88E-03	2.88E-03	2.83E-03	2.88E-03	2.88E-03
std dev	2.20E-03	3.88E-04	3.88E-04	3.88E-04	3.88E-04	3.88E-04
mode	2.20E-03	2.05E-03	2.05E-03	2.05E-03	2.05E-03	2.05E-03
trials	100	2,000	3,000	3,000	3,000	6,000

APPENDIX: GENERIC DISTRIBUTIONS FOR CPFs AND RfDs

Carcinogens: For their CPFs for compounds tested in small mammals, the U.S. EPA commonly sets the value as the 95% upperbound of the slope, scaled to human adults, of the linearized multistage model relating the dose administered in the laboratory and the toxicological response in test mammals.²¹ From Agency publications, it is not possible to infer the underlying probability distributions from which the published CPFs represent the 95% upper confidence limits. In the absence of data or knowledge on the shape of the underlying distribution for CPFs in humans, it is possible to hypothesize a variety of distributions, one of which is investigated in this paper.

The lognormal model for a generic CPF distribution is based on research by Crouch and his colleagues^{7, 8, 9} and on the often spoken statement that the uncertainty in the variate may be as large as a factor

of 10 above the central measure and as low as a factor of 10 below the central measure of the distribution. This suggests a lognormal model for the underlying distribution. By fixing two standard deviations of the logarithm of the random variate at 10, and by scaling the distribution so the 95% fractile of the cumulative distribution function falls at the published CPF value, this function has the appropriate properties:

$$x1 \sim (\text{CPF} / 6.645) \cdot \exp [1.1513 \cdot N(0,1)] \quad (3)$$

Non-Carcinogens: Similarly, the U.S. EPA commonly establishes RfDs for compounds that are one, two, three or four orders of magnitude below NOAEL values from animal experiments. One of the factors of 10 accounts for inter-individual variability in susceptibility. Hattis and his co-workers¹³ have found that some inter-individual susceptibilities are distributed lognormally. On the assumption that four standard deviations of the logarithm of susceptibility equal a factor of five and that two standard deviations above the mean of the logarithm of the susceptibility fall at the factor of 10 used by the U.S. EPA, this function has the appropriate generic properties:

$$x2 \sim (2.236 \cdot \text{RfD}) / \exp [0.402 \cdot N(0,1)] \quad (4)$$

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REFERENCES

1. Allen, B.C., Shipp, A.M., Crump, K.S., Kilina, B., Hogg, M.L., Tudor, J. and Keller, B., "Investigation of Cancer Risk Assessment Methods," Final Report Summary, prepared for the U.S. EPA by Clement Associates, Inc., Jan. 1987.
2. Burmaster, D.E. and von Stackelberg, K., "Monte Carlo Simulations of Uncertainties in Risk Assessments of Superfund Sites Using Crystal Ball," *Proc. of the 1989 Nat. Conf. on Environmental Engineering, ASCE*, July 1989.
3. Burmaster, D.E. and von Stackelberg, K., "A New Method for Uncertainty and Sensitivity Analysis in Public Health Risk Assessments at Hazardous Waste Sites Using Monte Carlo Techniques in a Spreadsheet," *Superfund '88, Proc. of the 9th Nat. Conf.*, Washington, DC, HMCRI, Silver Spring, MD; Nov. 1988, 550-556.
4. Campbell, J.E. and Cranwell, R.M., "Performance Assessment of Radioactive Waste Repositories, Science," Mar. 18, 239, 1389-1392
5. Chambers, J.M., *Graphical Methods for Data Analysis*, Wadsworth International Group, Belmont, CA, 1983.
6. Cleveland, W.S., *The Elements of Graphing Data*, Wadsworth Advanced Books and Software, Monterey, CA, 1985.
7. Crouch, E.A.C., Wilson, R. and Zeise, L., "The Risks of Drinking Water," *Water Resources Research*, 191983, 1359-1375.
8. Crouch, E.A.C., "Uncertainties in Interspecies Extrapolations of Carcinogenicity," *Environ. Health Persp.* 50, 1983, 321-327.
9. Crouch, E. and Wilson, R., "Regulation of Carcinogens," *Risk Analysis*, 1, 1981, 47-57.
10. Eschenroeder, A.Q. and Faeder E.J., "A Monte Carlo Analysis of Health Risks from PCB-Contaminated Mineral Oil Transformer Fires," *Risk Analysis*, 8, 1988, pp 291-297.
11. Environ Corporation, "Potential Health Risks from Former Manufactured Gas Plants Sites: Toxicity and Chemical Profiles." Prepared for Pacific Gas and Electric Company, Southern California Edison, and the Southern California Gas Company, 1986.
12. Hastings, N.A.J. and Peacock, J.B., "Statistical Distributions: A Handbook for Students and Practitioners," Butterworth & Company, London, 1974.
13. Hattis, D., Erdreich, L. and Ballew, M., "Human Variability in Susceptibility to Toxic Chemicals—A Preliminary Analysis of Pharmacokinetic Data from Normal Volunteers," *Risk Analysis*, 7, 1987, 415-426.
14. ICF-Clement Associates, Inc., "Comparative Potency Approach for Estimation of the Total Cancer Risk Associated with Exposures to Mixtures of Polycyclic Aromatic Hydrocarbons in the Environment," Final Report, Washington, DC, 1987.
15. Iman, R.L. and Helton, J.C., "An Investigation of Uncertainty and Sensitivity Analysis Techniques for Computer Models," *Risk Analysis*, 8, 1988, 71-90.
16. LaGoy, P.K., "Estimated Soil Ingestion Rates for Use in Risk Assessment," *Risk Analysis*, 7, 1987, 355-359.
17. Market Engineering Corporation, 1988, Crystal Ball™ User's Guide, Suite 600, 1675 Larimer Street, Denver, CO, 1988.
18. Morgan, B.J.T., *Elements of Simulation*. Chapman and Hall, London, 1984.
19. Palisade Corporation, Newfield, NY, 1988.
20. Rubenstein, R.Y., *Simulation and the Monte Carlo Method*, John Wiley & Sons, New York, NY, 1981.
21. U.S. EPA, "Exposure Factors Handbook, Final Report," Office of Health and Environmental Assessment, EPA/660/8-89/043, March 1989.
22. U.S. EPA, *Superfund Public Health Evaluation Manual*, EPA/540/1-86/060, OSWER Directive 9285.4-1, Oct. 1986.
23. U.S. EPA, *Superfund Exposure Assessment Manual*, OSWER Directive 9285.5-1, Dec. 1986.
24. U.S. Department of Health, Education, and Welfare, "1979, Weight and Height of Adults, 18-74 Years of Age, United States, 1971-1974," Office of Health Research, Statistics, and Technology, Washington, DC, May 1979.
25. Whitmore, R.W., "Methodology for Characterization of Uncertainty in Exposure Assessments," a report from the Research Triangle Institute to the Office of Health and Environmental Assessment, U.S. EPA, EPA/600/8-85/0009, Aug. 1985.

Use of a Retention Index System to Better Identify Non-Target Compounds

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ABSTRACT

A thorough assessment of the health risks posed by hazardous waste sites requires that the chemical pollutants present be well characterized. Because the typical "Target Compound List" analysis provides for the specific determination of only 126 organic compounds, the identification of any other chemicals amenable to GC/MS analysis depends upon them being reported as "Tentatively Identified Compounds" (TIC). Proper identification of such TICs can be critical to the completeness of site-specific risk analysis.

TICs are non-target compounds found during a GC/MS run, which are identified solely by a reverse search of their mass spectra versus the NIST/EPA/MSDC mass spectral library. Because no use currently is made of GC retention time data in identifying TICs, the identifications are less accurate than for target compounds. Given the increasing interest in using TIC data in risk analysis and other Superfund-related activities, the Contract Laboratory Program (CLP) has begun to improve the process by which TICs are identified. The first step will be to make better use of the GC retention time data.

This paper reports the analysis of GC retention time data for TICs in the CLP Analytical Results Database (CARD). CARD is the computer data base in which organic and inorganic analysis results generated by CLP Laboratories for Superfund are stored. We have applied the retention index (RI) system of Lee et al.¹ to the semi-volatile TIC data in CARD in order to validate the TIC data and to test the RI System for use in TIC data reporting and review. Lee's RI system is based on polycyclic aromatic hydrocarbons (PAH) where the index values are naphthalene = 200, phenanthrene = 300, chrysene = 400 and picene = 500.

CARD has data on the GC retention times of TICs and on those of naphthalene-d8, phenanthrene-d10, chrysene-d12 and perylene-d12 which are internal standards added to each sample. This database enabled us to directly calculate RIs for all TICs which eluted between naphthalene-d8 and perylene-d12. Preliminary comparison of the RI data from the TICs to the RI values reported by Lee, et al., shows excellent agreement. Retention indices for non-target PAH were generally within five points of the expected values. Many non-PAH compounds also showed statistically well-behaved RIs which agreed with those from U.S. EPA method 1625C.

INTRODUCTION

The organic chemical analysis methods currently specified by Superfund's Contract Laboratory Program (CLP) provide for the analysis of 126 target compounds (the "Target Compound List" or TCL) by gas chromatography (GC) and GC-mass spectrometry (GC-MS). Up to 30 "tentatively identified compounds" (TICs) per sample must also be reported by comparison of the mass spectra of non-TCL peaks

in the GC-MS chromatograms to the approximately 40,000 to 50,000 mass spectra in the NIST/U.S. EPA/MSDC data base. Because no actual chemical standards are routinely used to confirm the identity of TICs and because the amount of time that can be devoted to spectral interpretation in commercial, production-oriented laboratories is limited, both the identity and concentrations of reported TICs are far less accurate than they are for the target compounds.

CLP management recognizes that the proper identification and reporting of tentatively identified compounds is becoming a more important issue. For example, thorough risk assessment at hazardous waste sites depends on the proper identification of potentially toxic compounds. Also, TIC data are being used to fulfill studies mandated under the Superfund reauthorization, such as the listing of the 275 most common toxic substances found at waste sites, which is being conducted by the Agency for Toxic Substances and Disease Registry. TIC identifications must be reliable if policy decisions are to be made using them.

To address the need for better TIC data reporting, the CLP established the Tentatively Identified Compounds Improvements Workgroup at its Organics Conference in October, 1988. The Workgroup is responsible for devising methods for more reliable identification of non-target compounds; it consists of members from the U.S. EPA and other government research laboratories and U.S. EPA Regions, the laboratory community, instrument manufacturers and other interested parties.

One area being explored by the Workgroup is the use of Retention Index (RI) systems based on the use of GC retention time data. Under a given set of conditions, the Retention Index is a predictable characteristic of a given compound and can be used to identify it. The use of Retention Indices is particularly attractive, since GC retention time data for TICs currently are reported by CLP laboratories in computer-readable form (diskette) and since no systematic use currently is made of GC retention time data to identify TICs. Thus the number of pieces of data used to identify TICs can easily be increased from one (mass spectrum) to two (mass spectrum and retention index).

This paper will consider the use of a Retention Index system based on Polycyclic Aromatic Hydrocarbons (PAH) to evaluate data from semi-volatiles analysis.

METHODS

The PAH Retention Index system was first proposed in 1979 by Lee, et al.,¹ and was extended by Willey, et al.,² and Vassilaros, et al.,³. Whalen-Pederson and Jurs⁴ devised a system to predict the Retention Index of a PAH using molecular structure descriptors. More recently, the prediction of Retention Indices by multivariate regression analysis of molecular structure descriptors has been extended to mononitrated PAHs and polychlorinated biphenyls by Robbat and co-workers^{5,6}.

The PAH Retention Index system is based on naphthalene (RI=200),

Table 1
Polycyclic Aromatic Hydrocarbons and Heterocyclics Comparison of
Literature Retention Indices and Tentatively Identified
Compound Retention Indices

Compound	CAS No.	Number	Liter RI	Median	Differ1	Mean	Differ2	STD_DEV	Minimum	Maximum
1. Benzothiophene	95158	38	201.47	202.28	-0.81	202.5	-1.03	1.27	202.01	210.04
2. 1H-Indole	120729	3	205.26	222.28	-17.02	221.61	-16.35	1.15	220.29	222.28
3. Isoquinoline	119653	5	215.61	210.04	5.57	210.88	4.73	2.28	208.66	214.68
4. Azulene	275514	3	219.95	200.67	19.28	200.68	19.27	0.13	200.56	200.82
5. Naphthalene, 1-methyl-	90120	155	221.04	225.42	-4.38	225.27	-4.23	1.64	219.06	234.52
6. Quinoline, 2-methyl-	91634	8	224.13	224.58	-0.45	224.6	-0.47	2.09	222.28	228.98
7. 1,1'-Biphenyl	92524	71	233.96	237.5	-3.54	237.34	-3.38	1.05	233.72	238.82
8. Naphthalene, 2-ethyl-	939275	15	236.08	239.67	-3.59	242.08	-6	4.87	234.52	250.82
9. Naphthalene, 1-ethyl-	1127760	9	236.56	240.17	-3.61	240.24	-3.68	0.61	239.54	241.54
10. Naphthalene, 2,6-dimethyl-	581420	3	237.58	241.18	-3.6	242.35	-4.77	2.13	241.06	244.8
11. Naphthalene, 2,7-dimethyl-	582161	4	237.71	241.67	-3.96	242.55	-4.84	1.85	241.54	245.32
12. 1,1'-Biphenyl, 2-methyl-	643583	7	238.77	275.3	-36.53	275.15	-36.38	0.95	273.67	276.07
13. Naphthalene, 1,3-dimethyl-	575417	24	240.25	244.03	-3.78	243.74	-3.49	1.95	239.92	250.5
14. Naphthalene, 1,7-dimethyl-	575371	19	240.66	243.65	-2.99	243.18	-2.52	1.61	240.51	246.51
15. Naphthalene, 1,6-dimethyl-	575439	18	240.72	241.85	-1.13	241.65	-0.93	1.52	238.73	244.15
16. Naphthalene, 2,3-dimethyl-	581408	38	243.55	244.17	-0.62	244.18	-0.63	1.62	240.75	250.84
17. Naphthalene, 1,4-dimethyl-	571584	14	243.57	245.9	-2.33	246.62	-3.05	2.57	242.7	250.98
18. Naphthalene, 1,5-dimethyl-	571619	24	244.98	241.33	3.65	241.47	3.51	0.85	240.35	244.17
19. Naphthalene, 1,4-dimethyl-	573988	33	246.49	244.96	1.53	245.77	0.72	2.23	241.6	250.4
20. Naphthalene, 1,8-dimethyl-	569415	40	249.52	244.43	5.09	245.02	4.5	2.32	241.11	250.98
21. 1,1'-Biphenyl, 4-methyl-	644086	9	254.71	273.77	-19.06	274.15	-19.44	1.14	272.89	275.78
22. Naphthalene, 2,3,6-trimethyl-	829265	20	263.31	262.64	0.67	263.31	0	1.83	261.08	267.2
23. 9H-Fluorene, 9-methyl-	2523377	5	272.38	289.77	-17.39	289.52	-17.14	0.57	288.51	289.93
24. 5H-Indeno<1,2-b>pyridine	244995	11	279.31	309	-29.69	309.16	-29.85	0.99	307.78	310.89
25. Anthracene, 9,10-dihydro-	613310	3	284.89	285.09	-0.2	286.63	-1.74	2.75	285	289.81
26. 9H-Fluorene, 2-methyl-	1430973	7	288.21	288.62	-0.41	288.93	-0.72	1.07	287.38	290.64
27. 9H-Fluorene, 1-methyl-	1730376	10	289.03	288.48	0.55	288.41	0.62	0.32	287.85	288.82
28. 9H-Fluorene-9-one	486259	13	294.79	294.4	0.39	294.74	0.05	0.76	293.91	296.32
29. Dibenzothiophene	132650	91	295.81	296.68	-0.87	296.67	-0.86	0.33	295.34	298.2
30. Acridine	260946	3	304	309.53	-5.53	308.76	-4.76	1.33	307.22	309.53
31. 9H-Carbazole	86748	56	312.13	309.36	2.77	309.34	2.79	0.87	306.82	312.09
32. Dibenzothiophene, 4-methyl-	7372885	3	312.72	312.79	-0.07	312.81	-0.09	0.11	312.72	312.93
33. Naphthalene, 1-phenyl-	605027	5	315.19	312.92	2.27	329.73	-14.54	23.47	312.32	356.64
34. Phenanthrene, 3-methyl-	832713	19	319.46	320.35	-0.89	320.53	-1.07	1.52	318.58	324.64
35. Phenanthrene, 2-methyl-	2531842	29	320.17	319.62	0.55	320	0.17	0.82	319.16	322.24
36. Anthracene, 2-methyl-	613127	58	321.57	320.24	1.33	320.48	1.09	1.66	316.6	324.58
37. Terphenyl	26140603	3	321.99	385.9	-63.91	385.59	-63.6	1.16	384.31	386.57
38. 4H-Cyclopenta<def>phenanthrene	203645	58	322.08	323.38	-1.3	323.62	-1.54	1.27	319.05	329.46
39. Phenanthrene, 9-methyl-	883205	18	323.06	321.25	1.81	320.99	2.07	1.49	318.99	324.15
40. Phenanthrene, 4-methyl-	832644	40	323.17	323.22	-0.05	322.07	1.1	2.2	316.73	327.32
41. Anthracene, 1-methyl-	610480	30	323.33	320.07	3.26	320.52	2.81	1.46	318.34	323.61
42. Phenanthrene, 1-methyl-	832699	7	323.9	320.35	3.55	321.16	2.74	3.63	315.82	326.84
43. 9,10-Anthracenedione	84651	59	330.53	331.2	-0.67	330.89	-0.36	1.02	327.45	333.98
44. Naphthalene, 2-phenyl-	612942	26	332.59	330.68	1.91	330.74	1.85	0.52	329.91	331.82
45. Phenanthrene, 3,6-dimethyl-	1576676	9	337.83	337.93	-0.1	338.92	-1.09	2.23	335.79	342.92
46. Phenanthrene, 2,7-dimethyl-	1576698	3	339.23	333.93	5.3	336.4	2.83	4.67	333.48	341.79
47. 9-Anthracenecarbonitrile	1210124	4	350.6	360.07	-9.47	360	-9.4	0.38	359.51	360.34
48. 11H-Benzo<a>fluorene	238846	135	366.74	367.09	-0.35	366.92	-0.18	2.15	362.61	372.72
49. Phenanthrene, 1-methyl-7-(1-methylethyl)-	483658	10	368.67	366.71	1.96	366.2	2.47	1.47	364.42	368.23
50. 11H-Benzofluorene	243174	39	369.39	367.19	2.2	366.79	2.6	2.01	362.17	370.07
51. Pyrene, 4-methyl-	3353126	55	369.54	370.98	-1.44	371.35	-1.81	2.85	363.64	375.47
52. Pyrene, 2-methyl-	3442782	18	370.15	370.8	-0.65	370.24	-0.09	2.61	366.33	374.64
53. Pyrene, 1-methyl-	2381217	42	373.55	367.17	6.38	368.02	5.53	2.67	363.21	374.39
54. Benzonaphtho<2,1-d>thiophene	239350	15	389.21	390.43	-1.22	390.43	-1.22	0.41	389.96	391.65
55. Benzo<ghi>fluoranthene	203123	33	389.6	391.97	-2.37	392	-2.4	0.69	390.93	394.83
56. Benzo<c>phenanthrene	195197	47	391.39	391.86	-0.47	395.87	-4.48	5.74	390	404.69
57. Benzonaphtho<1,2-d>thiophene	205436	20	392.92	390.28	2.64	389.88	3.04	1.29	386.32	391.65
58. Cyclopenta<c>pyrene	27208373	3	396.54	392.12	4.42	394.18	2.36	3.91	391.72	398.69
59. Triphenylene	217594	3	400	403.95	-3.95	403.07	-3.07	1.75	401.05	404.19
60. Benz<a>anthracene, 11-methyl-	6111780	5	412.72	413.8	-1.08	413.64	-0.92	0.98	412.48	414.73
61. Benz<a>anthracene, 1-methyl-	2498773	7	414.37	416.67	-2.3	417.64	-3.27	3.51	412.22	422.15
62. Benz<a>anthracene, 8-methyl-	2381319	3	417.56	407	10.56	406.36	11.2	1.47	404.69	407.41
63. Chrysene, 3-methyl-	3351313	20	418.1	416.07	2.03	416.19	1.91	2.39	412.82	421.77
64. Benz<a>anthracene, 12-methyl-	2422799	12	419.39	417.33	2.06	417.96	1.43	2.2	415.45	421.33
65. Chrysene, 5-methyl-	3697243	3	419.68	414.14	5.54	414.33	5.35	0.73	413.73	415.14
66. Benz<a>anthracene, 7-methyl-	2541697	11	423.14	415.37	7.77	414.77	8.37	1.39	412.23	416.04
67. 2,2'-Binaphthalene	612782	4	423.91	424.11	-0.2	426.39	-2.48	4.68	423.93	433.41
68. Benzo<j>fluoranthene	205823	149	440.92	451.24	-10.32	450.21	-9.29	3.37	442.68	455.59
69. Benzo<e>pyrene	192972	48	450.73	450.96	-0.23	450.40	0.33	2.26	444.06	453.79

phenanthrene (RI=300), chrysene (RI=400) and picene (RI=500). The Retention Index is calculated by interpolation between the bracketing standards:

$$RI = 100 \times \frac{(RT_{\text{UNKNOWN}} - RT_{Z_2})}{(RT_{Z+1} - RT_{Z_2})} + 100(Z) \quad (1)$$

where RT_{Z_2} and RT_{Z+1} are the retention times of the standards before and after the unknown and Z is 2 for naphthalene, 3 for phenanthrene and 4 for chrysene.

The semi-volatile analysis method used by the CLP (based on U.S. EPA Method 625) employs the perdeuterated analogues of naphthalene, phenanthrene and chrysene as internal standards; perdeuterated perylene (RI=456.22) is also an internal standard. These internal standards are added to all semi-volatile samples for quantitation purposes. The retention times of all of these internal standards, as well as of all TICs and all other results and QC data, are reported on floppy diskette by CLP organics laboratories. Prior to uploading the diskette data to the CLP Analytical Results Database (CARD), the data are stored in SAS (Statistical Analysis System) files on the U.S. EPA mainframe computer at Cincinnati, Ohio. An extract was made from these files which contained the Chemical Abstracts Service Registry number (CAS Number) and retention time of all semi-volatile TICs reported and the retention times, from the same samples, of the four internal standards mentioned. Only data for which valid CAS numbers was reported was retained. Retention Indices were then calculated using Equation 1 and the four perdeuterated internal standards as retention index markers. For compounds eluting between chrysene and perylene, Equation 1 was modified so that the retention time term was multiplied by 56.22, not 100. The calculated Retention Indices were analyzed using the SAS procedure UNIVARIATE and were compared to the values in references 1 to 3. Table 1 shows the result of this analysis, including the name and CAS number of reported PAHs and heterocyclic compounds, the number of times each was reported as a TIC, the trimmed mean (± 2 standard deviations) of the Retention Index, the standard deviation of the RI, the median, minimum and maximum RI, and for comparison, the literature value of the RI.

RESULTS

PAH and related compounds

Of 878 semi-volatile TICs reported in the CARD data (through Aug. 1, 1989) which were reported to elute between naphthalene and perylene, 69 PAHs had RI values reported in the literature.^{1,3} Agreement between the literature values for RIs and the means and medians from the CARD data is quite good, especially considering that the RI system was not originally used in reporting the data. This result may be due in part to the fact that condensed aromatic compounds such as these have mass spectra with strong molecular ions, which would tend to make library searching more reliable. Inspection of Table 1, which is sorted by the literature value of the RI, shows that similar compounds (e.g., ethylnaphthalenes/dimethylnaphthalenes or methylanthracenes/methylphenanthrenes) have not been completely distinguished from each other by library matching alone. The mean and median RI values calculated from CARD for compounds in these groups appear to be average values for the entire groups. If the retention indices for such groups are plotted, multi-modal distributions indicative of the presence of several compounds are obtained, as in Figure 1. On the other hand, 1-phenylnaphthalene (33) and 2-phenylnaphthalene (44) are nicely distinguished.

There are eight PAH compounds for which agreement between the literature RI values and those calculated from CARD is poor. These are 5H-indeno (1,2-b) pyridine, 4-methylbiphenyl, 2-methylbiphenyl, 9-methylfluorene, indole, 8-methylbenz(a)anthracene, terphenyl and azulene. The possible reasons for the poor agreement include errors in library matching, variations in the initial GC oven temperature and changes in the chemical nature of the stationary phase with extended use. It also appears that azulene may be confused with naphthalene, and

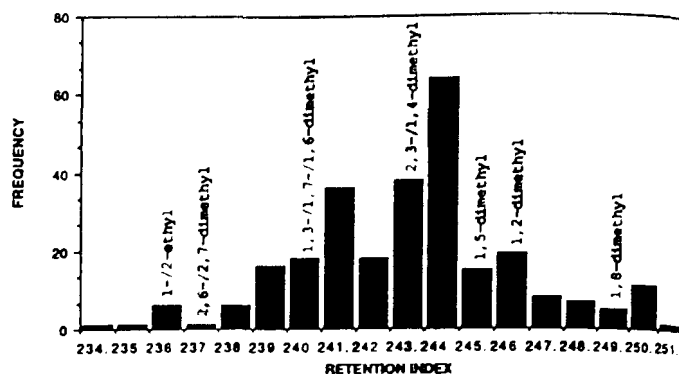


Figure 1
Retention Indices for C2-naphthalenes

indole with methylquinoline.

Regression analyses of the literature RI values for PAHs versus the median RIs from CARD were conducted using the SAS procedure PROC REG. When the regression was performed on the median RI of all 69 compounds versus the literature values, the explained variance was 97.55%. Removal of the eight compounds, mentioned above, for which the residual was over 10 index points, resulted in an explained variance of 99.75%. Clearly there is a strong relationship between the literature RI values and those calculated from CARD. This suggests that most of the 69 compounds in Table 1 have been correctly identified, at least at the structural isomer level.

These results show that systematic application of the PAH Retention Index system, by contract laboratories, in conjunction with mass spectral library searching, might result in greatly enhanced qualitative identification of non-target compounds. Better quantitation would depend on methods for better estimating calibration response factors.

Non-PAH Compounds

The utility of this RI system would be greatly improved by extending it to non-PAH compounds. Retention time information for many compounds which are not on the CLP Target Compound List has been published in the Office of Water's method 1625C⁹ and in method 525 for drinking water¹⁰. Retention indices were calculated from the method 1625 data for 23 compounds and compared to those from the CARD data; the results are presented in Table 2.

The poor RI matching for some of the normal alkanes is probably a result of poor library matching due to the similarity of all alkane spectra. In contrast to PAHs, alkanes have a very weak or no molecular ion, with a characteristic "hydrocarbon" spectrum which does not vary much for alkanes above hexane. Note, however, that the retention index from method 1625C is within the reported range from CARD for all of the alkanes.

Other compounds in Table 2 show better agreement between the method 1625C RI and the values from CARD. The exceptions are 1,2,4,5-tetrachlorobenzene and squalene, both of which suffer from small samples, and 7H-benz <de> anthracen-7-one (benzanthrone). The PAH Retention Index system ought to be as useful for non-PAH compounds as is any other system; example of such a system is one based on n-alkanes, as is the Kovats index. The traditional Kovats index is not applicable to the CLP semi-volatile method, since the CLP method is a temperature-programmed GC method, whereas the Kovats index is used for isothermal GC methods. Retention time data from Revision 1 (12/87) of RCRA method 8270¹¹ were examined and were found to be in conflict with method 1625C and the CARD data. The use of method 8270 as a reference for retention time data is not recommended.

Table 3 gives the RI of other method 1625C compounds which were not found in the CARD TIC data, and Table 4 gives RI data from the drinking water method 525, with means and medians from CARD. Agreement between method 525 and the CARD data is quite good.

Table 2
Miscellaneous Compounds from Method 1625C
Comparison of Method 1625C Retention Indices
And Tentatively Identified Compound Retention Indices

Compound	CAS No.	Number	RI-1625C	Median	Differ1	Mean	Differ2	STD DEV	Minimum	Maximum
alpha-terpineol	98555	5	201.95	200.95	1	202.02	-0.07	2.56	200.71	206.6
Dodecane	112403	44	202.93	202.57	0.36	211.02	-8.09	14.55	200.58	258.54
Benzene, 1,2,3-trichloro-	87616	6	206.5	206.17	0.33	206.18	0.32	0.17	205.98	206.4
1,3-Benzodioxole, 5-(2-propen	94597	10	220.65	221.27	-0.62	221	-0.35	1.16	219.5	222.31
Benzene, 1,2,4,5-tetrachloro-	95943	2	228.94	237.25	-8.31	237.25	-8.31	0.48	236.9	237.59
1,3-Benzenediamine, 4-methyl-	95807	3	236.42	237.2	-0.78	237.46	-1.04	0.89	236.73	238.45
Tetradecane	629594	55	239.02	238.28	0.74	246.27	-7.25	22.71	235.31	317.66
Benzene, 1,1'-oxybis-	101848	17	241.14	240.12	1.02	240.86	0.28	1.56	239.3	244.89
longifolene	475207	3	242.6	242.92	-0.32	244.2	-1.6	2.23	242.89	246.78
2,6-di-t-butyl-p-benzoquinone	719222	15	250.41	250.77	-0.36	250.89	-0.48	0.78	249.88	252.17
Benzene, pentachloro-	608935	9	261.3	261.14	0.16	261	0.3	0.65	259.98	262.05
2-Naphthalenamine	91598	2	266.34	264.44	1.9	264.44	1.9	1.57	263.33	265.56
Benzothiazole, 2-(methylthio)	615225	3	273.5	273.65	-0.15	273.85	-0.35	0.48	273.51	274.4
Hexadecane	544763	217	282.28	272.96	9.32	293.46	-11.18	42.12	239.98	413.27
Octadecane	593453	65	300.4	297.42	2.98	298.06	2.34	5.72	276.67	325.14
Eicosane	112958	81	319.68	331.89	-12.21	339.46	-19.78	25.54	303.52	420.75
Benzidine	92875	18	354.67	350.73	3.94	350.86	3.81	1.05	348.96	352.96
Docosane	629970	87	361.83	362.09	-0.26	380.24	-18.41	37.05	302.92	455.11
Tetracosane	646311	29	388.87	381.45	7.42	383.42	5.45	5.57	375.04	394.07
Squalene	7683649	3	391.65	439.55	-47.9	438.85	-47.2	4.75	433.8	443.21
7H-Benz<de>anthracen-7-one	82053	53	405.24	386.68	18.56	389.18	16.06	3.81	382.79	396.82
Hexacosane	630013	51	413.85	403.82	10.03	355.44	58.41	70.91	216.13	434.7
Octacosane	630024	140	440.07	421.01	19.06	391.74	48.33	56.62	268.1	454.84

Table 3
Retention Indices Of Other Method 1625C Compounds

CAS No.	Compound	RI ^a	RI ^b
614-00-6	N-nitrosomethylphenylamine	206.88	206.33
1888-71-7	hexachloropropene	208.13	207.47
121-73-3	3-chloronitrobenzene	208.94	208.28
700-12-9	pentamethylbenzene	219.51	218.83
108-46-3	1,3-benzenediol	220.32	219.64
137-17-7	2,4,5-trimethylaniline	220.81	220.13
120-75-2	2-methylbenzothiazole	222.11	221.43
95-79-4	5-chloro-o-toluidine	222.43	221.75
634-36-6	1,2,3-trimethoxybenzene	226.83	226.14
608-27-5	2,3-dichloroaniline	232.03	231.33
3209-22-1	2,3-dichloronitrobenzene	240.81	240.10
130-15-4	1,4-naphthoquinone	242.44	241.72
2027-17-0	2-isopropyl-naphthalene	247.32	246.59
100-25-4	1,4-dinitrobenzene	247.48	246.75
99-30-9	2,6-dichloro-4-nitroaniline	248.13	247.40
134-32-7	alpha-naphthylamine	264.23	263.47
96-45-7	ethylenethiourea	267.97	267.21
89-63-4	4-chloro-2-nitroaniline	274.47	273.70
99-55-8	5-nitro-o-toluidine	274.63	273.86
103-33-3	azobenzene	277.40	276.62
122-39-4	diphenylamine	277.40	276.62
62-44-2	phenacetin	289.27	288.47
92-67-1	4-aminobiphenyl	295.61	294.81
23950-58-5	pronamide	300.00	299.19
882-33-7	diphenyldisulfide	308.95	308.00
92-93-3	4-nitrobiphenyl	312.13	311.20
86-74-8	carbazole	314.31	313.40
2243-62-1	1,5-naphthalenediamine	319.48	318.60
91-80-5	methapyrilene	340.36	339.60
92-84-2	phenothiazine	343.34	342.60
7700-17-6	crotoxyphos	348.51	347.80
492-22-8	thioxanthone	351.29	350.60
60-11-7	p-dimethylaminoazobenzene	368.39	367.80
101-14-4	4,4'-methylenebis(2-chloroaniline)	400.42	400.00
119-90-4	3,3'-dimethoxybenzidine	401.89	401.48
72-33-3	ethynylestradiol 3-methylether	426.85	426.63
87-65-0	2,6-dichlorophenol	202.93	202.27
933-75-5	2,3,6-trichlorophenol	237.72	237.01
58-90-2	2,3,4,6-tetrachlorophenol	266.34	265.58
1689-84-5	2,5-dibromo-4-hydroxybenzonitrile	284.23	283.44

^a referenced to naphthalene-d₈, phenanthrene-d₁₀, chrysene-d₁₂, perylene

^b referenced to naphthalene, phenanthrene, chrysene, perylene

Table 4
Retention Indices Of Method 525 Compounds

Compound	CAS No.	Method 525 RI ^{a,b}		GARD RI	
		A	B	Mean	Median
2,3-dichlorobiphenyl	16605-91-7	282.57	285.14	--	--
siazine	122-34-y	288.86	290.72	--	--
atrazine	1912-24-9	290.96	292.42	294.66	294.65
lindane	58-89-9	295.85	296.07	296.38	296.38
2,4,5-trichlorobiphenyl	15862-07-4	308.18	309.35	316.82	316.82
heptachlor	76-44-8	317.82	318.75	320.50	320.48
2,2',4,4'-tetrachlorobiphenyl	2437-79-8	324.81	326.92	--	--
aldrin	309-00-2	328.21	329.17	--	--
heptachlor epoxide	1024-57-3	340.43	342.24	343.19	343.15
2,2',3',4',6-pentachlorobiphenyl	60233-25-2	343.31	346.32	--	--
gamma-chlordane	5103-74-2	347.73	350.00	--	--
alpha-chlordane	5103-71-9	352.48	354.90	--	--
trans-nonachlor	39765-80-5	354.18	356.54	--	--
2,2',4,4',5,6-hexachlorobiphenyl	60145-22-4	360.96	364.71	--	--
endrin	72-20-8	374.20	369.40	368.46	368.39
bis(2-ethylhexyl)adipate	103-23-1	388.63	389.83	384.28	383.70
2,2',3',3',4,4,6-heptachlorobiphenyl	52663-71-5	400.18	400.51	--	--
methoxychlor	72-43-5	401.77	401.65	--	--
2,2',3',3',4,5,6,6'-octachlorobiphenyl	40186-71-8	402.48	402.34	--	--

^a Referenced to acenaphthylene (RI=244.63) phenanthrene, chrysene, benzo(g,h,i)perylene (RI=501.32).

^b Columns A and B refer to the 2 temperature programs in Method 525.

CONCLUSIONS

The PAH Retention Index system is a promising candidate for the improvement of "Tentatively Identified Compounds" reporting. Because it uses compounds already present in the calibration mixture as retention time markers, it will not require major modification to the present CLP semi-volatile method. The PAH RIs of hundreds of PAH and heterocyclic compounds, which can be used to confirm the identity of TICs without further laboratory work, are found in the literature.^{1,3} Tables 2,3 and 4 in this paper give additional RIs on non-PAH compounds. Thus, data reviewers could begin to use the system immediately.

The ability to predict the RI based on molecular structure

descriptors^{4,8} can short-cut the establishment of RIs for the rest of the compounds in the NIST/EPA/MSDC mass spectral data base, by eliminating the need to measure the retention time of all the 50,000 compounds in the data base.

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REFERENCES

1. Lee, M.L., Vassilaros, D.L., White, C.M. and Novotny, M., "Retention Indices for Programmed-Temperature Capillary-Column Gas Chromatography of Polycyclic Aromatic Hydrocarbons," *Anal. Chem.* 51, pp. 768-773, 1979.
2. Willey, C., Iwao, M., Castle, R.M. and Lee, M.L., "Determination of Sulfur Heterocycles in Coal Liquids and Shale Oils," *Anal. Chem.* 53, pp. 400-407, 1981.
3. Vassilaros, D.L., Kong, R.C., Later, D.W. and Lee, M.L., "Linear Retention Index System for Polycyclic Aromatic Compounds. Critical Evaluation and Additional Indices," *J. Chrom.* 252, pp. 1-20, 1982.
4. Whalen-Pederson, E.K. and Jurs, P.C., "Calculation of Linear Temperature Programmed Capillary Gas Chromatographic Retention Indices of Polycyclic Aromatic Compounds," *Anal. Chem.* 53, pp. 2184-2187, 1982.
5. Doherty, P.J., Hoes, R.M., Robbat, A., Jr. and White, C.M., "Relationship between Gas Chromatographic Retention Indices and Molecular Connectivities of Nitrated Polycyclic Aromatic Hydrocarbons," *Anal. Chem.* 56, pp. 2697-2701, 1984.
6. Robbat, A., Jr., Corso, N.P., Doherty, P.J. and Marshall, D., "Multivariate Relationships between Gas Chromatographic Retention Index and Molecular Connectivity of Mononitrated Polycyclic Aromatic Hydrocarbons," *Anal. Chem.* 58, pp. 2072-2077, 1986.
7. Robbat, A., Jr., Corso, N.P., Doherty, P.J. and Wolf, M.H., "Gas Chromatographic Chemiluminescent Detection and Evaluation of Predictive Models for Identifying Nitrated Polycyclic Aromatic Hydrocarbons in a Diesel Fuel Particulate Extract," *Anal. Chem.* 58, pp. 2078-2084, 1986.
8. Robbat, A. Jr., Xyrafas, G. and Marshall, D., "Prediction of Gas Chromatographic Retention Characteristics of Polychlorinated Biphenyls," *Anal. Chem.* 60, pp. 982-985, 1988.
9. U.S. EPA, Office of Water Regulations and Standards, "Analytical Methods for the National Sewage Sludge Survey," Aug. 1, 1988.
10. U.S. EPA, "Methods for the Determination of Organic Compounds in Drinking Water," EPA-600/4-88/039, Environmental Monitoring Systems Laboratory, Cincinnati, OH, Dec. 1988.
11. U.S. EPA, "Test Methods for Evaluating Soil Waste Physical/Chemical Methods (SW 846) 3rd edition, Proposed Update Package, Office of Solid Waste, Washington, D.C., Dec. 1987.

Toxin-Exposure Medical Surveillance: A Focus on Cost-Effective Risk Management

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ABSTRACT

Employers of workers exposed to hazardous substances are faced with a dilemma created, on the one hand, by a Congressional mandate to "provide a safe workplace for their employees," while, on the other hand, striving to maintain profitability by cost-containment. The issue is further complicated by a prevailing litigious climate generating far-reaching precedents from civil and criminal prosecution. Considering such external pressures, it is critical that employers incorporate an effective medical risk-management program in their business plan. The medical surveillance portion of that program is all too often treated as just a "physical examination." The long-term liability associated with toxin-exposure/absorption-related disease dictates that the prudent employer utilize available professional expertise and biological technology to design a compliant, cost-effective medical surveillance program.

INTRODUCTION

This paper will discuss the changing relationships between public sentiment, current regulations, the recent focus of the legal profession on toxic torts and advances in today's medical technology. The antiquated view of medical surveillance as "just a physical examination" will be compared to the necessity for a medical risk-management program that embodies a comprehensive, well-designed medical surveillance program for toxin-exposed employees. Finally, specific guidelines for the employer will be discussed to facilitate the design and implementation of a compliant, toxin-exposure medical surveillance program.

DISCUSSION

"For the first time in the history of the world, every human being is now subjected to contact with dangerous chemicals, from the moment of conception until death." It may seem strange to start a paper regarding medical surveillance with a quote from Rachel Carson's *Silent Spring*. The publishing of this book in 1962, however, was the catalyst for the formation of the U.S. EPA in 1970 amidst strong public sentiment regarding "poisoning of the planet" from chemicals. This land swell of public concern over the health and environmental impact of chemicals has progressively increased since 1970 and resulted in the passing of CERCLA among other legislation. Public sentiment, with regard to human exposure to chemical hazards, has gradually turned from fear to anger toward those responsible. Deviant generators of chemical waste and those who carelessly expose their employees to toxic chemicals will have difficulty finding a sympathetic ear in today's courtroom.

That management has injured employees as a result of either their ignorance of health issues or their disregard for them is unquestioned. One has but to look at Gaulley Gap, the radon dial painters of WWII or, more recently, the Manville asbestos cases. The recent accelera-

tion of toxic torts, prosecution of corporate directors (The Chicago Magnet Wire case) and even CERCLA itself is a direct result of such ignorance and disregard.

Many of the current medical regulations regarding toxin-exposure medical surveillance are in a state of flux and can be confusing. There are generic guidelines but there also are specific standards for certain chemicals and action levels that must be taken into consideration for many others. Uncontrolled hazardous waste sites represent the potential for a multitude of health and safety concerns. The standards promulgated in 29 CFR 1910.120 regarding a health and safety program are summarized in the *Inter Agency Guidance Manual* published in 1985 by NIOSH, OSHA, USCG and the U.S. EPA.

This manual assumes that a medical surveillance program will be used to complement engineering controls, personal protective equipment (PPE) and decontamination procedures. In addition, it assumes that the average toxic waste site contains many unknown chemicals. Even though site characterization may identify specific chemicals, it must be assumed that other chemical hazards may exist. The manual states, "The program should be designed by an experienced occupational health physician or other qualified occupational health consultant in conjunction with the Site Safety Officer. The director of a site medical program should be a physician who is board-certified in occupational medicine or a medical doctor who has had extensive experience managing occupational health services. If an occupational health physician is not available... (the program) ... may be performed by a local physician with assistance from an occupational medicine consultant."

The regulations divide a site medical program into surveillance, treatment, record-keeping and program review. Medical surveillance includes three types of examinations: (1) pre-employment screening (baseline); (2) followup examinations (periodic); and (3) termination (exit) examinations. It should be emphasized that the regulations clearly state, "Because conditions and hazards vary considerably at each site, only general guidelines are given." In most cases the final decision regarding the details of the site medical program is left to the physician consultant. These recommendations should be considered as minimal standards. Most forward-thinking employers do not feel comfortable with the liability protection afforded by such standards.

Behind-the-scene changes rapidly are taking place in the regulatory arena and the U.S. EPA is emerging as a dominant player in the enforcement of environmental laws. OSHA, as an agency of the government, acts slowly both in the promulgation and enforcement of laws, and as of September 1989, the U.S. EPA is adopting the OSHA hazardous site worker standards promulgated by 1910.120. Due to the bureaucratic hierarchy, the U.S. EPA will now have the power to act swiftly to enforce standards and prosecute violators. In addition, the

U.S. EPA will have the ability to promulgate new standards more effectively than OSHA.

To further complicate the picture, there are numerous other powerful and respected groups exerting pressure on Congress. Unions and consumer advocacy groups are starting to take an active role in lobbying and enforcement of specific worker protection standards. Professional associations like the American Conference of Governmental Industrial Hygienists (ACGIH) and the American Industrial Hygiene Association (AIHA) are pushing for more stringent worker protection standards. In particular, these groups are recommending that board-certified occupational physicians should have the responsibility for designing medical surveillance programs. In addition, they are insisting on a more generic industry standard designed to stabilize the current fragmented approach to biological monitoring.

The High Risk Notification Bill: California Proposition 65, complete revision of OSHA's permissible exposure limits (PELS), changes in hazardous waste transportation standards and revisions of the formaldehyde and benzene standards are just a few of the upheavals in this industry. Many states are passing laws that are far more stringent than their federal counterparts. Compliant health evaluation programs designed for today could be obsolete by tomorrow. Only health professionals with a focus and expertise in this regulatory-driven industry will be capable of designing and maintaining compliance-assured medical surveillance programs that provide health protection for the employee and maximum liability protection for an employer.

The escalation of litigation regarding on the job injury and disease is reflective of the clout from the combination of public sentiment and rapid changes in worker protection laws. The Chicago Magnet Wire Case is an example of the extent of personal liability exposure and its consequences. A recent large settlement against an employer was the result of the plaintiff showing that benzene exposure can cause chronic as well as acute leukemia (Skeen v. Monsanto Co. Feb. 21, 1989). This case is a good example of the necessity for optimal environmental and biological monitoring and good recordkeeping (the exposure to benzene occurred in the mid-1970s). Benzene is a toxin that can be monitored for absorption prior to the onset of disease. Not only is the frequency of toxic torts increasing, but also the level of awards and punishment are likewise increasing. At present, there is no reason to believe that this trend will diminish. On the contrary, there is every indication that it will accelerate in the foreseeable future.

The employer who is involved in the hazardous waste remediation business must keep in mind several seldom considered facts when planning for the health and safety of his employees. In the first place, the general guidelines noted above were revised in 1985 but were actually written in 1980. The sole purpose of the *Inter-Agency Guidance Manual* was to provide a comprehensive guide for site safety. The Occupational Health and Safety Act of 1970 clearly states that it is the responsibility of the employer to provide a safe workplace. There is no qualification with regard to the limitations of current technology, unforeseen chronic adverse health effects or specific budgetary restrictions. In fact, some interpretations hold the employer responsible regardless of the circumstances. The design of an effective medical risk management program depends on the assumption that the employer is ultimately responsible for worker health and safety, regardless.

MEDICAL EXPERTISE AND BIOMEDICAL TECHNOLOGY

Modern 20th century medicine is generally accepted to be excellent. American medicine is thought by many to be the best in the world. Both of these commonly accepted statements may be true, but they must be evaluated relative to the end-point that would be considered the ultimate. That end-point, quite simply stated, is the prevention of disease. Inarguably, medical authorities and the lay population would agree on that issue. If our ultimate goal is prevention of disease, we are far from achieving such a state.

Even the most conscientious employer will be met with frustrations and limitations represented by the technological inadequacies of modern medicine. In the hazardous substance exposure business, the primary concern is absorption of chemicals through the skin, lungs, eyes, ears, ingestion or penetration. If we had the ultimate diagnostic tool, we could

scan an individual and detect even the most minimal absorption before the onset of disease. Unfortunately, this tool is not available and in its place we must rely on a very inexact vast human experiment. This experiment constitutes the inadvertent exposure of large numbers of humans to chemicals for an unknown period of time and monitoring for the onset of disease. When disease is diagnosed, we must then retrospectively look backwards in the hope we can correlate some exposure to the disease. At this point, it may be too late for the rehabilitation of the individual to normal health, and it also may be too late for the employer to convince an agency or jury of his innocence regarding the employee's injury or disease.

This discussion does not imply that we are unable to detect absorption with current medical technology. In many cases, we can, but the ability to monitor a chemical in a biologic system is just now emerging. NIOSH recently announced that of the over 100,000 chemicals used in manufacturing today, chronic adverse health effects are known to occur with less than 20% of that number. The commonality of chemical pathways for metabolism and excretion is becoming clearly defined and identified. In fact, we are advancing far more rapidly in the area of absorption identification than in the area of treatment modalities for existing absorption disease. (Consider, for example, lung cancer resulting from absorption of asbestos).

The above description of the limitations of biological monitoring is not designed to further confuse the reader, but rather to illustrate that technological overkill in a medical surveillance program, in addition to excessive cost, can be as fruitless as a "bare minimum" approach. It also points out the complex and dynamic nature of medical technology, and the advances we may expect, in the early detection of chemical absorption prior to the onset of disease. The object is to again emphasize that only experienced environmental health professionals are capable of staying abreast of these changes and translating this information into maximum protection for the employer and employee.

THE MEDICAL SURVEILLANCE PROGRAM

How does this translate into practical information and guidelines for the modern remediation firm? It is critical that employers in the hazardous substances business recognize that a health surveillance evaluation is more than just a physical examination. It is an integral element in a plan, required by law and demanded by humanitarian principles, and designed to protect workers from adverse health effects...to attempt the prevention of disease as opposed to the discovery of disease. Just as the chain is only as strong as its weakest link, the soundness of such a plan is only as effective as the most poorly planned and executed element. If we accept the premise that a site health and safety plan constitutes a risk-management program, then it logically follows that the health surveillance element of that plan is critical in the overall effectiveness of the program.

Many Superfund sites are located in rural areas, and a remediation firm may have multiple sites scattered around the nation. In all likelihood, many of these sites will be in areas void of occupational physicians trained and experienced in toxin-exposure medical surveillance. It will be necessary to depend on local physicians for the surveillance data. Because this situation is the rule rather than the exception, the examination protocol, in addition to being standardized and thorough, must be "user friendly" and coordinated with concise clinic operations manuals. This is the only mechanism by which the company's medical data can be reliably obtained from multiple medical practitioners.

There are four basic sources of information utilized to design an examination protocol for a medical surveillance program: (1) the employees' exposure profile and working conditions, (2) current regulations, (3) the company's philosophy toward worker health and safety and (4) current technology. (Fig. 1). The examination protocol provides procedural guidelines for the physician and his staff to complete a health evaluation of each employee. The protocol should provide the physician with a completed personal and occupational history which he can augment at his discretion. With the current technological limitations in biological monitoring, the history provides, by far, the majority of the information from the examination. It should be thorough, detailed, designed with planned redundancy, and, by necessity, it must be long.

Because of its length, it must be completed with forethought and without pressure before the employee presents himself for his medical evaluation.

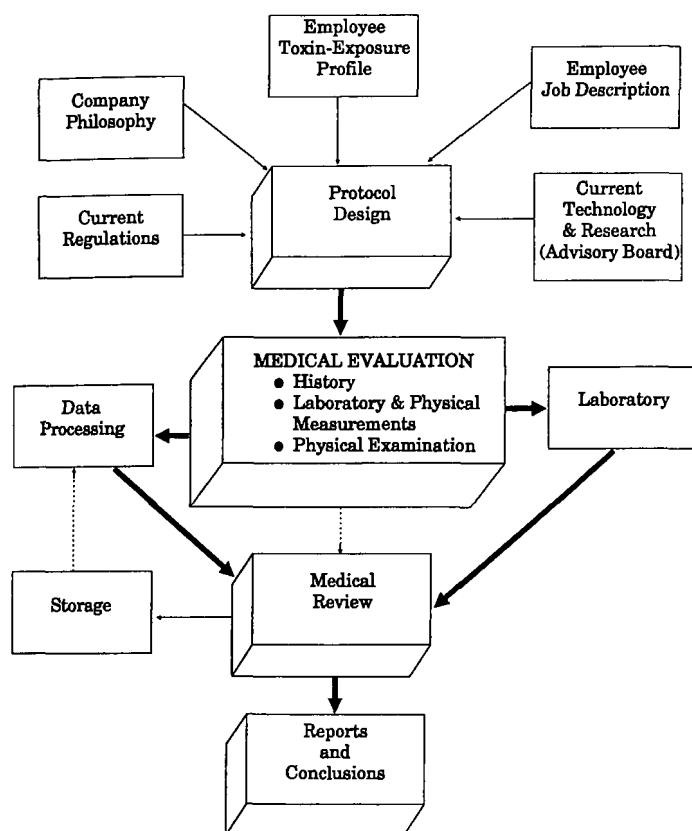


Figure 1

The Anatomy of a Toxin-Exposure, Health Surveillance Evaluation

Likewise, the examination protocol guides the physician in the hands-on physical examination necessary to determine present state of health and physical capabilities. In addition to programed responses (Yes or No), it should encourage the physicians comments and suggestions. Lastly, the protocol guides the medical staff in physical measurements and ancillary tests like audiometry (hearing tests) and spirometry (breathing tests). Clinic laboratory equipment used to measure breathing, hearing, etc. must meet certain specifications by law. In addition, the technician who operates the equipment must be certified according to the standards. If these requirements are not met, the data obtained are questionable. Likewise, the original test results must be kept in retrievable fashion for 30 yr after termination.

The protocol should direct the medical team in the obtaining and packaging of specimens (blood and urine) for mailing to a specific laboratory. The selection of a reference and specialty laboratory to analyze blood and urine is critical to a sound medical monitoring program. Although such services are widely available, there is considerable variation in quality and reliability of results. A detailed discussion of the vicissitudes of this industry is not appropriate for this paper. The recurring theme is, again, the necessary reliance of the employer on a carefully selected occupational physician for guidance in the selection of laboratory services.

The end-point of all the medical data (history, physical examination and laboratory analysis) is review by the physician. It is here that the axiom "garbage in, garbage out" is appropriate. If these data are not extracted carefully, accurately and professionally, the results of the physician's review could be erroneous. Equally as important, the company's financial outlay for medical surveillance could be wasted. Many employers select physician consultants with little regard to qualifications. These consultants are selected to design and implement complex health monitoring programs simply because they work in a clinic

that provides general occupational medicine services. Enormous sums of money and significant corporate and personal liability are put on the line when inexperienced and poorly informed health professionals are selected to manage medical surveillance programs. A working knowledge of the regulations and standards, experience in toxicology and training in the pathophysiology of disease from chemical absorption are essential skills for the physician reviewing biological monitoring data. Following review of the medical data generated by the examination process, the physician must generate a written report with recommendations to the employer and employee. This report must reach the employee within 15 days following the examination. Abnormalities must be addressed and a disposition made with regard to followup and restrictions. It is the employer's responsibility to see that all medical data collected under 1910.120 are stored in retrievable form for 30 yr after termination. If a court action regarding a previous employee should arise 10 yr after a specific examination, OSHA and the court will expect the employer to provide such records in readable form. Failure to do so could result in severe penalties and a less than adequate defense. It should be obvious at this point that medical surveillance is, in truth, a complex program, not just a physical examination. In addition to assuring the ongoing health of a company's work-force, it must be recognized and utilized as an integral part of a corporate risk-management program. The tendency among less well-informed employers/managers when attempting to comply with regulations regarding medical surveillance, is to "cut corners" with the cheapest examination available. This approach may look good on the bottom line of a profit and loss statement, but the penalties from violations and the cost of litigation could be catastrophic. In many cases, a substandard program is more expensive than a professionally-designed and compliance-assured program. Cost is always a factor in business, but contracting with the lowest bidder may be false economy.

GUIDELINES

Every cost-effective medical surveillance program should contain the following services and benefits:

- A board certified occupational medicine physician with experience in toxin-exposure disease
- A corporate-wide examination protocol designed by, or in consult with, that physician
- Review of the examination protocol by someone knowledgeable and current in the related standards and regulations
- Designated, qualified clinics convenient to each site which have been trained in the use of the examination protocol
- A nationally recognized laboratory to analyze biological specimens
- Concise, compliant medical results in the form of a report received within 15 days of the examination
- Reliable storage of all medical records in retrievable form for 30 yr plus the term of employment

Fortunately for the employer, there are firms today which can provide these medical services. If difficulty is encountered in locating such a firm, a board certified occupational medicine physician should be consulted for advice. A list of such physicians can be obtained by writing the authors or the American College of Occupational Medicine.

CONCLUSION

The standards regulating the hazardous materials industry require an employer to provide a medical surveillance program for exposed workers. The intent of such legislation is to insure the health and safety of the employee, but, from a business perspective, the standards provide liability protection for the corporation and its directors. Such legislation is viewed by many employers as an unnecessary burden, but, in fact, it could be a blessing in disguise for companies which are not informed in matters of risk management.

It has been demonstrated that a toxin-exposure health surveillance program is very complex and requires specialized medical expertise. Only an informed occupational physician who specializes in hazardous materials exposure can coordinate the appropriate regulations and bio-

medical technology to provide a true medical risk-management program. The prudent employer designing a site health and safety plan would be well advised to consider his health surveillance program as an integral part of a sound risk-management program. To this end, he should con-

sult with environmental physicians who have experience in the field of absorption disease for guidance. Cutting corners on medical surveillance could jeopardize a company's entire risk-management program and, as a result, the company's future.

Characterization of "Significant Risk" Under The Massachusetts Contingency Plan

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ABSTRACT

The Massachusetts Contingency Plan (MCP) was promulgated on Oct. 3, 1988 to implement the State Superfund law (the "Massachusetts Oil and Hazardous Material Release Prevention and Response Act," Massachusetts General Laws Chapter 21E, 1983). The assessment and remediation of state superfund sites are carried out in a phased approach. Site risk characterization is a critical part of the Comprehensive Site Assessment (Phase II) required under the MCP.

M.G.L. Chapter 21E (the statute) requires the achievement of a "Permanent Solution" at all disposal sites, if feasible. A Permanent Solution eliminates any "significant or otherwise unacceptable risk" of harm to health, safety, public welfare or the environment during any foreseeable period of time. When feasible, a Permanent Solution will restore the disposal site to background levels. The answer to the question of what constitutes a significant risk (and subsequently, "How Clean Is Clean Enough?") became a major issue in the development of the regulations implementing the statute.

The MCP approach employs risk assessment processes outlined in the National Academy of Sciences study "Risk Assessment in the Federal Government: Managing the Process"² and is consistent with the methods adopted by the U.S. EPA for use at Federal Superfund sites. However, the state approach specifically defines significant risk in a manner which differs from the risk range approach used by the U.S. EPA.

This paper will describe the Massachusetts methodology and draw comparisons with the U.S. EPA approach to evaluating "significant risk" at hazardous waste disposal sites.

INTRODUCTION

One or more factors may drive the remediation at a disposal site in Massachusetts. These factors include the risk of harm to human health, the risk of harm to the environment and the feasibility of restoring the site to background conditions. This discussion will focus primarily upon the characterization of the risk of harm to health [310 CMR 40.545 (g)]. Additional consideration should be given to the characterization of risk of harm to safety, public welfare and the environment [310 CMR 40.545 (h)]. Currently, these concerns are being addressed through, primarily, qualitative methods.

In 1987, the Massachusetts Department of Environmental Quality Engineering (now the Department of Environmental Protection, DEP) contracted Wehran Engineering to survey state and federal environmental officials and the current scientific literature in an effort to develop a working definition of "significant risk" for use in the MCP. The result was "The 'Significant Risk' Project". The Project surveyed the states of California, Michigan, New Jersey, New York and Wisconsin, as well as the U.S. EPA concerning methods of standard setting and their use,

risk management policy and approach, definition and use of the term "significant risk" and their approach to a hypothetical pollution control scenario.

Concurrent with this process, three goals were identified for the risk characterization process to be used in the Massachusetts Contingency Plan:

- Disposal sites in Massachusetts would be remediated to levels which would be protective of the public health
- Disposal sites would be remediated in a consistent manner throughout the Commonwealth's four regions
- Disposal sites would be remediated in a manner consistent with existing state regulatory programs

To achieve these goals, the Massachusetts Contingency Plan outlines [four methods] for the characterization of risk of harm to human health at Massachusetts disposal sites. Four methods were developed (as opposed to one set method) to more closely address the complex idiosyncrasies of individual sites. Central to this process is the inclusion of "Total Site Risk Limits" in the regulations. These specific risk limits contrast sharply with the risk range approach practiced at the federal level.

The four methods were crafted to satisfy the three principal goals of the MCP. Since these methods are intended to achieve the specific requirements of the Massachusetts statute, they often go beyond the approach developed by the EPA for use at Federal Superfund sites. However, as the EPA updates the guidance given in the "Superfund Public Health Evaluation Manual"⁵, the differences between the two programs will narrow. The recently completed "Supplemental Risk Assessment Guidance for the Superfund Program"⁴ prepared by the U.S. EPA Region I Risk Assessment Work Group is in fact consistent with the Massachusetts DEP's "Guidance for Disposal Site Risk Characterization and Related Phase II Activities - In Support of the MCP"⁵.

The risk characterization process mandated by the Massachusetts Contingency Plan is described below, with emphasis on the definition and use of the term "significant risk."

DEFINING AND EVALUATING "SIGNIFICANT RISK" UNDER THE MCP

The Massachusetts Contingency Plan (MCP), promulgated by the Department of Environmental Protection (DEP), became effective on Oct. 3, 1988. The MCP establishes requirements and procedures for identifying, evaluating and cleaning up releases of oil or hazardous materials to the environment. The regulations are based upon the State "Superfund Law" (The Massachusetts Oil and Hazardous Materials Release Prevention and Response Act of 1983) and major amendments passed by voter referendum in 1986.

The MCP responds to the public's clear mandate by establishing a cleanup process that is consistent, strict and highly protective of public health and the environment. Risk characterization and evaluation are at the heart of the cleanup process.

As part of the requirements of the Comprehensive Site Assessment (in Phase II of the six phase process), the regulations provide a framework for determining: (1) whether remediation at a disposal site is required and (2) the extent of remediation needed to attain a permanent or temporary solution. The Phase II risk characterization directs consistent and conservative evaluations of human health, safety, public welfare and environmental risks at all of the disposal sites in the Commonwealth.

To supplement the language of the regulations and provide more detailed guidance for their implementation, the Department has published "Guidance For Disposal Site Risk Characterization And Related Phase II Activities - In Support of the Massachusetts Contingency Plan" (May 17, 1989). The guidance primarily addresses the characterization of risk of harm to human health. The evaluation of the risk of harm to safety, public welfare or the environment relies upon existing environmental standards and site-by-site considerations. The Department recognizes that more guidance is needed in this area.

CHARACTERIZING RISK POSED BY DISPOSAL SITES

The Massachusetts Superfund law (M.G.L. Chapter 21E) requires that cleanups must eliminate "significant or otherwise unacceptable risk" of harm to human health, safety, public welfare and the environment.

As the MCP was drafted, a great deal of discussion centered on the questions of: (1) what constitutes a significant risk?, and (2) what methodology should be used to characterize risk at a disposal site? Risk assessment and risk management are not unique to the state and federal Superfund programs. The Commonwealth of Massachusetts has implemented a number of regulatory programs which address environmental contamination in specific media, including air, drinking water, groundwater and surface water. One goal of the Contingency Plan was to preserve that the integrity of these existing programs; remediation at disposal sites would, at a minimum, meet any applicable or suitably analogous standards of these programs and the policies of these programs would be applied when appropriate.

The Department also recognized that many disposal sites are far more complex than the situations commonly addressed by the medium-specific programs. In particular, it was felt that the reliance upon standards and guidelines developed for single contaminant or single-medium situations might be inadequate to protect the public health at a disposal site involving multi-media contamination and/or a mixture of contaminants.

Finally, the Department wished to minimize costs to those performing the risk characterizations by relying upon standards, guidelines and/or existing sets of cleanup levels whenever possible.

What emerged from these discussions were four risk characterization methodologies, only one of which would be appropriate at any given disposal site. The regulations describing these methodologies can be found in 310 CMR 40.545(3)(g) of the Contingency Plan. Only one of the four methods involves the classic, full risk assessment. Less complex sites would use simpler risk characterization methods.

THE FOUR METHODS

As detailed in the regulations and elaborated upon in the Department's Guidance Document, the characterization of risk of harm to human health is evaluated using one of four methods. As only one of the four methods is considered appropriate at any given disposal site, it is extremely important that the correct risk characterization methodology be chosen at the beginning of the process. Since the promulgation of the regulations in 1988, increasing emphasis is being placed on the proper selection of a method for site evaluations in the risk characterization process. The first revision of the Department's Guidance Document attempted to more fully describe and explain the selection process. The Methods are meant to be considered in a stepwise fashion, from the simplest (Method 1) to the most complex (Method 3b).

Method 1

Method 1 applies at sites where, under existing regulations, there are standards (NOT guidelines, NOT policies) applicable to each oil and/or hazardous material (OHM) in every medium (air, water or soil) to which persons might be exposed.

In this Method, the risk characterization compares the OHM exposure point concentrations to the standards identified. Remediation is required if any concentration exceeds such a standard, and the standards become requirements for a permanent solution.

Presently, Method 1 does not apply to a large percentage of disposal sites under investigation in Massachusetts. Of the 23 contaminants most commonly found at state sites, ambient air quality standards exist only for lead, drinking water standards exist only for 12 of the 23 chemicals and no public health soil standards exist at this time.

If Method 1 is not appropriate, Method 2 is to be considered.

Method 2

Under Method 2, exposure point concentrations of OHM are compared to specific sets of cleanup levels to be incorporated into the MCP (310 CMR 40.800). These specific sets of cleanup levels will be developed by the Department for certain types of disposal sites which present common problems. For example, a specific set of cleanup levels may be developed for leaking underground gasoline storage tanks in a residential area where there are private wells and where no exposure is thought to occur other than via drinking water. These levels will be specific for both the contaminants reported at a site and the potential exposures at such a disposal site.

In this Method, the risk characterization consists of the comparison of OHM exposure point concentrations to corresponding values contained in the specific set of cleanup levels. Remediation is required if any concentration exceeds an identified cleanup level, and the set of cleanup levels becomes a requirement of a permanent solution.

To date, no specific set of cleanup levels has been established; Method 2, therefore, is unavailable for any disposal site. The Department currently is working on a number of such sets of cleanup levels, including sets for PCB-contaminated soil and Coal Gasification Waste disposal sites and petroleum contaminated sites.

When neither Method 1 nor Method 2 apply to a site (or when 2 is applicable, but not used), then either Method 3a or 3b is appropriate. It must be determined at this point whether the site fits the characteristics of a "Single Medium" disposal site (to be evaluated per Method 3a) or a "Multi-Media" disposal site (to be evaluated per Method 3b). Both Methods may make use of site-specific risk assessment techniques.

Method 3a

Method 3a is appropriate if exposure to the oil or hazardous materials at or from the disposal site occurs via one contaminated medium. Using Method 3a, exposure point concentrations are compared to corresponding public health standards, guidelines or Departmental policies. If no such value is available for a particular chemical, then a site-specific guideline associated with an excess lifetime cancer risk equal to one in one million and/or a Hazard Index equal to 0.2 should be proposed by the primary responsible party.

In this Method, the risk characterization consists of the comparison of the exposure point concentrations to the identified standards, guidelines, policies and/or proposed site specific guidelines. When remediation is required, these standards, guidelines, policies and/or proposed site-specific guidelines become requirements for a permanent solution.

Method 3a has been used to characterize the risk at approximately 10 to 25% of the disposal sites assessed to date. (This figure is an estimate as the Department has not tracked the number of sites using each Method.) One common type of disposal site which would be characterized by this Method involves a contaminated drinking water supply where no additional exposures are thought to occur. The risk characterization process would employ the drinking water standards and guidelines developed by the Department's Division of Water Supply and Office of Research and Standards, as well as any applicable Departmental policies. Any proposed site-specific guideline would be developed in a manner consistent with Departmental policy, using standard risk assessment

techniques. This Method differs from Method 1 in that it is limited to single-medium situations and both guidelines and policies may be used in addition to standards.

If Methods 1, 2 and 3a are not considered appropriate, then the site is evaluated using Method 3b.

Method 3b

Method 3b is appropriate if a receptor may potentially experience exposures to the oil or hazardous materials at or from the disposal site via more than one contaminated medium, and if Methods 1 and 2 are not applicable. In Method 3b, exposure point concentrations are compared to applicable or suitably analogous standards, promulgated under existing regulations. In addition, a site-specific risk assessment is conducted and the "Total Site Risk" estimates are compared to the risk limits presented in the MCP. For one or more hypothetical receptors, the estimated "total site risks" reflect potential exposures to all the OHM via all the exposure pathways. Guidance is given for the development of these hypothetical receptors for whom the total site risks are estimated. Note that even the chemicals for which standards exist are included in the calculation of the total site risk. Under Method 3b, the most flexible cleanup requirements may be developed while complying with total site risk requirements and applicable/available public health standards.

The risk characterization process under Method 3b consists of the comparison of exposure point concentrations to applicable or suitably analogous standards, and the comparison of "Total Site Risks" to the Total Site Risk Limits. Total site cancer risks are compared to a total site cancer risk limit of one in one hundred thousand (1.0×10^{-5}). Total site non-cancer risks are compared to a total site non-cancer risk limit which is a Hazard Index equal to 0.2. When remediation is required, the identified standards and the Total Site Risk Limits serve as remediation requirements.

Method 3b has been used to characterize the risk at approximately 75 to 90% of the disposal sites evaluated under the MCP to date. It is assumed that this level will be reduced in the future as more standards are set and as the Department develops specific sets of cleanup levels for use in Method 2. (Further consideration and evaluation of background contamination levels will affect the implementation of this process).

OTHER REMEDIATION CRITERIA

As noted earlier, the MCP also requires the characterization of the risk of harm to public welfare, safety and the environment. In addition, there must be an evaluation of the feasibility of remediating a site to background levels.

These additional factors may drive remediation of a site where, based on assessment of significant risk to human health, no adverse effects are expected. Such an approach is consistent with the Department's obligation to protect both public health and the environment.

The Department has attempted to develop a comprehensive means of characterizing disposal site risks which relies extensively on the identification of "otherwise unacceptable." Under the MCP, remedial alternatives may be developed that protect public health, while providing flexibility in the setting of cleanup levels for specific chemicals. In this manner, the Department has developed a process which methodically approaches the answer to the question, "How clean is clean enough?"

COEXISTENCE WITH FEDERAL PROGRAMS

The Commonwealth of Massachusetts publishes quarterly lists which detail the number of state disposal sites and their status. As of July, 1989, there were 1152 Confirmed Disposal Sites which require further investigation, 1634 Locations To Be Investigated and 270 Sites at which remedial action has been completed and for which no further actions are planned (not all of these fall under the requirements of the MCP). Included among the 1152 confirmed sites are 24 NPL sites. One additional site has been proposed for the NPL.

Federal Superfund Sites are subject to the requirements of CERCLA, and SARA (collectively known as "Superfund") in addition to the State Superfund law, M.G.L. Chapter 21E. It should be noted here that

most NPL sites would be considered "Multi-media Sites" under the Massachusetts Contingency Plan, and would thus be subject to the Method 3b risk characterization process.

While there are many similarities between the two programs, several important distinctions can be made, particularly in the risk characterization process. Care must be taken in the development of the Endangerment Assessment (EA), the Remedial Investigation (RI), the Feasibility Study (FS) and the Record of Decision (ROD) to identify the requirements of the Massachusetts regulations and to explicitly meet them. It is, of course, most difficult to integrate newly promulgated regulations into a site remediation process which is already underway.

The most obvious difference between the two programs is the MCP's Total Site Risk Limits. The U.S. EPA has established an excess lifetime cancer risk range (10^{-4} to 10^{-7}) into which the risk based cleanup goal should fall. Depending upon the site, however, the risk range has been applied to: (1) the risk associated with a single chemical via a single exposure route or (2) the risk associated with a mixture of chemicals via a single exposure route or (3) the sum of exposure route risks which could approximate a total site cancer risk. Somewhat more disturbing is an interpretation that all estimations of risk which fall into the U.S. EPA risk range of 1×10^{-4} to 1×10^{-7} may be considered as acceptable. This poses particular concern when the estimated risk is as high as 9×10^{-4} . In comparison, the MCP Method 3b total site cancer risk limit is 1×10^{-5} . The intention of a risk limit is to guard that no potential receptor would experience an excess lifetime cancer risk greater than 1×10^{-5} , regardless of how many potential exposure pathways existed at that disposal site.

An additional difference is the estimation of the total site non-cancer risk, (i.e., Hazard Index, HI). Massachusetts has adopted a HI of 0.2. The exposures related to a disposal site are allowed to contribute only 20% of an estimated allowable daily dose. The approach taken by the Department is similar to that used by the U.S. EPA Office of Drinking Water to develop drinking water standards and health advisories. In its Superfund program, the U.S. EPA does not have a risk limit or range for non-carcinogenic risk. U.S. EPA Region 1 recommends (in the absence of such guidance) that a $HI < 1$ is acceptable and that a $HI > 10$ may be cause for remediation.

In addition, there are strict requirements to evaluate [all] oil or hazardous material at or from a disposal site (eliminating the use of indicator chemicals) and specific consideration is given to the foreseeable future use of the site and the levels of contaminant which would exist in the absence of the disposal site (background). These distinctions can influence the choice of remedial alternatives necessary to achieve a permanent solution at a Federal Superfund site in Massachusetts.

CONCLUSION

"Significant Risk" is a concept which has no absolute definition. When circumstances require developing a working significant definition, many factors must go into that risk management decision. For the State Superfund program in Massachusetts, such factors included an explicit mandate to protect human health, public welfare, safety and the environment, and a need to be consistent with existing state regulatory programs. The result is a risk characterization process which would utilize one of four Methods. Method 3b, which applies to the majority of disposal sites in Massachusetts, relies heavily upon risk assessment to determine the need for remediation and the level of remediation required. A Total Site Cancer Risk Limit of one in one hundred thousand and a Total Site Non-Cancer Risk Limit which is a Hazard Index equal to 0.2 apply at these Method 3b sites.

The State Superfund program is not inconsistent with the Federal program, although care must be taken to insure that the requirements of both are met. The Massachusetts Contingency Plan's reliance on the total site risk approach rather than chemical- and medium-specific standards comes at a time when the Massachusetts Department of Environmental Protection is shifting its structure and focus away from solely medium-oriented programs.

DISCLAIMER

This paper has not been subjected to Department of Environmental Protection (DEP) review and therefore does not necessarily reflect the views of the DEP. No official endorsement should be inferred.

REFERENCES

Sections of the previous text have appeared in an article written by the same authors, and may be referred to for additional information (ref. -1).

1. Madison, M.T., Locke, P.W., and Murphy, M.J., *Risk Assessment Procedures Favored by MCP Guidance Document*, Massachusetts Waste Management Report, Hazardous Waste & Related Issues, Editor: Robert A. Parlow, Esq., 3 (2) 11, May, 1989.
2. National Academy of Sciences, *Risk Assessment in the Federal Government: Managing the Process*, National Academy Press, Washington, DC, 1983.
3. U.S. EPA - Region I, *Supplemental Risk Assessment Guidance for the Superfund Program, Draft final, Risk Assessment Work Group*, U.S. EPA 901-89-001, June, 1989.
4. Massachusetts DEP, *Guidance For Disposal Site Risk Characterization and Related Phase II Activities - In Support of the Massachusetts Contingency Plan*, Office of Research and Standards, May 17, 1989.
5. U.S. EPA *Superfund Public Health Evaluation Manual*, Office of emergency and Remedial Response, Washington D.C., EPA 540/1-86/060 (OSWER Directive 9285.4-1, Oct. 1986 and revised versions).
6. ERT - A Resource Engineering Company, *The "Significant Risk" Project*, prepared for Wehran Engineering, Methuen, MA, Document No. P-G359-100, Jan., 1988.

Defense Priority Model for DoD Site Ranking

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ABSTRACT

The Defense Priority Model (DPM) is intended to permit the use of site-specific monitoring data from RI/FS and other site reports to refine priorities for remedial action. This model combines both quantitative and qualitative information on: (1) the hazards posed by pollutant sources, (2) the potential exposure pathways of surface water, groundwater and air/soil and (3) the potential human and ecological receptors. The information is combined to reach a final score for each site that lies between 0 and 100.

The DPM differs from the HRS in that it is used to rank all sites, not just those for NPL consideration. In addition, it is designed to be applied later in the data acquisition process when more accurate and detailed data will be available. There are also some minor differences in the data that the two models consider relating to pollutant mobility, food chain exposure and the use of pollutant concentration in the model. In general, the DPM uses more detailed data and is a more focused model than the HRS.

This model is being used by DoD to assess relative risk of sites which are ready for remedial design/remedial action in the fiscal year 1990. This will give a good indication of its performance and will help to identify areas where further development can prove beneficial.

INTRODUCTION

Work began on what is now the Defense Priority Model (DPM) in 1984 when the Air Force recognized the need for a defensible methodology for ranking hazardous waste containing sites for cleanup. The initial work was conducted by Barnhouse and his colleagues at Oak Ridge National Laboratory and resulted in the development of the Hazard Assessment Risk Model (HARM)^{1, 2}. This model was then evaluated using comparative testing by a number of reviewers and the results led to the incorporation of a number of changes and the development of HARM II³.

The Air Force determined that the model needed to be computerized to be maximally useful and decided that expert systems technology would be preferable to direct computerization using Lotus(r) or dBase(r). Expert systems technology offered some significant advantages including:

- Ability to incorporate uncertainty
- Ability to accommodate missing data
- Ability to use alternative pathways to obtain an indication of an answer
- Ability to manage flow through the program so that only appropriate questions are asked of the user
- Ability to include expert knowledge and make this available to the user
- Ability to include both quantitative and qualitative data in the decision-making process.

The initial implementation encoded HARM II using the expert systems

shell KES(r) from Software A&E on an IBM compatible PC/AT. This allowed for a rapid prototyping, but it did not support sufficient power or screen management. A decision was therefore made to convert the code to prolog, an AI programming language. Most of the KES code did not have to be rewritten, but complex definitions that translated the KES code into prolog were prepared. The prolog chosen was Arity Prolog version 5.1.

This initial implementation was tested by six professionals ranking a total of 15 sites with two reviewers per site to determine whether the model provided a sufficiently broad range of answers, whether the sites ranked in a logical order and whether the model could be widely used. The answers to all of these questions were affirmative. Additionally, some of the reviewers' suggestions for improving the model and the computerized presentation were incorporated⁴.

Meanwhile, the U.S. EPA reviewed HARM II in 1987 along with several other site rating models to determine the best point to start developing their revised Hazard Ranking System under the NCP⁵. Their decision was to continue to develop HRS, adding in those features felt to be missing, since no existing model met all of their requirements. This study did lead, however, to an identification of some of the relative shortcomings in HARM II⁶. These were:

- There was no soil or air pathway
- The 3 mi. limit on water use was too stringent
- DPM does not consider the quantity of waste at a site
- DPM does not consider pollutant mobility, only groundwater mobility
- There is no provision for including documented evidence of human exposure

Subsequently, a number of these points as well as those identified during the comparative testing have been incorporated into the model⁷.

In November of 1987, the Office of the Secretary of Defense proposed use of the model (renamed the DPM) for use in ranking DoD sites for remedial action under the Defense Environmental Restoration Program (DERP) and solicited comments from interested parties⁸. Comments were received from the U.S. EPA and three states; model improvements have been made in response to these comments.

This paper attempts to provide an overview of the Defense Priority Model currently being used by DoD to rank sites for remedial action.

OVERVIEW OF THE MODEL STRUCTURE

DPM considers the hazards associated with source materials, pathways that may result in exposure and the presence of potential receptors. There are three pathways in DPM:

- Surface Water
- Groundwater
- Air/Soil (considers vaporized compounds and dust).

DPM supports both human and environmental receptors, though the human receptors are more highly weighted. The environmental receptors include both aquatic and terrestrial populations as appropriate.

Figure 1 demonstrates how the various pathway scores are combined to yield the six pathway/receptor scores per site. These six scores are then combined using a root mean square methodology to obtain a single site score (Fig. 2). All scores are normalized so that they range from 0 to 100. This score, by itself, has no meaning and should not be compared to the HRS ranking number for inclusion on the NPL. Most sites evaluated to date scored in the 20 to 30 range, but sites have scored as high as 89 and as low as 3, so a broad range of values can be expected⁹.

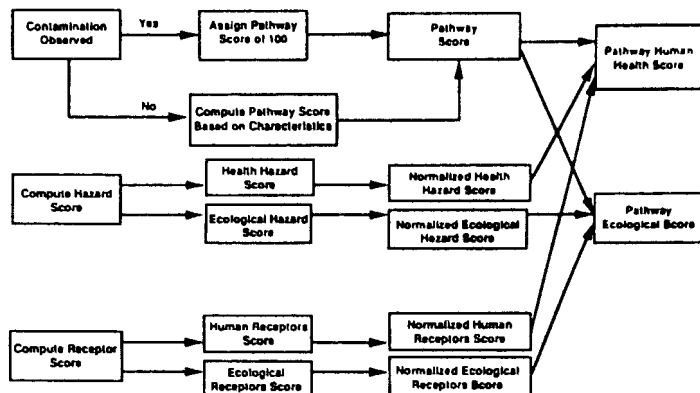


Figure 1
How Pathway Scores Are Computed

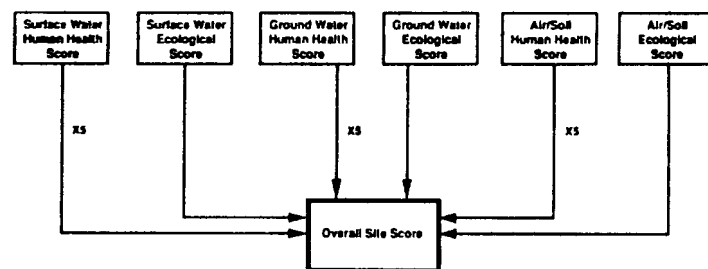


Figure 2
How Site Scores Are Computed

PATHWAYS

To more thoroughly understand what is included in the pathway scores, it is necessary to examine each pathway more closely with regard to the types of data that are used to obtain a pathway score. Different factors have different weights. The basic approach is to obtain a score for each variable and to multiply this score by its weighting factor. The weighted scores for all factors in a pathway are then added and divided by the maximum possible score to obtain a normalized value. For each of the pathways, if a release is observed in that pathway, a maximum score is assigned. However, this score can be modified by a weighting based on how well the waste/hazard is contained.

Surface Water Pathway

The surface water pathway of DPM rates the potential for contaminants from a waste site to enter surface waters via overland flow routes or from groundwater recharge. If pollutants are not directly observed in surface water, but are present in sediments or soil, there is a potential for surface water contamination. The following variables are scored to provide an indication of this exposure potential:

- Distance to nearest surface water (scores are assigned up to 1 mi.)
- Net Precipitation
- Surface erosion potential (combination of slope and particle size)
- Rainfall intensity
- Surface permeability
- Flooding potential (location within floodplain)

The most important factor by far is flooding potential; net precipitation is the least important. The containment of the waste is also determined and becomes an important weighting factor.

Groundwater Pathway

The groundwater pathway ranks the potential for pollutant exposure to occur from contaminated groundwater. If actual groundwater contamination has not been detected but there is contamination in soil or surface water, there is a potential for future groundwater contamination. The following factors are scored to obtain a groundwater pathway score:

- Depth to seasonal high groundwater
- Permeability of the unsaturated zone
- Infiltration potential (measured from net precipitation and the form of the waste)
- Potential for discrete features in the unsaturated zone to "short circuit" the pathway to the water table

Waste containment effectiveness is also a weighting factor on the pathway score. Of the above factors, the depth to the seasonal high water table is the most important factor.

Air/Soil Pathway

The original HARM model did not have an air/soil pathway. Consequently, it was felt that this model did not account adequately for exposure resulting from volatilization of organics from the soil or surface water; neither did it account for exposure to contaminated dust. The factors that are considered in scoring this pathway are:

- Average temperature
- Net precipitation
- Wind velocity
- Soil porosity
- Days per year with significant precipitation
- Site activity.

All of these factors are weighted evenly. A factor for waste containment is also used to modify the final score.

CONTAMINANT HAZARDS

The contaminant hazard component of DPM separately rates human health and ecological hazards of identified or suspected contaminants in each of the three pathways. Hazard scores are calculated differently depending on whether environmental contamination has been detected. For a medium in which contamination has been detected, health hazard scoring is based on the concept of an acceptable daily intake (ADI). The highest concentration observed at a site is used. The observed concentration is first converted to a daily intake (ug/day) and then is divided by the appropriate benchmark concentrations (provided in the manual or on the computer system) which are estimated ADI's. Ecological hazard scoring for observed contaminants is similar, although an ecological benchmark is used instead. The sum of the ecological hazard quotients (concentration divided by the benchmark) is used for all detected components.

For a medium in which contamination has not been detected, a health hazard score is based on the ADIs and bioaccumulation factors of contaminants known to be present at the site being rated. In this case, the score is based on the score for the highest scoring contaminant.

Scoring is similar for all pathways, though the appropriate benchmarks will vary. For example, if the pathway is surface or groundwater, aquatic benchmarks will be used as well as terrestrial benchmarks. For the air/soil pathway, however, only terrestrial factors are employed.

RECEPTORS SCORING

The receptors portion of the DPM methodology rates the potential for human and ecological populations to be exposed to contaminants from a waste site. The potential receptors are considered separately for each pathway and for human and ecological targets.

Human Receptors for Surface Water

The following factors are scored to obtain a measure of human exposure to surface water pollution:

- Size of population obtaining drinking water from potentially affected downslope/downstream surface waters (up to 5 mi.)
- Water use of the nearest surface water
- Population within 1500 ft. of the site
- Distance to the installation boundary
- Land use and zoning within 2 mi. of the site

The first two factors listed above are weighted most heavily.

Human Receptors for Groundwater

The following factors are used as indicators of potential human receptor exposure to contaminants suspected in groundwater:

- Estimated mean groundwater travel time from waste location to nearest downgradient water supply well(s)
- Estimated mean groundwater travel time from current waste site to any downgradient surface water body that supplies water for domestic use or for food chain agriculture
- Groundwater use of the uppermost aquifer
- Size of population potentially at risk from groundwater contamination
- Population within 1000 ft. of the site
- Distance to the nearest installation boundary

Of these factors, the estimated groundwater travel time is considered most important; the water use of the uppermost aquifer also is important.

Human Receptors for Air/Soil

The following factors are used as measures of the potential for human exposure:

- Size of population near the site (4 mi.)
- Land use in vicinity of the site
- Distance to nearest installation boundary

Land use has the most pronounced impact on the final score.

Ecological Receptors—All Pathways

Exposure of potential ecological receptors is determined by whether there are sensitive environments (i.e., wetlands or habitats of endangered species) within 2 mi. of the site and whether there are critical environments (i.e., lands or waters specifically recognized or managed by federal, state or local government agencies or private organizations as rare, unique, unusually sensitive or important natural resources).

COMBINING PATHWAY SCORES TO OBTAIN A FINAL SITE SCORE

The scores for each pathway are obtained by combining the information on the pathway and the hazards for health and ecological receptors. The result are six subscores, one for each receptor/pathway combination. These scores are then combined using a root mean square methodology with the human health scores weighted five times heavier. The final score is then normalized by dividing by the maximum possible score to obtain a site score ranging from 0 to 100.

AUTOMATION OF THE DPM

The computerized version of the DPM using Prolog has permitted

the introduction of a number of improvements over the paper version. Some of these are due to the use of expert systems technology while others are merely due to the greater accuracy and ease of storing and retrieving data that computers provide¹⁰. The new features in the computerized version include:

- Ability to answer a question once even if it is used in several separate pathways and calculations
- Ability to record certainty of answers
- Ability to automatically convert units
- Ability to use alternate data if information is missing
- Range checking of answers
- Ability to change responses and to rapidly recalculate a final score

In addition, the automated version can generate a report that includes, in addition to the scores, full documentation of the final score through comments and the certainty indication. The automated version also controls the user's passage through the model and only presents those requests for information that are deemed necessary depending on previously supplied answers.

FUTURE DIRECTIONS

Work is progressing on DPM and the experience of using it for the FY-90 scoring will create a large body of data on actual sites. These data will be analyzed and changes in the weightings used in DPM will be incorporated where they are felt to be necessary. There is also a plan to convene a group of experts to determine whether additional data should be included in the model to facilitate future decisionmaking. There are also plans to incorporate more expert system features such as logical checking across related responses, more table look-up features and increasing the size of the benchmark data base.

ACKNOWLEDGEMENT

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REFERENCES

1. Barnthouse, L.W., Breck, J.E., Jones, T.D., Kraemer, S.R., Smith, E.D. and Suter II, G.W., *Development and demonstration of a hazard assessment rating methodology for Phase II of the Installation Restoration Program*, ORNL/TM-9857, Oak Ridge National Laboratory, Oak Ridge, TN, 1986.
2. Barnthouse, L. W., Breck, J.E., Suter II, G. W., Jones, T.D., Easterly, C., Glass, L., Owen, B.A. and Watson, A.P. *Relative toxicity estimates and bioaccumulation factors in the Defense Priority Model*, ORNL-6416, Oak Ridge National Laboratory, Oak Ridge, TN, 1986.
3. Smith, E.C. and Barnthouse, L. W., *User's Manual for the Defense Priority Model*, ORNL-6411, Oak Ridge National Laboratory, Oak Ridge, TN, 1986.
4. Hushon, J.M., Mikroudis, G.M. and Pandit, N., *Final Report on Phase I of DPM*, Roy F. Weston, Inc., West Chester, PA, 1988.
5. Industrial Economics, Inc., *Analysis of Alternatives to the Superfund Hazard Ranking System*, Cambridge, MA, 1988.
6. Parker, W.H., Jr., Deputy Assistant Secretary of Defense letter to J. Cannon, Acting Assistant Administrator for the Office of Solid Waste and Emergency Response, U.S. EPA, July 26, 1989.
7. Hushon, J.M., Mikroudis, G.M., and Subramanian, C., *Defense Priority Model (DPM) User's Manual, Version 2.0*, Roy F. Weston, Inc., West Chester, PA, June 1989.
8. *Federal Register*, 52, no. 222, p. 44304-5, Nov. 1987.
9. Hushon, J.M., Mikroudis, G.M., and Pandit, N., *op. cit.*
10. Hushon, J.M., Mikroudis, G.M., and Subramanian, C., *Automated Defense Priority Model (ADPM) User's Manual, Version 2.0*, Roy F. Weston, Inc., West Chester, PA, June 1989.

Uncertainty Analysis for Risk Assessment

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INTRODUCTION

Within the context of the prime questions for risk assessment in hazardous waste management, i.e., "How is the risk estimated?," "What is the magnitude of the risk?" and "Is this risk acceptable?," the concern for the uncertainties becomes the focal point of all decision-makers. Mathematically, risk can be defined as a function of the probability of a negative consequence occurring and the value of that consequence. Therefore, the uncertainty included in the risk assessment may be composed of the uncertainties associated with: (1) the probability estimation (2) the perception of potential consequences (3) the functional relationships involved and (4) the acceptable risk limits. Consequently, the uncertainty analysis addressed herein must deal with all these uncertainties simultaneously.

For the probability estimation, a method based on event/fault tree analyses is developed for the convenience of review and revision. Through the anatomy of risk, the perceptive confusion of the risk can be precipitated. Applying the concept of revealed preference, the risk acceptability is analyzed. Sensitivity analysis is utilized to evaluate the variability of different risks and their acceptabilities while meeting the prescribed confidence limit. The risk assessment for dioxin analysis in a laboratory setting is used as an illustrative example for the uncertainty analysis.

RISK FOR TCDD SAMPLE ANALYSIS

The risk problem addressed here is concerned with the determination of the specific level of safety measures required for the tetrachlorodibenzo-p-dioxin (TCDD) sample process and analysis at a U.S. EPA regional laboratory.

To develop a range of potential risk situations, the laboratory procedures followed were those used by U.S. EPA laboratories and their contractors, beginning with sample packaging in the field and continuing through the final disposal of the TCDD sample residue. In addition, it was assumed that the laboratory was located in a populated office/residential complex. The basic risk elements included the following key steps of the risk pathways (Figure 1):

- Sample packing in the field
- Trans-shipment of packaged sample
- Pre-analysis storage
- Sample cataloguing or inventory
- Extraction and cleaning of the sample in the laboratory
- Concentration and digestion for 2,3,7,8-TCDD
- GC/MS sample preparation
- Intra-laboratory transport of the prepared concentrates of dioxin
- GC/MS analysis
- Data log-in for the computer
- Disposal of the residue of sample and wastewater

- Contamination of the air in the building and to the surrounding community

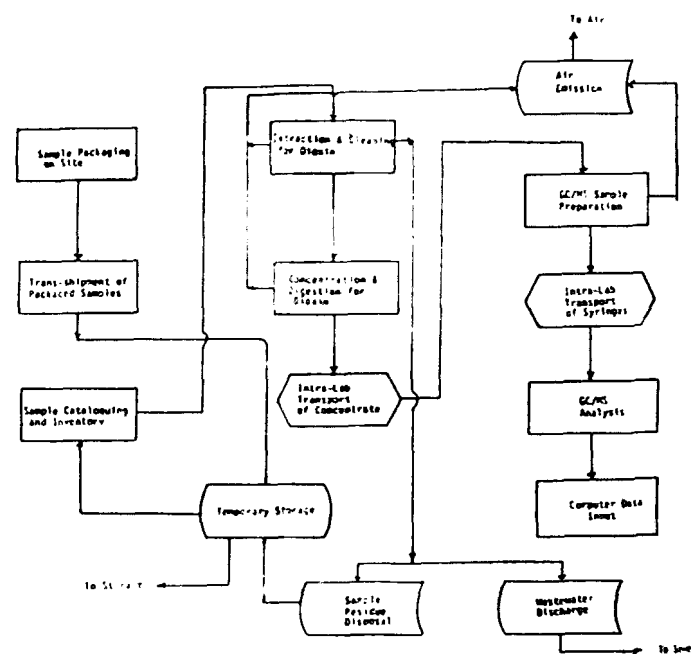


Figure 1
Elements of Risk for Dioxin Analysis

RISK ESTIMATIONS

To prepare for the risk estimation analysis, a series of alternative risk scenarios was developed (Fig. 2). In developing the risk scenarios, alternative risk occurrence pathways and exposure situations for the laboratory personnel, the co-workers in the building and the surrounding communities were considered.

To illustrate the risk relationship between potential hazards and events that may result from contamination to laboratory personnel, co-workers located in the same building and the surrounding populace, a fault tree was constructed.

Contamination pathways for the dioxin may include one or more independent pathways. This is clearly delineated by the separate pathway columns in the fault tree. The hierarchy of the fault tree structure is established by the horizontal levels in the fault tree.

The mathematical relationship quantifying the probability of dioxin contamination during its sample analysis was developed based on the accompanying fault tree and the assigned probability values of specific events as designated by the alpha-numeric variables printed next to the event in the fault tree. The fault tree formula is shown in Table 1.

The variables used to define specific events are consistent with the designation of tree branches in the event tree (Fig. 2). For instance, A2 designates the event of contamination due to the sample packaging and A2a designates the event of contamination caused by the contaminated vermiculite and/or plastic bags used in the packing. The only unique events included in the fault tree analysis are those events associated with the final consequences of the dioxin contamination such as events A2c1 or A2c2.

Table 1
Probability Model Formulation

$P(T) = P(A2) + P(A+) + \text{Any combination of } (A2, B2, C2, \dots, G2)$	$P(C2) = P(D2a) \sum_{i=1}^2 P(D2a1/D2a) + P(D2b) P(D2b1/D2b) + P(D2c) P(D2c1/D2c)$
WHERE $P(A2) = P(A2a) [P(A2a1/A2a) + P(A2a2/A2a)] + P(A2f) P(A2f1/A2f) + P(A2c) [P(A2c1/A2c) + P(A2c2/A2c)] + P(A2c) P(A2c1/A2c) P(A2c2/A2c1)$	$P(D+) = P(E2) + P(E+)$
$P(A+) = P(B2) + P(B+)$	$P(E2) = P(E2a) \sum_{i=1}^2 P(E2a1/E2a) + P(E2b) \sum_{i=1}^2 P(E2b1/E2b) + P(E2c) \sum_{i=1}^2 P(E2c1/E2c)$
$P(B2) = P(B2a) \sum_{i=1}^2 P(B2a1/B2a) + P(B2b) \sum_{i=1}^2 P(B2b1/B2b) + P(B2c) \sum_{i=1}^2 P(B2c1/B2c)$	$P(E+) = P(F2) + P(F+)$
$P(B+) = P(C2) + P(C+)$	$P(F2) = P(F2a) \sum_{i=1}^2 P(F2a1/F2a) + P(F2b) \sum_{i=1}^2 P(F2b1/F2b) + P(F2c) \sum_{i=1}^2 P(F2c1/F2c)$
$P(C2) = P(C2a) \sum_{i=1}^2 P(C2a1/C2a) + P(C2b) \sum_{i=1}^2 P(C2b1/C2b) + P(C2c) \sum_{i=1}^2 P(C2c1/C2c)$	$P(F+) = P(G2a) \sum_{i=1}^2 P(G2a1/G2a) + P(G2b) \sum_{i=1}^2 P(G2b1/G2b) + P(G2c) \sum_{i=1}^2 P(G2c1/G2c)$
$P(C+) = P(D2) + P(D+)$	

Based on this fault tree analysis, as shown in Figure 2, the probability of occurrence for each of the potential dioxin contamination scenarios during its routine through the processing laboratory was evaluated. However, as historical data which can be directly utilized to provide a basis for such assessments is almost non-existent for most of the events, many of the values given for each event are based primarily on subjective judgments. Other values are based on the values used for similar situations in the chemical industry.

RATIONALE FOR ASSESSING PROBABILITY VALUES

With few exceptions, most of the TCDD samples are in solid form. Because of the TCDD's low solubility and high adhesion to soil particles, it is not likely to be separated from the soil in any medium. Meanwhile, the undeniable facts do suggest that TCDD is quite persistent in its existence, and it appears unlikely to be degraded by itself. Therefore, the TCDD contamination to any exposed person will generally result from inhalation, ingestion or absorption through the skin.

POTENTIAL ROUTES OF CONTAMINATION

Inhalation

TCDD-contaminated dust and TCDD vapors generated during the sample analysis procedure may accumulate in the air through the existing air circulation systems. Levels would be higher than those occurring where there is much better ventilation.

Direct Ingestion

Dust which settles on food or dirt on hands and is then transferred to the mouth could be ingested. This route would be of particular concern where non-voluntary co-workers, without the knowledge of specific spills or contamination, are involved. However, exposure that occurs via this route may vary considerably among individuals depending on their behavior regarding protection of food, washing of hands, etc. The judgmental value of probability placed upon this direct ingestion route is very shaky and its accuracy can be seriously questioned.

Absorption through the Skin

Dust which settles on exposed skin and direct contact with the dirt provides opportunities for TCDD to be absorbed through the skin. However, this route for exposure in the laboratory is affected by the following considerations:

- Most of the skin area of the laboratory personnel is covered by clothing
- The contact time, if any, may be very short
- TCDD cannot pass through the skin unless it is removed from the dust particles; consequently, this route may be considered minimal when compared with all of the other possibilities

Other Potential Exposures

- Direct contact with TCDD when it is concentrated in the solvents
- Inhalation of fumes of TCDD while it is being extracted, digested and concentrated
- Direct contact of TCDD by non-workers or involuntary co-workers because of improper handling of the sample residues or the pre-inventory samples

In view of all the potential routes of the various TCDD exposure pathways, the air transport route probably would cause the highest or most severe exposure levels.

ESTIMATION OF TCDD CONCENTRATIONS IN THE AIR

Although laboratory and personnel movement play important roles, for this exercise the following are utilized: dust levels inside the laboratory building are generally low; the activity of people inside and outside the restricted rooms is moderate, causing minimum air turbulence or physical agitation of the dirt and subsequent escape of the dirt from the central area; the building is well ventilated, with the supply air intake point located downstream along the prevailing wind of the exhaust point of the returning air; and the ventilation could create some recycling of the exhaust air and accumulation of the contaminated dust particles.

The TCDD levels in the soil were found to range from 70 to 200 ppb. It was assumed that the total dust levels in the air ranged from 0.4 to 1.0 mg/m³. Assuming the TCDD levels in the dust particles are the same as in the soil, the concentration of TCDD in the air = TCDD concentration in soil x total particulate concentration in air = 3×10^{-8} to 2×10^{-7} mg/m³.

Due to its low vapor pressure, it has been widely assumed that very little TCDD would evaporate from contaminated soil. However, many investigators are now discovering that low vapor pressure compounds which also have low water solubility evaporate more readily from soil; thus TCDD may have an enhanced vaporization rate from the samples, particularly after it has been cleaned, extracted, digested and concentrated. For these reasons, it was assumed that the vapor pressure of TCDD may be much higher than 10⁻⁶ mm of mercury. All these facts suggest that TCDD vapors could cause exposure inside the poorly-ventilated rooms.

The toxicity of the TCDD to animals is fairly well documented; extrapolation of these effects to humans is unknown. It is assumed that its risk ratio is in the range of 200 to 300, which is the same as the worst ratios for vinyl chloride.

Estimates of the probability values are based on the general perception of the likelihood of occurrence of the events in consideration and should be considered as the conservative figures. Conditional probability values following each of the key events are also based on the investigators' judgments. In order to compensate for the uncertainties of these judgmental values, a fairly liberal range is given for each of the probability values. A subsequent sensitivity analysis for selected events should be conducted to assess the resultant probability of the contamination to both laboratory personnel and the community and the sensitivity of the various assumed values.

RISK ACCEPTABILITY ANALYSIS

In order to assess the acceptability of the risk associated with the dioxin laboratory analyses for both the laboratory personnel directly and indirectly involved and for the surrounding community, basic characteristics of the risk in terms of the probability of occurrence and the

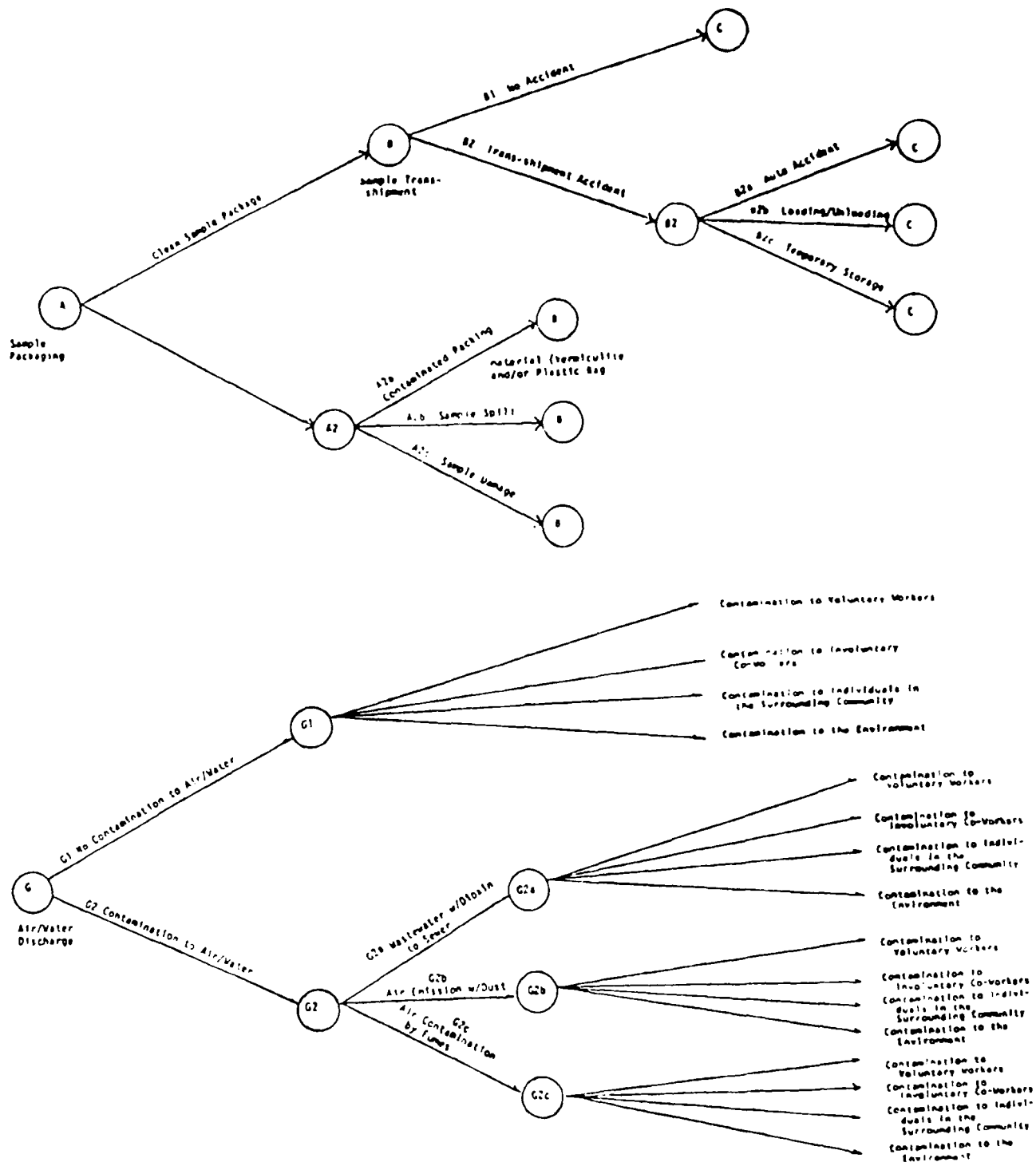


Figure 2
Event Tree for Risk Scenarios

potential consequence to both individuals and the society must be analyzed in detail. First, the basic characteristics of the risk must be defined and delineated. Second, the incremental risk acceptance value for each of the risks identified in terms of risk referent shall be developed. Finally, the objective risk value computed, based on the potential consequence, should be compared with the risk referent value to determine the acceptability of the current practice.

Based on the risk classification as outlined in Table 2, the risks associated with the dioxin laboratory analysis can be characterized as

immediate statistical accidents and categorized as follows:

- Risk for the laboratory personnel specifically assigned to the dioxin analysis: ordinary voluntary risk
- Risk for the co-workers located in the same building: ordinary voluntary regulated risk
- Risk for the surrounding community of the U.S. EPA Regional laboratory: ordinary involuntary risk.

The procedures to be followed for the determination of risk accepta-

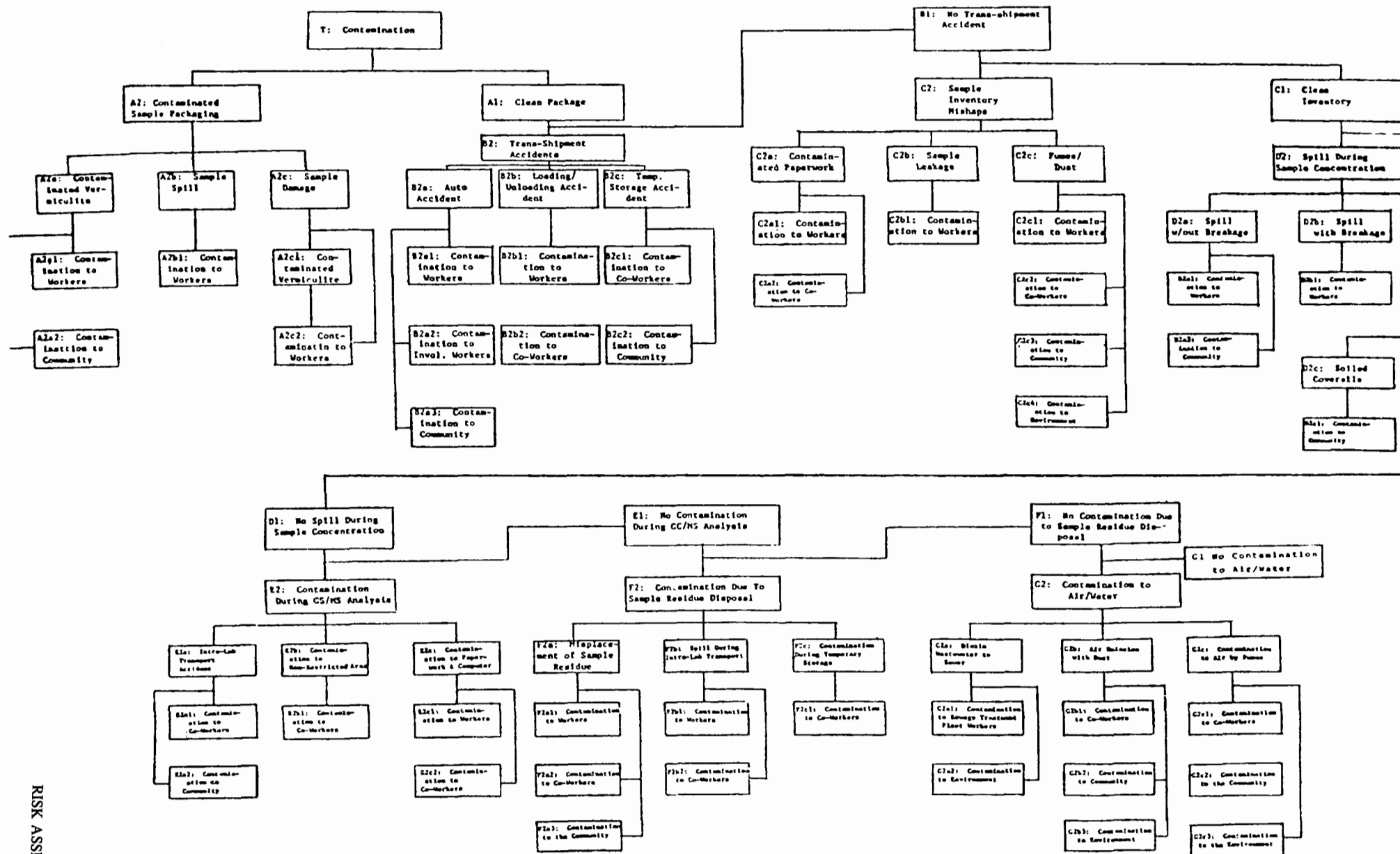


Figure 3
Fault Tree

Table 2
Risk References for Immediate Statistical Accidents

Risk Classification	Fatalities Per Year	Consequences Health Affects Year	Prop. Damage MS/Per Year	Reduction of Life Span (Years)
Naturally Occurring:				
catastrophic:	1×10^{-6}	5×10^{-6}	0.02	3×10^{-2}
Ordinary:	7×10^{-5}	4×10^{-4}	3	0.2
Man Originated				
Catastrophic-				
Involuntary	1×10^{-7}	5×10^{-7}	2×10^{-2}	3×10^{-4}
Voluntary	2×10^{-6}	2×10^{-6}	.4	6×10^{-4}
Regulated				
Voluntary	3×10^{-5}	3×10^{-6}	.4	6×10^{-2}
Ordinary-				
Involuntary	5×10^{-6}	3×10^{-5}	1	1×10^{-2}
Voluntary	1×10^{-4}	6×10^{-2}	200	0.1
Regulated				
Voluntary	1×10^{-4}	6×10^{-2}	30	0.1
Man Triggered				
Catastrophic-				
Involuntary	2×10^{-7}	1×10^{-6}	4×10^{-2}	6×10^{-4}
Voluntary	4×10^{-6}	4×10^{-6}	0.8	6×10^{-3}
Ordinary				
Involuntary	1×10^{-5}			3×10^{-2}
Voluntary	1×10^{-3}			2
Regulated				
Voluntary	2×10^{-4}			0.2

Source: Rowe, W., An Anatomy of Risk, John Wiley & Sons, NY, 1977.

The procedures to be followed for the determination of risk acceptability for the TCDD processing centers are:

- o Develop an appropriate risk classification scheme.
- o Determine the risk reference value for each class of risk encountered in the dioxin analysis procedures.
- o Compute risk referents for each class of risk.
- o Compare the estimated risk from fault tree analysis with the risk referent values.

bility for the TCDD processing centers are:

- Develop an appropriate risk classification scheme
- Determine the risk reference value for each class of risk encountered in the dioxin analysis procedures
- Compute risk referents for each class of risk
- Compare the estimated risk from fault tree analysis with the risk referent values

In view of the risk confronted by different sectors of population in the laboratory and its surroundings, appropriate risk classifications developed for each sector of the population are summarized in Table 3. The dioxin analysis is essentially a typical man-originated, ordinary event. However, since the reliability and statistical validity of existing data characterizing various consequences of the dioxin exposure accidents are absent, only piecemeal information covering personal injuries and immobility could be collected and reviewed. Thus, the risk reference value characterizing the personal injury in terms of health effects per year is the only consequence included in the risk acceptability evaluation as shown in Table 3. In fact, based on limited data, personal injury seems to be the only visible and pronounced consequence due to dioxin exposure being reported so far.

OBTAINING RISK REFERENT VALUES

These risk reference values are estimated directly from historical and societal risk data that are analogous to the situations and consequences involved in dioxin analysis. Transforming the risk reference values into appropriate risk referents requires the following four steps:

- Determine the appropriate risk proportionality factor (F1) which incorporates the societal attitude due to its expectations associated

Table 3
Summary of Risk References for
Dioxin Exposure in Laboratory

Type Risk	Risk Classification	Risk Reference (Hlth. Eff./Yr.)
Personal injury or immobility for laboratory workers	Voluntary, ordinary	3×10^{-1}
Personal injury or immobility for co-workers in the laboratory	ordinary regulated voluntary man originated	6×10^{-2}
Personal injury to the population in local community	ordinary involuntary, man originated	3×10^{-5}

with the degree of voluntarism of the affected population.

- Determine the appropriate risk proportionality derating factor (F2) which discounts the existing societal risk acceptable level due to the indirect benefit/cost balance considerations for the dioxin exposure via laboratory analysis (Table 4).
- Develop and quantify the risk controllability factor (F3) which characterizes the basic control approach, the degree of control, the state of implementation and the judgment of control effectiveness (Table 5).
- Determine the referent using the factors derived in the above three steps by the formula:

$$\text{Risk Referent} = (\text{Risk Reference}) \times F1 \times F2 \times F3 \quad (1)$$

These factors are subjective. The first two factors in Equation 1 address the inherent propensity of effected populations to take risks and also incorporates the additional decision dimension of indirect benefits/cost balance. This acknowledges the tendency of people to accept higher levels of risk when the potential benefits far outweigh the potential costs. On the other hand, people may become increasingly risk averse when the potential benefits are likely to be offset by the costs.

The risk proportionality and its derating factors, as determined for different sectors of populations, are shown in Table 4. Though not to the same degree, the controllability factor also varies due to the target population, as shown in Table 5.

Incorporating all the factors determined above, the appropriate risk referents for different affected population sectors are derived as shown in Table 6.

Table 4
Risk Proportionality and Risk Proportionality Derating Factor

Factor	Value
Proportionality Factor	1.0
Derating Factor	
Laboratory Worker	0.2
Co-Worker in the Building	0.1
Surrounding Community	0.1

RESULTS

On the basis of the above judgments and limited data, the risk referent values were compared to the estimated values the risks for both technicians and their co-workers in U.S. EPA laboratory are considered to be acceptable. On the other hand, the risks for the surrounding community may be marginally acceptable.

Table 5
Controllability Factor

	Control Approach	Degree of Control	State of Implementn.	Control Effectiveness
Laboratory Worker	1.0	1.0	0.5	1.0
Co-Workers in the Building	0.5	1.0	0.5	1.0
Surrounding Community	0.3	0.3	0.1	0.5

Table 6
Risk Referents and Estimated Maximum Risks

Population Sector	Risk Reference	Risk Reference	Est. Max. Risk
USEPA Lab Personnel	3×10^{-1}	$3. \times 10^{-2}$	3.2×10^{-3}
USEPA Co-Workers in the Same Building	6×10^{-2}	1.5×10^{-3}	1.2×10^{-3}
Surrounding Community	3×10^{-5}	1.4×10^{-8}	1.1×10^{-6}

SENSITIVITY ANALYSIS

Sensitivity analysis is a post-solution evaluation technique, intended to determine the degree of confidence which can be placed on the selected solution. In this dioxin analysis example, a wide range of probability values for all events included in the fault tree as shown in Table 7 has been evaluated. Monte-Carlo simulation has been used to analyze the variability of the estimated risk values. The estimated maximum risks cited in Table 6 have a confidence limit of 95%.

Thus, all the risks shown in Table 6 can be considered as conservative judgmental values for all potential accidents described in the fault tree. A difference of magnitude in the order of two to three may still be within the range of cumulative errors. In reality, the risk estimated for the community may be too high and it is therefore considered to be marginally acceptable.

For the facility considered, the sensitivity analysis for specific faulty events indicates that with minimum modification of sample inventory, waste disposal procedures and installation of particulate air filters, the risk to the community can be significantly reduced to 1.1×10^{-8} which is well within the acceptable level. In addition, maximum estimated risk for the co-workers may be lowered from 1.2×10^{-3} to 2.1×10^{-4} which is well below the acceptable level of 1.5×10^{-3} as reflected by the corresponding risk referent values.

CONCLUSIONS

Uncertainty Analysis for the risk assessment in hazardous waste site management can be resolved by the three-prong attack:

- Develop a structured risk estimation model based on an integrated event/fault tree analysis
- Based on a detailed anatomy of the risks involved, conduct the risk acceptability analysis using the revealed preference concept
- Perform a comprehensive sensitivity analysis for the estimated risks to determine the confidence limit of the risk values

In the illustrative example of the risk assessment for the potential hazards to laboratory workers, co-workers and the surrounding community due to the dioxin sample analysis, we have determined that:

- The risk to both laboratory workers and their co-workers in the building is acceptable.
- The risk to the surrounding community may be considered marginally acceptable. However, with minimal modifications to the facility, the risk can become acceptable.

REFERENCES

1. Rowe, W. *An Anatomy of Risk*, John Wiley & Sons, New York, NY, 1977.
2. Shih, C.S. and Ess, T., "Perspectives of Risk Assessment for Hazardous Waste Management,"—*Proc., Third National Conference on Uncontrolled Hazardous Waste Sites*, HMCRI, Silver Spring, MD, pp. 408-413, 1982.
3. Veseley, W., et al., *Fault Tree Handbook*, U.S. Nuclear Regulatory Commission, Washington, DC, NURGC-0492, 1981.

Incorporating Time Varying Parameters In The Estimation of Human Health Risk From Superfund Sites

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ABSTRACT

Risk assessment is a critical step in decision-making in federal and local governments as well as the private sector. It combines information about the frequency, intensity and duration of human exposures to chemical hazards with data on the toxicity of those compounds to yield estimates of the risk of carcinogenic and non-carcinogenic effects associated with those exposures.

Given the complexity and uncertainty inherent in human exposures there is a need to design great flexibility into the risk estimation process. Calculations often are repeated with slight variations in particular inputs to identify the contribution of individual chemical compounds and exposure pathways to the health risk posed by a complicated scenario. For this reason most analysts now perform risk assessments on microcomputer spreadsheets.

To accommodate the need to account for time varying inputs in risk assessments, we have developed a system on Macintosh computers in which programmed macros pass data and intermediate results between Microsoft Excel™ spreadsheets. The system has the capability to model time varying exposures in the estimation of the average daily dose of a substance for assessing the risk of both acute and chronic effects. Both human parameters i.e. skin surface area, breathing rate and body weight which vary with age and environmental parameters (i.e. rate of emissions from an incineration facility) may be assigned different values for each year of exposure.

The linked spreadsheets are designed to calculate exposure doses of chemical contaminants via inhalation, ingestion and dermal pathways. The carcinogenic risk for chronic effects and the "hazard index" for non-carcinogenic effects are automatically estimated for every chemical compound, pathway and receptor and then summed across all pathways and compounds to yield an assessed risk for each receptor.

INTRODUCTION

Early in 1989, Alceon Corporation was asked to perform a risk assessment for a proposed Park & Ride commuter rail station. The station is proposed to be built on the site of a former municipal solid waste (MSW) landfill. Portions of the landfill not covered with asphalt during construction of the Park & Ride facility will continue to receive deposits of ash for 7 yr from a MSW incinerator also located in close proximity to the proposed station.

In order to estimate the risk to human receptors at the Park & Ride facility, it was necessary to calculate the average daily dose (ADD) of each chemical compound of concern, to each category of receptor, through all exposure pathways. Many of the parameters used in these calculations take on a series of values over time due to changes in incinerator operation, variations in gas generation rates from the MSW landfill due to the aging of buried waste and the variations in body weight and inhalation rate of receptors.

As an alternative to using average values for these time varying parameters in the dose calculations, a series of spreadsheets containing detailed parameter information for each year of exposure and facility operation has been developed. These spreadsheets are linked by macros programmed: (1) to calculate the average daily dose of contaminant to each type of human receptor in each year of exposure; (2) to locate the year of maximum exposure (the year in which average daily dose is greatest) to be used in the estimation of potential acute health effects and (3) to calculate the average exposure across a 70 yr lifetime (the average of the average daily doses for all 70 yrs of life) for the estimation of potential chronic health effects.

DISCUSSION

The receptors of concern in this case are adult and child (student) commuters using the Park & Ride facility and a security guard posted in the facility parking lot. Exposures to the security guard are assumed to continue for an entire 45 yr career, (i.e., age 20 until retirement at 65 yrs of age), 8 hrs/workday, 5 workdays/wk. It is extremely conservative to assume that one employee would hold this position for 45 yrs. Exposures to commuters are assumed to occur for 0.5 hr. each commuting day as the commuters wait for the train and walk to and from their car or ride. Adults are assumed to commute for an entire 45 yr career (age 20 until 65, again a very conservative assumption) whereas children are assumed to commute for 6 yrs of secondary school (between the ages of 12 and 18 yrs). The security guard and adult commuter are assumed to experience exposures 50 wk/yr (a 2-wk vacation is assumed). The child commuters are assumed to commute to school 40 wks/yr.

Sources of contaminants to the air at the commuter rail facility include gaseous and particulate stack emissions, gas generated by the buried waste present in the landfill and particulate material released during the transport of ash and its disposal in the landfill. The most toxic carcinogenic and non-carcinogenic compounds released by these sources were identified in a sequential ranking exercise and designated as indicator compounds for the risk assessment.

Portions of the landfill not covered with asphalt during construction of the facility will remain active, receiving ash from the MSW incinerator for 7 yrs. It is estimated that the landfill will reach capacity after 7 more years of operation and it will be capped at that time. Starting in year 7, the ash will be transported elsewhere, eliminating the particulate contributed by fugitive dust from the landfill and landfilling activities. The gas generated by the landfill will continue to contribute to contaminant levels in the air at the commuter station since the capping does not include a collection system for gases. All active sections of the landfill will be fenced off, preventing direct contact with the soil by humans. Due to the security provided by the fence, human health risks may result only from airborne contaminants.

Pathways of exposure considered in the risk assessment include:

- (1) inhalation of organic and inorganic compounds in gaseous form,
- (2) inhalation of organic and inorganic compounds in particulate form,
- (3) (inadvertent) ingestion of organic and inorganic compounds contained in dirt adhered to skin during daily work and (4) dermal penetration of organic compounds also contained in dirt adhered to skin.

The inhalation exposure model used to estimate the dose of chemical contaminants to the child commuter by inhalation is examined here in detail since it incorporates several time varying parameters and provides an example of the technique used to handle these parameters.

Inhalation Exposure Model

The Inhalation Exposure Model is used to estimate the average daily dose (ADD) of a specific chemical to an individual exposed to air containing a known concentration of contaminant. All dose estimates are measured in units of milligrams of bioavailable chemical per kilogram of body weight per day. All the dose calculations are based on an estimation of the average daily dose on a day of exposure. Averaging factors are then used to calculate the average daily dose averaged over each year of exposure. The potential for health effects from compounds with systemic (non-carcinogenic) potencies, the Hazard Index, is estimated by dividing the maximum yearly ADD (the largest average daily dose occurring in any single year) by the reference dose for acute health effects (RefD) provided by U.S. EPA.⁵

$$\text{Hazard Index} = \text{ADD}_{\text{max}} / \text{RefD} \quad (1)$$

The estimated carcinogenic risk associated with exposure to the levels of carcinogenic contaminants present at the facility is calculated by multiplying the CPF (cancer potency factor provided by U.S. EPA,⁵ by the average of the yearly ADDs across a 70-yr lifetime. This calculation yields a unitless carcinogenic risk estimate.

$$\text{Risk} = \text{CPF} \times \text{ADD}_{\text{lifetime avg}} \quad (2)$$

As stated above, all calculations of average daily dose were performed by macros, written in Microsoft Excel™ for Macintosh computers, which link a series of spreadsheets, each containing some portion of the information required for the calculations. Table 1 is an excerpt from the spreadsheet in which the toxicological properties of the indicator compounds are stored. Since all the spreadsheets are linked together, calculations performed in other spreadsheets that require the cancer potency factors (CPF's) and reference doses (RefD's) draw the values directly from the toxicological properties table. Since each parameter value is stored in a single place, rather than in every spreadsheet in which it is used, updating the values with new information is very easy and efficient.

Table 1
Toxicological Properties of Indicator Compounds

Indicator Compound	Inhalation Cancer Potency Factor (mg/kg/d)-1	Inhalation Weight of Evidence (-)	Inhalation CPF Source (-)	Inhalation Reference Dose (mg/kg/d)	Inhalation AIC or RFD Source (-)
Organic Compounds					
benzene	2.90E-02	A	d		
benzo(a)pyrene	6.10E+00	B2	a	1.00E-02	d
methylene chloride	1.40E-02	B2	a	6.00E-02	#
carbon tetrachloride	1.30E-01	B2	a	7.00E-04	#
vinyl chloride	2.95E-01	A	b		
1,1-dichloroethylene	1.20E+00	C	a	9.00E-03	#
1,2-dichloroethylene				2.00E-02	#
1,2-dichloroethane	9.10E-02	B2	a		
trichloroethylene	1.30E-02	B2	a		
tetrachloroethylene	3.30E-03	B2	b	1.00E-02	#
hexachlorobenzene	1.70E+00		#	8.00E-04	#
2,3,7,8-TCDD	1.56E+05		#		
Inorg. Compounds					
arsenic	5.00E+01	A	a		
beryllium	8.40E+00	B2	a		
cadmium	6.10E+00	B1	a	5.00E-04	#
chromium III				5.10E-03	c
chromium VI	4.10E+01	A	a		
copper		D		1.00E-02	c
lead		B2	b	4.30E-04	c
nickel	1.19E+00	A	c		
zinc				1.00E-02	c
hydrogen sulfide				3.00E-03	#

Sources:
a US EPA, 1988, IRIS
b US EPA, 1987, PHRED
c US EPA, 1986, SPHEM

d GRI, Vol. 3, 1988
e US EPA, 1988, Special Report
used other pathway as surrogate

The spreadsheet macros allow the time varying nature of individual parameters to be accounted for in the averaging of dose across time. In the case of exposure by inhalation of contaminants, the following parameters are assigned values in the macros that vary with the age of the receptor: body weight and inhalation rate. In addition, other parameters are assigned values in the macros that vary with time such as the rate of gas generation from the landfill as the MSW ages and both the concentration of indicator compounds in particulate form and the fraction of particulate in the air which may be attributed to the site, before and after the landfilling of ash ceases.

The inhalation dose model follows:

$$\text{ADD} = [(\text{Ca} \times \text{Ir} \times \text{Te} \times (5 \text{ day}/7 \text{ day}) \times (40 \text{ wk}/52 \text{ wk}))] / \text{Bw}(3)$$

Add = average daily dose of a chemical to an individual (mg/kg/day)

Ca = concentration of contaminant in inhaled air (mg/m³)

Ir = inhalation rate (m³/hr)

Te = time duration of exposure per day of exposure (hr/day)

Bw = body weight of individual (kg)

As stated above, of the parameters used in the above calculation, Ir and Bw vary over the 6 yrs of child commuter exposure. The average daily inhalation rate of individuals varies with growth, with the peak rate occurring in the teenage years. The inhalation rate of commuting students involved in moderate activity was assigned the following values in the ADD calculation (data adapted from Snyder, et al.,⁴ and Anderson, et al.,¹ for the U.S. EPA,⁴:

Inhalation Rate (m ³ /hr)	Age (yr)
1.7	12 - 14
1.5	15 - 18

The average body weight of an individual increases with age until about age 17 at which point the average body weight reaches the average adult body weight, 70 kg (adapted from data presented by Snyder, et al.,⁴ and Anderson, et al.,¹ for the U.S. EPA,⁴:

Body Weight (kg)	Age (yr)
45	12-13
50	13-14
55	14-15
60	15-16
65	16-17
70	17-18

In addition to the variation in characteristics of the exposed individuals, the concentration of contaminant in the inhaled air, Ca, was projected to vary, due to variations over time in the generation of gas by the landfill. Depending on the length of time since disposal of the waste, the gas generation rate is known to vary significantly.³ For the 6 yrs of exposure to an individual child commuter, a single value of annual gas generation in m³ gas generated per kg of waste deposited was selected; however, across the 45-yr exposure durations of both the adult commuter and the security guard, the gas generation rate from the landfill, and thus the concentration of contaminant in air, were assigned a series of declining values.

The concentration of contaminant in air also varies due to planned changes in the operation of the landfill, such as the cessation of the disposal of ash after 7 yrs of Park & Ride facility operation. Since ash disposal in the landfill would occur only in the first 7 yrs of facility operation, the fraction of the concentration of particulate material occurring in the air as fugitive dust from the trucking and disposal of the ash is not included in the total concentrations of particulate to which adult commuters and the security guard were exposed after year 7. The child commuter, however, has an exposure duration of 6 yrs; years; therefore, the particulate contribution from ash landfilling activities is included throughout the child commuter's exposure.

Table 2 is an excerpt from one of the spreadsheets that performs the health effects calculations. Airborne concentrations of contaminants and various exposure factors are called to this spreadsheet by macros. The macros use the parameter values for each year of interest to calculate the ADDs. The actual macros are not shown in the excerpt. The ADDs are then passed to a summary spreadsheet such as the one shown in Table 3. The summary spreadsheet calculates the hazard index and incremental lifetime carcinogenic risk attributed to each indicator compound. Finally, the total hazard index and incremental lifetime risk estimate across all indicator compounds, associated with a single pathway (such as the inhalation of gaseous contaminants) for a single receptor (such as the child commuter), are tabulated.

Table 2
Excerpt from Spreadsheet Health Effects Calculation

General Variables	Age (yrs)	Exposure at Station? (Toggle)	Landfill Active 7 Yrs (Toggle)	Landfill Inactive (Toggle)	Inhalation Rate (m3/hr)	Body Weight (kg)
0	0	0	0	0	0.5	2.5
1	0	0	0	0	1	9
Hours per Day	2	0	0	0	1	11
3	0	0	0	0	1	13
4	0	0	0	0	1	17
0.5	5	0	0	0	1.2	20
6	0	0	0	0	1.4	23
7	0	0	0	0	1.4	26
Days per Week	8	0	0	0	1.4	30
9	0	0	0	0	1.4	33
10	0	0	0	0	1.7	35
5	11	0	0	0	1.7	40
12	1	1	0	0	1.7	45
Weeks per Year	13	1	1	0	1.7	50
14	1	1	0	0	1.7	55
15	1	1	0	0	1.5	60
40	16	1	1	0	1.5	65
17	1	1	0	0	1.5	70
Bioavailability	18	0	1	0	1.5	70
19	0	0	1	1	1.5	70
1	20	0	0	1	1.5	70
21	0	0	0	1	1.5	70

CONCLUSION

As more work is done in the field of uncertainty analysis, risk assessment calculations will include increasingly refined representations of reality. Rather than assigning discrete values that vary with time to parameters used in the health effects calculations, a distinct probability distribution for each year of interest will be assigned to the time varying parameters.

Table 3
Child Commuter Inhalation of Gaseous Contaminants

Name of Compound	Year 1-7 Exposure Point Concentration in Air (mg/m3)	Estimated ADD (max year) from Exposures (mg/kg/d)	Estimated ADD (life) from Exposures (mg/kg/d)	Hazard Index for NonCarc	Incremental Lifetime Risk for Carc
Organic Compounds					
benzene	2.98E-04	3.09E-06	2.01E-07		5.82E-08
benzo(a)pyrene	4.80E-09	4.77E-11	3.11E-12	4.77E-09	1.80E-11
methylene chloride	2.67E-04	2.77E-06	1.80E-07	4.81E-05	2.82E-06
carbon tetrachloride	2.98E-05	3.09E-08	2.01E-09	4.41E-05	2.81E-10
vinyl chloride	7.43E-05	7.71E-07	5.02E-08		1.46E-08
1,1-dichloroethylene	4.46E-05	4.62E-07	3.01E-08	5.13E-05	2.61E-08
1,2-dichloroethylene	3.57E-04	3.71E-06	2.41E-07	1.85E-04	
1,2-dichloroethane	1.19E-04	1.24E-06	8.04E-08		7.22E-08
trichloroethylene	7.74E-04	8.03E-06	5.23E-07		6.80E-08
tetrachloroethylene	4.78E-04	4.94E-06	3.22E-07	4.94E-04	1.06E-08
hexachlorobenzene	2.40E-09	2.49E-11	1.62E-12	3.11E-08	2.76E-12
2,3,7,8-TCDD	4.50E-12	4.67E-14	3.04E-15		4.74E-10
Inorganic Compounds					
hydrogen sulfide	3.26E-03	3.38E-05	2.20E-06	1.13E-02	
0.9 rv					
1.0 pre7case					
1.0 post7case					
Totals -->				1.21E-02	7.82E-08

REFERENCES

- Anderson E., et al., "Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments," U.S. EPA, Revised Draft Final Report, Office of Health and Environmental Assessment, Contract No. 68-02-3510, Sept. 1984.
- GRI, "Management of Manufactured Gas Plant Sites, Volume III, Risk Assessment," GRI-87-0260.3, May 1988.
- Lockman & Associates, "Landfill Gas and Landfill Gas Constituent Emissions Modeling, for a Hypothetical 3000-ton per day Southern California Landfill," Monterey Park, CA, 1985.
- Snyder W.S., Cook M.J., Nasset E.S., Karhausen L.R., Howells G.P., and Tipton I.H., "Report of the Task Group on Reference Man," International Commission on Radiological Protection Number 23, Pergamon Press, Oxford, 1975.
- U.S. EPA, "Superfund Public Health Evaluation Manual (SPHEM)," Office of Emergency and Remedial Response, Washington, DC, EPA/540/1-86/060, 1986.
- U.S. EPA, "Public Health Risk Evaluation Database (PHRED)," Office of Solid Waste and Emergency Response, Washington, DC, 1978.
- U.S. EPA, "Integrated Risk Information System (IRIS)," Volume 1 and Electronic Information System, Office of Health and Environmental Assessment, EPA/600/8-86/032a, Mar. 1987.
- U.S. EPA, "Special Report on Ingested Inorganic Arsenic: Skin Cancer; Nutritional Essentiality," EPA/625/3-87/013, Science Advisory Board, Washington, DC, 1988.

Terrestrial Food-Chain Model for Risk Assessment

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ABSTRACT

To assess the potential impact of a proposed Hazardous Waste Incinerator in Niagara Falls, New York on terrestrial wildlife species, IT Corporation developed a simplified food web model to predict body burdens of selected constituents of concern. Appropriate habitat areas within 5 km of the incinerator were identified and eight species were selected for a detailed assessment. Only areas capable of supporting long-term habitation for the selected target species were considered appropriate for selection. An exposure assessment was performed for each species at each habitat.

INTRODUCTION

For the purpose of assessing the impact of the stack emissions to terrestrial species, appropriate habitat areas within 5 km of a proposed hazardous waste incinerator (HWI) were identified and eight species were selected for a detailed assessment of the impact of non-carcinogenic compounds. Five mammalian species were evaluated to assess potential effects of carcinogens. An exposure assessment was performed for each species and the risks associated with these exposures were calculated.

To conduct this terrestrial species assessment, assumptions and adjustments to toxicological data generally available in the literature were made. The majority of these data are derived using standard laboratory animals or agricultural crop species. Plants and animals in the natural environment tend to have longer exposures than those in the laboratory due to life span, multiple exposure pathways and differences in subspecies metabolism. The application of uncertainty factors provides a conservative adjustment for the use of laboratory derived data. General assumptions used in this assessment regarding incorporation of the selected indicator constituents into the biological system are:

- Toxicity is assumed to be independent of dosing schedule
- An average daily food/water consumptions are used for all calculations which assume no variation
- The food-chain model used in this assessment incorporates emissions into single trophic levels of the food chain with bio-accumulation and bio-magnification at subsequently higher species levels
- The HWI produces emissions for an indefinite time

A screening methodology was applied to the waste stream and 11 constituents were selected as indicators for evaluation. Ambient air concentrations and deposition rates for the selected constituents of concern were calculated using the U.S. EPA's ISCLT air dispersion model.

ECOLOGICAL ASSESSMENT END-POINTS

Because of the complexity of interactions within a food-chain, it is difficult to assess the potential impacts to all receptors for all end-points.

Receptors (the selected target species) are the components of the ecosystem that may or may not be adversely affected by the selected indicator constituents. End-points are the particular types of impacts a constituent has on a receptor.

Possible end-points for ecological risk assessments can be divided into four levels: individual; population; community; and ecosystem. These levels may be further assessed as:

Individual end-points of biological interest

- Changes in respiration
- Changes in behavior
- Increased susceptibility to illness
- Decreased growth
- Death

Population end-points of biological interest

- Decreased genotypic and phenotypic diversity
- Decreased fecundity
- Decreased growth rate
- Increased frequency of disease
- Increased mortality rate

Community end-points of biological interest

- Decreased species diversity
- Decreased food web diversity
- Decreased productivity

Ecosystem end-points of biological interest

- Decreased diversity of communities
- Altered nutrient cycling
- Decreased resilience

Presently, there are no regulatory standards concerning individual end-points of biological interest for non-human terrestrial species. There is, however, a general consensus defining adverse effects at the population level. For this reason, this level was chosen as the most appropriate end-point for use in terrestrial species assessments.

HABITAT EVALUATION

Areas inscribed by concentric 400 mi circles radiating out for 5 km from the HWI were addressed based on the determined ISCLT depositional pattern. Based on these results, no areas of high deposition beyond this radius were evident. Areas that could support the selected target species were delineated. Only areas capable of supporting long-term habitation of the target species were considered appropriate for selection. This selection process was based on the following criteria: habitat must have a sufficient receptor-specific food supply, adequate area to accommodate the receptor's normal range, sufficient water supply and a lack of continuous intervention by man. Areas selected are

representative of or a composite of the following biomes: Grasslands, Temperate Forest and Taiga.

SELECTION OF TARGET SPECIES

Not all organisms are suitable for use as target species to evaluate constituent impacts. General considerations and assumptions must be applied in selecting target species³. The following criteria were applied in the selection of target species:

- Target species must be capable of accumulating the selected indicator constituent to measurable amounts
- Target species should be easily collected or observed and be available should field calibration or verification studies become necessary
- Relevant information pertaining to interactions between the target species and the selected indicator constituent(s) should be available in the scientific literature
- Target species should, as a group, represent all levels of the food web
- Target species should represent various exposure pathways

Target Species

The representative species of wildlife selected for this assessment are:

Avian:

Buteo jamaicensis (Raptor) Red-tailed Hawk
Philohela minor (Non-passerine) Woodcock

Mammalian:

Blarina brevicauda (carnivore) Short-tailed Shrew
Marmota monax (herbivore) Woodchuck
Odocoileus virginianus (herbivore) White-tail Deer
Sylvilagus floridanus (herbivore) Cottontail Rabbit
Vulpes vulpes fulva (omnivore) Red Fox

Reptilian:

Chelydra serpentina (omnivore) Snapping Turtle

Figure 1 shows a general review of the potential routes of exposure and Figure 2 shows the simplified food web relationship of these target species. Individual pathway parameters of exposure are presented in Table 1.

EXPOSURE ASSESSMENT PATHWAY MEDIA CALCULATIONS

From previously derived emission rates, the ISCLT model and the California Air Resources Board deposition algorithm were used to calculate the total deposition rate and air concentration at the defined receptor locations.

The deposition rate was used to determine the average soil concentration which, in turn, was used to estimate the concentration accumulated in vegetation from root uptake at each of the selected habitats. Emission rates were used to calculate surface water concentrations which, in turn, were used to estimate the body burden of fish in the Niagara River and Gill Creek within a 5 km radius of the HWI. The air concentration from the initial air modeling effort was used to calculate the amount of each selected indicator constituent which would be inhaled directly by the target species.

Exposure Scenario

A food chain or food web was constructed for each target species. A food web is, by definition, a series of food chains connecting producers and consumers in an ecosystem. Producers are the plants which make up the base trophic level. Consumers are the representatives of all other trophic levels including herbivores, carnivores, omnivores and parasites.

The principal mode of constituent transport is via the atmospheric pathway with deposition onto soil, surface water and vegetation. Subsequent fate and transport processes result in the final constituent concentrations in the selected media as determined below.

The total daily uptake (mg/kg/day) of the target species was calculated by adding the amount of constituent ingested through: (1) consumption of vegetation, (2) direct ingestion of soil, (3) surface water, (4) fish tissue, (5) inhalation and (6) ingestion of other target species.

Methodology for Calculation of Soil Concentrations

Soil concentrations of the selected indicator constituents were calculated for each receptor location based on total deposition rates

Table 1
Estimated Diets for Selected Target Species

Species	Average Body Weight kg	Water ml/day	Soil g/day	Inhalation Air L/day	Arthropods Earthworms g/day	Herbaceous Plants g/day	Shrubs Trees g/day	Prey g/day	Fish g/day
Avian									
Red-tailed Hawk	0.750	45.0 ^a		360 ^d				112.0 ^f	
Woodcock	0.135	8.1 ^a	0.013 ^c	65 ^d	20.0 ^f				
Mammalian									
Short-tailed Shrew	0.022	3.2 ^b	0.002 ^c	10 ^d	22.0 ^g				
Woodchuck	4.200	87.0 ^a	0.420 ^c	1362 ^d		252.0 ^h			
White-tail Deer	50.00	3000 ^a	5.000 ^c	22454 ^d		1750 ^h	1750 ^h		
Cottontail Rabbit	1.450	210.0 ^b	0.145 ^c	470 ^d		43.5 ^h	43.5 ^h		
Red Fox	5.200	312.0 ^a	0.520 ^c	1686 ^d		78.0 ^h	78.0 ^h	156.0 ^h	
Reptilian									
Snapping Turtle	10.00	600.0 ^b		1248.0 ^e		60.0 ^h			540.0 ^h

a Average of 0.06 ml/g/day water required for metabolic homeostasis

b Average of 0.15 ml/g/day water required for metabolic homeostasis

c Soil ingestion equals 1.0×10^{-4} of body weight

d Average of 0.6755 ml/g/hr oxygen required for metabolic homeostasis

e Average of 0.260 ml/g/hr oxygen required for metabolic homeostasis

f Average of 0.150 g/g/day food required for metabolic homeostasis

g Average of 1.00 g/g/day food required for metabolic homeostasis

h Average of 0.06 g/g/day food required for metabolic homeostasis

* Newell et al., 1987. Niagara River Biota Contamination Project: Fish Flesh Criteria for Piscivorous Wildlife.

specific for each location.

The basic formula used to determine the concentration of the selected indicator constituents in soil due to aerial deposition is:

$$\text{Soil concentration (mg/kg)} = \frac{\text{DR (ug/m}^2\text{/yr)} \cdot T \cdot K \cdot R}{\text{MD (m)} \cdot \text{BD (kg/m}^3\text{)}} \quad (1)$$

Where:

- DR Deposition Rate
T Accumulation Time of 30 years
K Conversion Constant $\frac{1 \text{ mg}}{1000 \text{ ug}}$
R 1.0 Representing no loss of constituents due to physical or chemical means
MD Mixing Depth of 0.50 meters
BD Bulk Density of soil at receptor site 1250 kg/m³

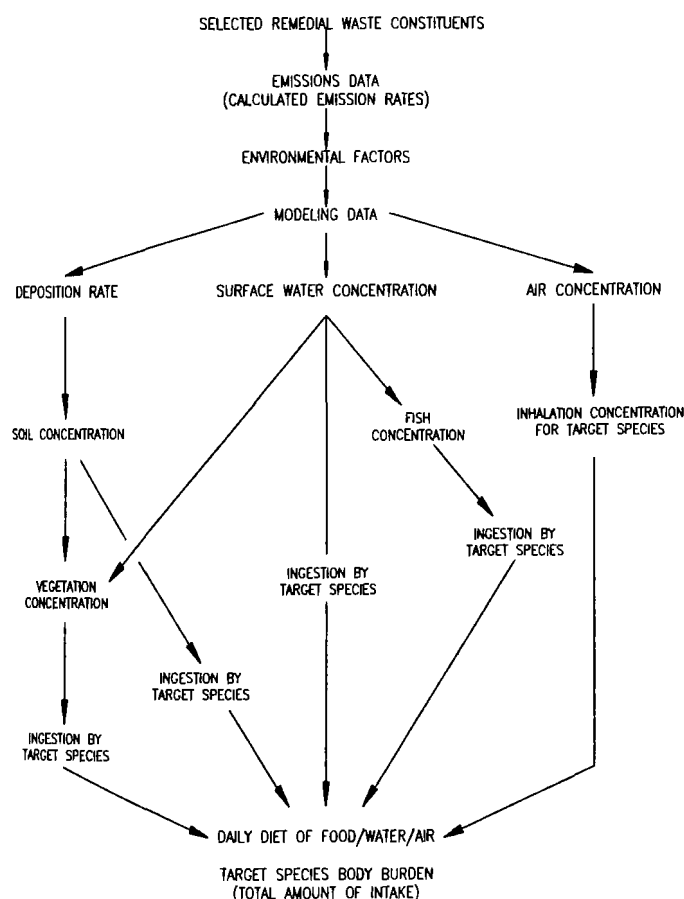
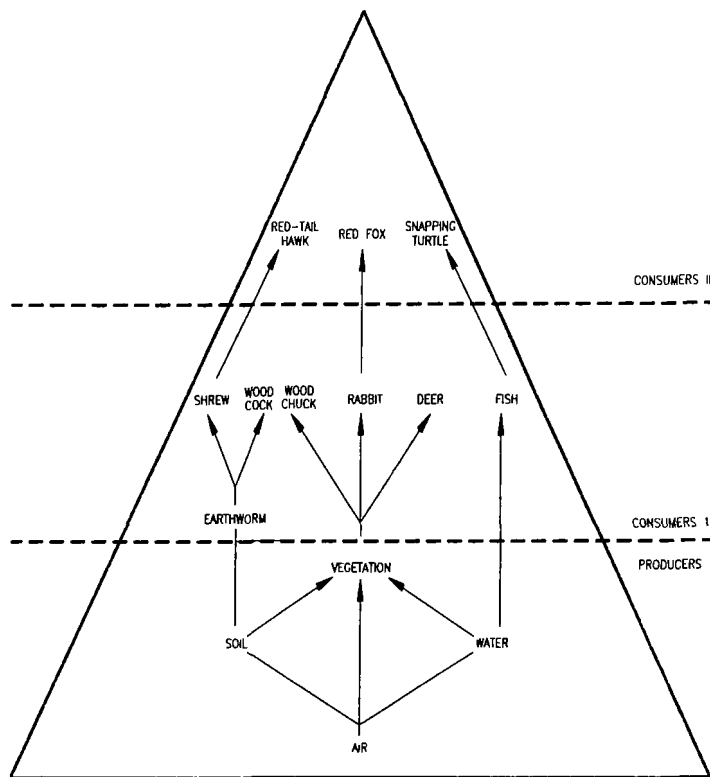


Figure 1
General Pathway

Methodology for Calculation of Surface Water Concentrations

The surface water concentrations were derived based on the Tier I analysis as referenced by the U.S. EPA⁸. Subsequently these concentrations will serve as the exposure concentrations for the calculation of constituent uptake by fish through the surface water pathway and transfer via the food chain into the target species. The following equation was used to calculate the surface water concentrations:

$$\text{Surface Water Concentration (mg/L)} = \frac{\text{ER (g/s)} \cdot \text{EC} \cdot R \cdot K}{\text{River flow (ft}^3\text{/s)}} \quad (2)$$



* SIMPLIFIED FOOD WEB INTERACTION OF TARGET SPECIES

Figure 2
Food Web

where:

- ER = emission rate
EC = emission constant, which represents the percentage of stack emissions deposited on the surface water
R = fraction of selected indicator constituents in the water column

$$K = \text{conversion constant} \quad \frac{1000 \text{ mg}}{\text{g}} \cdot \frac{1 \text{ ft}^3}{28.32 \text{ L}}$$

River Flow = The average annual flow of the body of surface water.

Methodology for Calculation of Plant Tissue Concentration

Generally, there are four main pathways by which a constituent in the soil can enter a plant. These are:

- Root uptake and subsequent translocation by the transpiration stream
- Vegetative uptake of vapor from the surrounding air
- Uptake by external contamination of shoots by soil and dust, followed by retention in the cuticle or penetration through it
- Uptake and transport in oil cells which are found in oil containing plants like carrots and cress

The amount of an organic constituent found in a plant will be the sum total of each of these transport routes minus metabolic losses. Their respective importance will depend upon the nature of the organic constituent, the nature of the soil and the environmental conditions under which plant exposure occurs. For the purpose of this risk assessment, both foliar deposition and root uptake are addressed.

Using the soil concentration and total deposition rates derived previously, the plant tissue concentration can be determined using the

following formula:

$$\text{Plant Tissue Conc. (mg/kg)} = \frac{\text{Surface Deposition (mg/kg)} + \text{Root Uptake (mg/kg)}}{(3)}$$

where:

Plant Tissue Conc. = Concentration of the indicator constituent in vegetation as the result of foliar deposition and root uptake.

Surface Deposition = Concentration of the indicator constituent in vegetation as the result of foliar deposition.

Root Uptake = Concentration of the indicator constituent in vegetation as the result of root uptake.

The following equation was used to calculate foliar surface deposition:

$$C_d \text{ (ug/kg)} = \frac{\text{TDR (ug/m}^2\text{/yr)} [R(1-e^{-kt})] F}{y \text{ (kg/m}^2) \cdot k \text{ (1/yr)}} \quad (4)$$

where:

C_d = Concentration of the indicator constituent in vegetation as the result of foliar deposition.

TDR = Total Deposition Rate

R = Vegetation interception fraction as derived from Baes et al., 1984.

k = Rate constant for surface degradation processes as calculated from Baes et al., 1984 (36.1 yr⁻¹)

T = Length of the growing season from Baes et al., 1984 (0.51)

F = Fraction of the year the plant is in the field (1.0).

y = Biomass of temporal/evergreen forest, Whittaker and Likens, 1973 (36.0).

The following equation was used to calculate root uptake concentrations:

$$\text{Root Uptake Concentration (mg/kg)} = \text{Soil Concentration} \times \text{RUF} \times \text{EP} \quad (5)$$

where:

Soil Concentration = use site-specific concentrations for selected indicator constituents.

RUF = Root Uptake Factor

EP = Edible Portion of plant, 50% (Heichel and Hankin, 1976) which accounts for the percentage from root uptake that is partitioned to the leaves and growing shoots of the vegetation.

Root Uptake Factors (RUFs) of organic constituents were derived based on work by Briggs et al.² Briggs studied the uptake of organic constituents from solution by barley shoots and established the following relationship between the root concentration factor (RCF) and the octanol/water partition coefficient (Kow) for the organics tested:

$$\text{RCF} = \text{Antilog} [0.77 (\log K_{ow}) - 1.52] + 0.82 \quad (6)$$

The RUF for each constituent can be determined from the RCF given the following relationship:

$$\text{RUF} = \frac{\text{RCF}}{(K_{oc}) (F_{oc})}$$

Where: Koc = Soil-organic carbon-water partition coefficient

Foc = percent organic carbon content of soil 0.05

RCF = Root Concentration Factor

Koc values for the selected indicator constituents were obtained from the U.S. EPA, *Superfund Public Health Evaluation Manual*.⁸ Foc values were obtained from the USDA Soil Survey. The Root Uptake

Factors for selected inorganic indicator constituents are those published by Baes, et al'.¹

Methodology for Calculation of Fish Tissue Concentration

The accumulation of the constituents in fish tissue involving the processes of bio-concentration and bio-magnification were calculated using the following formula:

$$\text{Fish Tissue Concentration (mg/kg)} = \text{Surface Water Concentration (mg/L)} \cdot \text{BCF (L/kg)} \quad (7)$$

where:

Surface Water Concentration = Site-specific values

BCF = Bio-concentration Factor of the selected indicator constituents

Methodology for Calculation of Target Species Total Daily Exposure

The methodology used in the calculation of the total daily exposure of each target species follows the methodology set forth by the U.S. EPA⁴. Since the methodology in the U.S. EPA's Manual has been developed for human exposure, target species-specific factors were developed to more accurately describe the exposures to individual species. These factors are presented in Table 1. This methodology assumes that the daily concentration of the selected indicator constituent bio-accumulated in the target species is assumed to equal the daily dose ingested and follow a linear additive bio-magnification model.

Total exposure of a target species is defined as the summation of exposure from each individual pathway. Sources of exposure can be represented mathematically as:

$$\text{Soil}_{exp.} \text{ (mg/day)} = \text{Soil Conc. (mg/kg)} \cdot \text{Soil Ingested (kg/day)} \cdot \text{GAF} \cdot \text{DF} \quad (8)$$

where:

Soil_{exp.} = Constituent exposure of the target species as the result of ingestion of soil.

Soil Conc. = Soil concentration.

Soil Ingested = The target species specific rate of ingestion of soil as defined in Table 1.

GAF = A Gut Absorption Factor of 100 percent was not used for this pathway as soil is not a normal dietary component. Constituent associations with foodstuffs and water, are for the most part reversible; whereas, particular binding of constituents to soil is for the most part irreversible. Therefore, for this exposure scenario a GAF of 10% for inorganics (Osweller et al., 1985) and 30% for organics (Devito et al., 1988) is used.

DF = Digestion Factor 55% (0.55) which represents the average of ruminant (65%) and non-ruminant (45%) target species (Maynard et al., 1979).

$$\text{Water}_{exp.} \text{ (mg/day)} = \text{Surface water conc. (mg/L)} \cdot \text{water Ingested (L/day)} \cdot \text{GAF} \cdot \text{DF} \quad (9)$$

where:

Water_{exp.} = Constituent exposure of the target species as the result of ingestion of water.

Surface Water Conc. = Water concentration.

Water Ingested = The Target species specific rate of ingestion of water.

GAF = Gut Absorption Factor 100% (1.0).

DF = Digestion Factor 100% (1.0).

$$\text{Vegetation}_{exp.} \text{ (mg/day)} = \text{Plant Tissue Conc. (mg/kg)} \cdot \text{Amount Ingested (kg/day)} \cdot \text{GAF} \cdot \text{DF} \quad (10)$$

where:

Vegetation_{exp.} = Constituent exposure of the target species as the result of ingestion of vegetation.

Plant Tissue Conc. = Plant concentration.

Amount Ingested = The target species specific rate of ingestion of vegetation.

GAF = Gut Absorption Factor 100% (1.0).

DF = Digestion Factor 55% (0.55) which represents the average of ruminant (65%) and non-ruminant (45%) target species (Maynard et al., 1979).

$$\text{Fish}_{exp.} \text{ (mg/day)} = \text{Fish Tissue Conc. (mg/kg)} \cdot \text{Fish Ingested (kg/day)} \cdot \text{GAF} \cdot \text{DF} \quad (11)$$

where:

Fish_{exp} = Constituent exposure of the target species as the result of ingestion of fish.

Fish Tissue Conc. = Fish concentration.

Fish Ingested = The target species specific rate of ingestion of fish as defined in Section E3.0.

GAF = Gut Absorption Factor 100% (1.0).

DF = Digestion Factor 55% (0.55) which represents the average of ruminant (65%) and non-ruminant (45%) target species (Maynard et al., 1979).

$$\text{Meat}_{\text{exp}} \text{ (mg/day)} = \text{P.S. Tissue Conc. (mg/kg)} \cdot \text{P.S. Ingested (kg/day)} \cdot \text{GAF} \cdot \text{DF} \quad (12)$$

where:

Meat_{exp} = Constituent exposure of the target species as the result of ingestion of meat.

P.S. Tissue Conc. = Prey species tissue concentration

P.S. Ingested = The target species specific rate of ingestion of meat as defined in Table 1.

GAF = Gut Absorption Factor 100% (1.0).

DF = Digestion Factor 55% (0.55) which represents the average of ruminant (65%) and non-ruminant (45%) target species (Maynard et al., 1979).

$$\text{Air}_{\text{exp}} \text{ (mg/day)} = \text{Air Conc. (ug/m}^3\text{)} \cdot \text{Air Inhaled (L/day)} \cdot \text{LAF} \cdot \text{K (m}^3\text{/L)(mg/ug)} \quad (13)$$

where:

Air_{exp} = Constituent exposure of the target species as the result of inhalation.

Air Conc. = Air Concentration.

Air Inhaled = The target species specific rate of inhalation as defined in Table 1.

LAF = Lung Absorption Factor 100% (1.0).

K = Conversion constants of m³/1000L and mg/100 ug.

Therefore, total daily oral exposure can be defined mathematically as:

$$\text{TDE}_{\text{oral}} \text{ (mg/kg/day)} = \text{Soil}_{\text{exp}} \text{ (mg/kg/day)} + \text{Water}_{\text{exp}} \text{ (mg/kg/day)} + \text{Diet}_{\text{exp}} \text{ (mg/kg/day)} \quad (14)$$

where:

TDE_{oral} = Total daily exposure of the target species as the result of all oral-associated pathways

Soil_{exp} = Constituent exposure of target species as the result of soil ingestion.

Water_{exp} = Constituent exposure of target species as the result of water ingestion.

Diet_{exp} = Constituent exposure of target species as the result of vegetation, fish, and meat ingestion.

While the Total Daily Exposure based on the inhalation exposure is equal to the inhalation pathway alone.

$$\text{TDE}_{\text{inhalation}} \text{ (mg/kg/day)} = \text{Air}_{\text{exp}} \text{ (mg/kg/day)} \quad (15)$$

where:

TDE_{inhalation} = Total Daily Exposure of the target species as the result of all air-associated pathways.

Air_{exp} = Constituent exposure of the target species as the result of the inhalation.

RISK CHARACTERIZATION

This section of the paper defines the risk characterization for terrestrial species based on methodologies developed for a human health risk assessment. Species-specific factors were developed to account for interspecies differences in uptake, absorption, excretion, etc. and adapt the models to assess risk to local target species.

A comparison was made between projected intakes and available reference levels (RFDs) for non-carcinogens and between calculated risks and target risks for potential carcinogens. For non-carcinogens, direct comparison is made between estimated intakes and available reference levels, whereas for carcinogens, estimated intakes are combined with upper bound carcinogenic potency factors to calculate risk.

The carcinogenic risk estimate for multiple constituents is represented by the following equation:

$$\text{Risk} = \sum (\text{CDI}_i \times \text{Carcinogenic Potency Factor}_i) \quad (16)$$

where:

CDI_i = Chronic Daily Intake for the ith Constituent

CPF = Carcinogenic Potency Factor from Superfund Exposure Assessment Manual (USEPA, 1988).

Carcinogenic Risk of Constituents

Eight carcinogenic indicator constituents are associated with stack emissions. These constituents were assessed to determine daily exposure by either inhalation or ingestion. Probabilities of additional carcinogenic risk of the selected indicator constituents were calculated for seven receptor locations via the following pathways:

- Ingestion Pathway
- Inhalation Pathway

From the data derived for inhalation and ingestion pathways, a total probability index can be calculated per constituent. This index is the summation of probability indices for inhalation and ingestion exposures at each receptor location.

Risk Calculation of Non-carcinogenic Effects

To address the non-carcinogenic effects of the selected indicator constituents, a hazard index approach has been adopted based on U.S. EPA Guidelines for Health Risk Assessment of Chemical Mixtures (U.S. EPA, 1986). The hazard index for a specific constituent is defined as the ratio of daily intake for that constituent to the constituent specific RfD. The constituent specific hazard indices were calculated using the following formula:

$$\text{HI}_{ip} = \text{CDI}_{ip} \cdot \text{RfD}_i \quad (17)$$

where:

HI_{ip} = individual hazard index for exposure to constituent i at location p

CDI_{ip} = daily dose for constituent i at location p

RfD_i = acceptable daily intake, or reference dose (RfD), for chronic exposure to constituent i

Any single constituent with an exposure level greater than the reference level will cause the hazard index to exceed unity (1.0), and when the index exceeds unity, there may be concern for a potential health risk. For multiple constituent exposures, the hazard index may exceed unity even if no single constituent exceeds its acceptable level. It is therefore emphasized that the hazard index is not a mathematical prediction of incidence or severity of effects.

DISCUSSION

A terrestrial food-chain assessment of a project such as a HWI is ultimately an integrated evaluation of historical, chemical, analytical, environmental, demographic and toxicological data that are as site-specific as possible. Ultimately the precision of an ecological risk assessment is limited by the size and quality of the data base. This limitation can be overcome by defining a range of extremes. Specific areas of uncertainty include:

- Receptor species
- Emissions data bases
- Air modeling
- Fate and transport estimates
- Exposure estimates
- Toxicological data and risk characterization
- Complex interactions of uncertainty elements

To minimize the effect of these uncertainties in the evaluation, each step should be biased toward conservative estimations. Since each step

builds on the previous one, this biased approach should more than compensate for adjustments made to the human health-based criteria.

REFERENCES

1. Baes, C.F., Sharp, R., Sjoreen, A., and Shor, R., "A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture," ORNL #5786, 1984.
2. Briggs, G., et al., "Relationships between Lipophilicity and Root Uptake, and Translocation of Nonionized Chemicals by Barley." *Pesticide Science*. 13:495, 1982.
3. DeVito, M., Umbreit, T.H. and Gallo, M.A., "Bio-availability as a Factor in Human Health Risk Assessment of a Newark, NJ TCDD Contamination Site." In: Proceedings of the Ninth Annual Meeting of the Society of Environmental Toxicology and Chemistry. Arlington, VA, 1988.
4. Heichel, G.H. and Hankin, L., In: *Biological Monitoring of Heavy Metal Pollution, Land and Air*, Martin and Coughtrey eds. Applied Science Publishers Ltd. Essex, England, 1976.
5. Martin, M.H., and Coughtrey, P.J., *Biological Monitoring of Heavy Metal Pollution: Land and Air*. Applied Science Publishers LTD. Essex, England, 1982.
6. Maynard, L.A., Loosli, J., Hintz, H. and Warner, R., *Animal Nutrition*. 7th Edition, McGraw-Hill Book Company, New York, NY, 1979.
7. Osweiler, G.D., Carson, T., Buck, W. and Van Gelder, G., *Clinical and Diagnostic Veterinary Toxicology*. 3rd ed. Kendall/Hunt Publishing Co. Dubuque, IA, 1985.
8. U.S. EPA, "Superfund Public Health Evaluation Manual." EPA 540/1-86/060. Office of Emergency and Remedial Response, Washington, DC, 1986.
9. Whittaker, R.H. and Likens, G., Carbon in the biota. In G.M. Woodwell and E.V. Pecan (eds.) pg. 281-300, 1973.

Contaminant Fate and Effects in Surface Water and Groundwater for Site Closure of a Remediated Dioxin (TCDD) Site

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ABSTRACT

A risk analysis was performed for the surface water and groundwater contaminant transport pathways for a remediated dioxin site. The site had been used to store barrels of herbicide containing 2,3,7,8-tetrachlorodibenzodioxin (TCDD). Leaks in the containers and subsequent TCDD migration had contaminated the soil at the site.

The site had been remediated by removing and incinerating the soil which was then backfilled into the excavated areas of the site. The hazard associated with the remaining TCDD levels was determined by modeling the TCDD leachate from the soil and subsequent transport in the groundwater to off-site environs. A first order leaching model was used with semi-analytical solutions to the groundwater contaminant transport equation for a porous medium. First order kinetic processes were used to govern the contaminant mass in a recharged surface water body. Maximum contaminant concentrations were bounded by using an instantaneous release of the entire TCDD contaminant mass.

TCDD was identified as a probable human carcinogen because of its classification as a B2 carcinogen through ingestion. Carcinogenic risks were determined for potable water obtained from the aquifer at a site boundary well and for the consumption of fish obtained from the surface water body adjacent to the site.

INTRODUCTION

The site evaluated in this study had been used to store herbicides containing 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). The soil in the herbicide storage area had become contaminated as a result of leaks in the storage containers. This soil was incinerated to reduce the TCDD contamination levels. After incineration, some residual TCDD remained in the soil that was backfilled into the excavated areas of the site.

The health hazards associated with the residual soil contamination were evaluated using simple analytical water and groundwater surface water models and conservative assumptions. The use of simplified models frequently is adequate for regulatory purposes if they are conservative. In addition, a sensitivity analysis was performed in order to show the bounding, worst case scenario.

The purpose of this paper is to present the methodologies used in this study and to demonstrate the effective use of simplified models when the available data do not warrant the use of more sophisticated models. This methodology is not limited to TCDD-contaminated sites and may be applied to other contaminants.

CONTAMINANT MIGRATION PATHWAYS

The contaminant migration pathways that were considered in the risk analysis included leaching of TCDD from the soil to the groundwater and discharge of TCDD-contaminated groundwater into a surface water body that was intercepting the groundwater aquifer.

EXPOSURE PATHWAYS

The exposure assessment considered two scenarios: (1) ingestion of drinking water obtained directly from the aquifer and (2) consumption of fish obtained from the surface water body. Individuals may be exposed to the fish which have bioconcentrated the TCDD from the contaminated water.

The exposure scenarios considered a maximally exposed individual residing at the site boundary. The hypothetical individual was assumed to obtain all drinking water from a well located at the site boundary along the contaminant plume centerline. In addition, fish obtained from the nearby surface water body were considered to constitute a major portion of the individual's diet. The surface water body was also assumed to lie at the site boundary and intersect the groundwater aquifer. U.S. EPA^{1,2} values were used for drinking water and fish consumption rates.

CONTAMINANT RELEASE SCENARIO

The release of the TCDD to the groundwater was modeled as two distinct scenarios: (1) an instantaneous release of the entire residual TCDD mass in the soil and (2) a time-variant release. The time-variant release scenario used a first-order kinetic model to predict the TCDD release from the soil to the groundwater. This procedure allowed the determination of an upper bound estimate, using the instantaneous release scenario, and a best estimate, using a time-variant release scenario. This approach estimated the risk and the uncertainty of the risk analysis.

CONTAMINANT RELEASE MODEL

The TCDD release model was evaluated using the conceptual model illustrated in Figure 1.

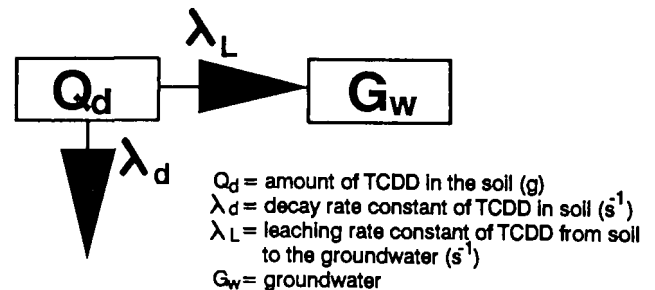


Figure 1
TCDD Release Model

The rate of change of TCDD in the soil with respect to time was described by a first-order loss process as follows:

$$\frac{dQ_d}{dt} = -(\lambda_L + \lambda_d) Q_d \quad (1)$$

where:

- Q_d = amount of TCDD in the soil (g)
 λ_d = decay rate constant of TCDD in soil (sec^{-1})
 λ_L = leaching rate constant of TCDD from soil to the groundwater (sec^{-1})
 t = time (sec)

The solution to the above equation is:

$$Q_d(t) = Q_{d0} (e^{-(\lambda_L + \lambda_d)t}) \quad (2)$$

where:

- Q_{d0} = amount of TCDD at $t = 0$

The Release Rate (R , g/s) was determined by:

$$R = Q_d(t) \lambda_L \quad (3)$$

Substitution of the solution for $Q_d(t)$ yields:

$$R = [Q_{d0} (e^{-(\lambda_L + \lambda_d)t})] \lambda_L \quad (4)$$

The total quantity of TCDD released (T , g) was determined by integrating the release rate from zero to infinity:

$$T = Q_{d0} \int_0^\infty e^{-(\lambda_L + \lambda_d)t} dt \quad (5)$$

Therefore, the total TCDD released (T , g) was given by:

$$T = \frac{Q_{d0} \lambda_L}{(\lambda_L + \lambda_d)} \quad (6)$$

The total TCDD mass at time $t = 0$ in the soil was given by:

$$Q_{d0} = A * D * p$$

where:

- A = the area of contamination (m^2)
 D = depth of contamination (m)
 p = bulk density (g/cm^3)

The leach rate constant used in this study was designed to evaluate low level radioactive waste repositories³. Although this work was done for radionuclides, these same parameters are defined for organic and non-organic contaminants and may be used to describe their transport through the soil. The leach rate constant (λ_L) was given by:

$$\lambda_L = \frac{p}{(XWT \theta) + (p K_d XWT)} \quad (8)$$

where:

- P = percolation rate (cm/sec)
 θ = volumetric water content (cm^3 of $\text{H}_2\text{O}/\text{cm}^3$ of waste)
 p = soil density (g/cm^3)
 XWT = waste thickness (cm)

The distribution coefficient may be related to organic adsorption phenomena by the organic carbon partitioning coefficient (K_{oc}) which is defined as:

$$K_{oc} = \frac{\text{mg of chemical adsorbed/kg of organic carbon}}{\text{mg of chemical dissolved/liter of solution}} \quad (9)$$

The distribution coefficient was defined in terms of the K_{oc} by:

$$K_d = K_{oc} * f_{oc} \quad (10)$$

where:

f_{oc} = the fraction of organic carbon in the soil

The decay rate constant of TCDD in the soil is given by:

$$\lambda_d = \frac{\ln 2}{T_{1/2}} \quad (11)$$

where:

$T_{1/2}$ is the half-life of TCDD in the soil (sec) (12)

The volumetric water content θ was determined using the following equation:

The retardation factor (R_d) was determined as follows (4):

$$R_d = \frac{n}{n_e} + \frac{\rho}{n_e} K_d \quad (13)$$

where:

- n_e = effective porosity
 n = total porosity
 ρ = soil density (g/cm^3)
 K_d = distribution coefficient (mL/g)

GROUNDWATER AND SURFACE WATER MODELS

A simple groundwater model was used which assumes a constant, unidirectional flow field in a homogeneous porous medium of infinite lateral extent and finite thickness. A more sophisticated model was not warranted due to the lack of data characterizing the aquifer. However, simpler models frequently give results adequate for regulatory purposes if they are conservative and provide a worst case scenario. An analytical solution to the groundwater transport equation was used to calculate the contaminant concentrations at a well located at the nearest site boundary. All release of TCDD from the soil was conservatively assumed to enter the aquifer without any interference or time delays in the unsaturated zone (Fig. 2).

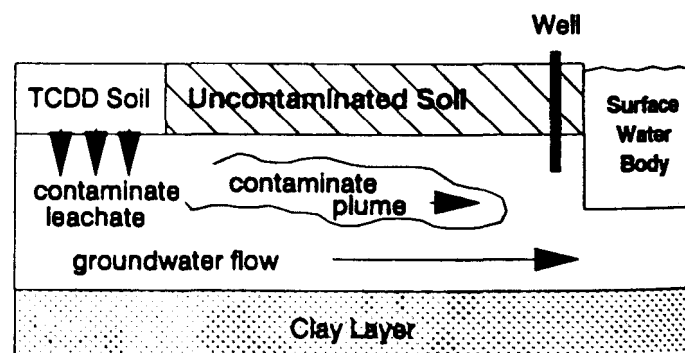


Figure 2
Cross Section of the TCDD Site

The equation for contaminant transport in groundwater is⁴:

$$\frac{\partial C}{\partial t} + \frac{\mu}{R_d} \nabla C = \nabla D \nabla C - \lambda C$$

$$C(0, x, y, z) = 0 \quad \frac{\partial C(t, x, y, z=0, b)}{\partial z} = 0$$

where:

- C = TCDD concentration (g/L)
 D = dispersion coefficients (m²/sec) = $\alpha\mu$
 α = dispersivity in x and y directions (m)
 R_d = retardation factor
 x, y, z = distance in the x, y and z directions from the point of origin (m)
 λ = decay constant (sec⁻¹)
 μ = pore velocity (m/sec)
 b = thickness of the aquifer (m)
 ∇ = the del operator
 t = time (sec)

If the source is represented by an area with length L and width w and the contaminant is released instantaneously at $t = 0$, then the solution to the above equation is⁴:

$$C(t, x, y, z) = \frac{Q_d}{n_e R_d} X(x, t) Y(y, t) Z(z, t) \quad (15)$$

where:

$$X(x, t) = \frac{1}{2L} \left[\operatorname{erf} \frac{x + L/2 - A}{(4D_x t / R_d)^{1/2}} - \operatorname{erf} \frac{x - L/2 - A}{(4D_x t / R_d)^{1/2}} \right] \exp(-\lambda_d t) \quad (16)$$

$$Y(y, t) = \frac{1}{2w} \left[\operatorname{erf} \frac{y + w/2}{(4D_y t / R_d)^{1/2}} - \operatorname{erf} \frac{-y + w/2}{(4D_y t / R_d)^{1/2}} \right] \quad (17)$$

$$Z(z, t) = \frac{1}{b} \quad (18)$$

where:

- $A = \mu t / R_d$
 Q_d = TCDD instantaneous release mass (g)
 C = dispersion coefficient in the x direction (m²/sec)
 D_x = dispersion coefficient in the x direction (m²/sec)
 $D_x = \alpha_L * \mu$
 D_y = dispersion coefficient in the y direction (m²/sec)
 α_L = longitudinal dispersivity (m)
 α_T = transverse dispersivity (m)
 L = the length of the source (m)
 w = the width of the source (m)
 R_d = retardation factor
 λ_d = decay constant (sec⁻¹)
 μ = pore velocity (m/sec)
 n_e = effective porosity
 erf = error function
 b = the thickness of the aquifer (m)
 t = time after release (sec)

This solution assumes complete mixing at the point where the concentration is calculated. The solution was modified for a continuous time-variant release by summing over a series of pulse releases. For a time-variant release, Q_d is a function of time described by $Q_d(t)$. When the pulse spacing is kept small relative to the standard deviation of the pulse at the receptor, a continuous time-variant release can be simulated by⁵:

$$C(t, x, y, z) = \sum_{i=1}^k \frac{Q_d(t_i)}{n_e R_d} X(x, t-t_i) Y(y, t-t_i) Z(z, t-t_i) \quad (19)$$

where:

- $Q_d(t_i)$ = the TCDD mass released during a pulse i (g)
 t_i = time of pulse release, i (sec)
 k = the number of pulses

Release rates were calculated on a yearly basis. The amount of contaminant in each pulse was given by:

$$R * \delta \quad (20)$$

where:

- R = release rate
 δ = the incremental time step

The incremental time step was determined by the dimensionless standard deviation of a pulse given as⁵:

$$\sigma = \left(\frac{2}{Pe} + \frac{8}{Pe} \right) 0.5 \quad (21)$$

where:

Pe = the pecelet number

The pecelet number represents the ratio of advection to dispersion and is given by:

$$Pe = \frac{x}{\alpha} \quad (22)$$

where:

- x = the longitudinal distance to receptor location
 α = longitudinal dispersivity

The incremental time step (δ) was determined by:

$$\delta = \sigma * GWT \quad (23)$$

where: GWT = groundwater travel time = $(x/\mu) R_d$

The contaminant flux entering a surface water body which intersects the aquifer for the conditions expressed for the groundwater model described previously is given by:

$$F(x, t) = \frac{Q_d}{2L(\pi D_x t / R_d)^{1/2}} \left[-\frac{\mu}{R_d} (\pi D_x t / R_d)^{1/2} [\operatorname{erf}(z_1) - \operatorname{erf}(z_2)] \right] \quad (24)$$

$$\frac{D_x}{R_d} [\exp(-z_1^2) - \exp(-z_2^2)] \exp(-\lambda_d t)$$

where:

$$z_1 = \frac{x - \frac{\mu}{R_d} t + \frac{L}{2}}{(4D_x t / R_d)^{1/2}} \quad (25)$$

and

$$z_2 = \frac{x - \frac{\mu}{R_d} t - \frac{L}{2}}{(4D_x t / R_d)^{1/2}} \quad (26)$$

where:

$F(x,t)$ = TCDD flux at distance x and time t (g/sec)
 Q_d = TCDD impulse release mass (g)
 D_x = dispersion coefficient in the x direction (m^2/sec)
 D_y = dispersion coefficient in the y direction (m^2/sec)
 L = the length of the source (m)
 R_d = retardation factor
 λ_d = decay constant (sec)
 μ = pore velocity (m/sec)
 erf = error function
 t = time after release (sec)

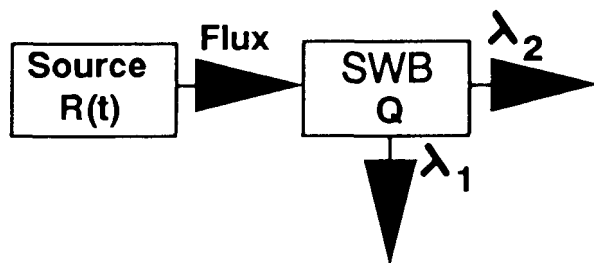
The corresponding flux for the time-variant release scenario is given by ⁵:

$$F(x,t) = \sum_{i=1}^k F(x,t-t_i) Q_d(t_i) \quad (27)$$

where:

$F(x,t)$ = TCDD flux at distance x and time t (g/sec)
 $Q_d(t_i)$ = the TCDD mass released during a pulse i (g)
 t_i = time of pulse release, i (sec)
 k = the number of pulses

The conceptual model illustrated in Figure 3 was used to model the contaminant mass in the surface water body.



SWB = Surface water body
 $R(t)$ = discharge rate of TCDD to SWB (mg/s)
 Q = amount of TCDD in the SWB (mg)
 λ_1 = loss rate constant due to water exchange (s^{-1})
 λ_2 = TCDD surface water decay rate constant (s^{-1})

Figure 3
 Conceptual Model for the Surface Water Body

The conceptual model may be represented mathematically by the following differential equation:

$$\frac{dQ}{dt} = R(t) - (\lambda_1 + \lambda_2) Q \quad (28)$$

where:

$R(t)$ = discharge rate of TCDD to the surface water body (mg/sec)
 Q = amount of TCDD in the surface water body (mg)
 λ_1 = loss rate constant due to water exchange (sec^{-1})
 λ_2 = TCDD surface water decay rate constant (sec^{-1})
 t = time (sec)

The solution to the above equation with the conservative assumption that $R(t)$ was a constant (R) and was equal to the maximum flux to the surface water body ($R = \max F(x,t)$):

$$Q(t) = \frac{R}{(\lambda_1 + \lambda_2)} (1 - e^{-(\lambda_1 + \lambda_2)t}) \quad (29)$$

It was assumed that the mass of TCDD in the surface water body reached steady state, thus the above equation simplified to:

$$Q = \frac{R}{\lambda_1 + \lambda_2} \quad (30)$$

where:

R = maximum discharge rate of TCDD to the surface water body (mg/sec)

The resulting steady-state concentration of TCDD in the surface water body was given by

$$C = \frac{\frac{R}{(\lambda_1 + \lambda_2)}}{V} \quad (31)$$

where:

C = steady state concentration of TCDD (mg/L)
 V = volume of the surface water body (L)

The water level in the surface water body was assumed to remain constant, thus the loss rate constant was given by:

$$\lambda_1 = \frac{F}{V} \quad (32)$$

where:

λ_1 = loss rate constant due to water exchange (sec^{-1})
 F = flow rate out of the surface water body (m^3/sec)
 V = volume of the surface water body (m^3)

CARCINOGENIC RISK CALCULATION

TCDD is classified by the U.S. EPA⁶ as a B2 carcinogen through ingestion, which identifies TCDD as a probable human carcinogen. The potential carcinogenic risks from the consumption of potable water and fish consumption were determined using chronic daily intake equations and carcinogenic potency factors according to guidance given by the U.S. EPA⁶. Potential carcinogenic risks were determined for concentrations determined in the surface water and groundwater at the receptor location for both the instantaneous and time-variant release scenarios.

CONCLUSION

In performing risk assessments, the analyst often is faced with a lack of the site-specific data needed to define the hydrologic conditions of the site. In this study, the lack of site data required the use of simplified models and conservative assumptions. The use of simplified models and conservative assumptions can provide adequate results for regulatory purposes. The use of both instantaneous and time-variant release scenarios allows the analyst to present a simplified quantitative assessment of the expected uncertainty in the analysis. The models used in this study are not limited to TCDD-contaminated sites and may be applied at other hazardous waste sites.

ACKNOWLEDGEMENT

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REFERENCES

1. U.S. EPA, Water Quality Criteria Documents, *Fed. Reg.*, 45, No. 231, Nov. 28, 1980.
2. U.S. EPA, *Superfund Public Health Evaluation Manual*, U.S. EPA Rept. No. EPA/540/1-86/060, U.S. EPA Office of Remedial Response, Washington, DC, Oct. 1986.
3. Rodgers and Associates Engineering Corporation, *Prototype Safety Analysis Report Below-Ground Vault Low-Level Radioactive Waste Disposal Facility*, RAE Rept. No. RAE-8716-5, Prepared for EG&G Idaho, Inc., by: Rodgers and Associates Engineering Corporation, Salt Lake City, UT, May, 1988.
4. Codell R.B. and Duguid J.D., Transport of Radionuclides in Groundwater, in *Radiological Assessment: A Textbook on Environmental Dose Analysis*, ed. J.E. Till and H.R. Meyer, pp. (4) 1-53, NRC Rept. No. NUREG/CR-3332, Washington, D.C., Sept. 1983.
5. Walton, J.C., Bensky M.S., Mease, M.E., and Bander T.J., Sensitivity of Radionuclide Transport in Groundwater to Source and Site Characteristics, *Proc. of the Waste Management 88 Conference*, pp. 269-276, University of Arizona, Tuscon, AZ 1988.
6. U.S. EPA, *Superfund Exposure Assessment Manual*, U.S. EPA Rept. No. EPA/540/1-88/001, U.S. EPA Office of Remedial Response, Washington, DC, April, 1988.

Groundwater Source Separation Using Chlorinated Organic Compound Degradation Series and Inorganic Indicators

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ABSTRACT

The investigation was performed to determine if the volatile organic compounds (VOCs) detected in groundwater adjacent to Winnebago Reclamation Landfill (WRL) are from leachate releases from the facility or from a VOC plume reported to be emanating from an upgradient NPL site, known as Acme Solvents Reclaiming, Inc. (Acme). The approach undertaken was to first compare the leachate chemistry and the groundwater chemistry to identify which wells have been affected by leachate from the landfill. The groundwater chemistry of VOC-impacted wells was compared with wells impacted by landfill leachate, indicating that a distinct leachate plume is present and different than the VOC plume.

The leachate plume from the landfill is well defined by chloride ion content and begins in the center of the landfill and extends to just past the downgradient edge of the landfill. There are chlorinated ethenes both in and outside of the leachate plume, indicating that the leachate plume is mixing in a pre-existing VOC plume. The presence of VOCs at the east end of the landfill is not attributed to the presence of landfill leachate since they are present hydraulically upgradient of the landfill, and the chloride concentrations at that location are not increased as would be expected if leachate was the source. Groundwater chemistry which does not show the presence of chlorides in elevated concentrations is not affected by landfill leachate.

The presence of VOCs at the southeast margin of the landfill gives the appearance of a bimodal distribution of VOCs in the groundwater in the area. This bimodal distribution may be due to one or more of the following causes:

- The wells between Acme and WRL do not intersect a flow path through the fractured dolomite that is responsible for the transport of VOCs from Acme.
- The appearance of a bimodal distribution could be the result of intermittent and spatially variable recharge.
- Biodegradation may play an important role in explaining the appearance of the bimodal distribution of VOCs. Biodegradation could increase the concentration of less chlorinated species which could give the appearance of a bimodal distribution of VOCs.

Introduction

The primary focus of the investigation performed was to determine if the volatile organic compounds (VOCs) detected in the groundwater were the result of a release of leachate from Winnebago Reclamation Landfill (WRL) or from a VOC plume emanating from an upgradient NPL site, known as Acme Solvents Reclaiming, Inc. (Acme). The differentiation of sources of released materials is necessary for determining responsibility for any required cleanup efforts. Warzyn's approach was to first compare the leachate chemistry with the ground-

water chemistry and identify which wells have been impacted by leachate from the landfill. Secondly, the groundwater chemistry of VOC affected wells was compared with wells impacted by landfill leachate.

A previous study of these two sites as part of the NPL listing process noted a bimodal distribution of organic constituents in the groundwater exists in this area. This analysis was interpreted to support the presence of separate groundwater plumes emanating each site¹. Both Acme and WRL were placed on the NPL and are being studied by consultants to the PRP groups. WRL was placed on the NPL due to the detection of arsenic and cadmium in a monitoring well adjacent to the landfill.

The key organic groundwater chemistry difference noted in previous studies was that the relative amount of trans-1,2-dichloroethene appeared to be greater in the groundwater under the landfill than under the Acme site¹. Wood et al. stated that vinyl chloride, 1,1-dichloroethene, cis- and trans-1,2-dichloroethene, 1,1-dichloroethane and chloroethane are either not commercially produced or are not in wide use across the whole country as are parent compounds such as tetrachloroethene, trichloroethene, 1,1,1-trichloroethane and methylene chloride². It is possible that the appearance of a bimodal distribution of dichloroethene may be the result of biodegradation of the VOC plume from the upgradient Acme site. Cline and Viste reported that U.S. EPA Methods 601 and 624 typically used to analyze water samples for VOCs do not differentiate between the cis- and trans-isomers of 1,2-dichloroethene, although the data are reported as the trans-isomer since it is the priority pollutant³. The cis-isomer is predominantly produced as the result biodegradation of trichloroethene¹.

SETTING

The WRL is located approximately 5 mi south of Rockford, Illinois, in the Rock River Hill Country of the Till Plains Section of the Central Lowland Province of Illinois⁴. The WRL occupies approximately 60 ac on a topographic high between Killbuck Creek to the west and unnamed intermittent streams to the north and south. Killbuck Creek, a perennial stream, flows within 250 ft of the western WRL boundary and merges with the Kishwaukee River approximately 2 mi to the north. There are no other surface water bodies within 1 mi mile of the WRL.

This municipal solid waste landfill has been licensed by the State of Illinois since 1972 and is nearing capacity. The facility has a bituminous liner and a leachate collection system. The leachate is disposed of off-site. A system of leachate/gas extraction wells is used to remove landfill gas and leachate. The western half of the landfill additionally collects leachate through a perforated pipe leachate collection system on the top of the liner, which gravity drains to central collection manholes.

Wastes accepted at the landfill are composed primarily of municipal refuse and sewage sludge. Prior to the startup of the gas collection sys-

terms in 1984, the landfill accepted wet sewage sludge (vacuum filter cake at approximately 20 to 23% solids). Currently, the landfill gas is used to power sludge dryers, which dry the sewage sludge prior to disposal. A very limited quantity of special wastes were disposed of at the facility prior to December, 1985. Special wastes accepted at the facility were accepted under approved permits issued by the Illinois Environmental Protection Agency (IEPA).

Approximately 1000 ft east of the WRL on an approximately 20-ac parcel is the Acme site. The Acme site was used for disposal of waste generated by Acme's solvent reprocessing facilities in Rockford, Illinois from approximately 1960 to 1973. The Acme site has been on the NPL since 1983. The materials disposed of at Acme are generally undocumented, but are known to have included solvent still bottom sludges, non-recoverable solvents, paints and oils. The waste materials were reported to have been transported to the site in drums which were either emptied into unlined disposal lagoons or stockpiled. The IEPA indicates four lagoons were actively used for the disposal of waste materials on-site. IEPA reported that between 10,000 and 15,000 drums may have been present on the site when it closed. The total quantity of waste disposed of at the site during its operation is unknown. IEPA inspections in late 1972 and early 1973 indicate the waste materials in the Acme ponds were not removed, but were covered with soil borrowed from other portions of the site. It is also reported that an unknown number of drums stored on-site were crushed and buried, rather than removed¹. Clean-up of the Acme site began in August 1986 and consisted of removal of buried drums and contaminated soils.

SITE HYDROGEOLOGY

Unconsolidated Materials

The surficial unconsolidated materials of the area are predominantly glacial drift deposits. The thickness of the unconsolidated materials ranges from 8 ft to greater than 70 ft. The body of the deposits thickens from east to west, forming a relatively thin mantle over the bedrock upland in the east, and filling the deep bedrock valley to the west. This transition begins beneath the eastern margin of the landfill where the bedrock surface slopes downward forming the preglacial bedrock valley wall. Based on regional information, the thickness of unconsolidated sediments is expected to be approximately 100 ft under Killbuck Creek near the WRL.

The soils beneath and east of the site are poorly-sorted sand and gravel glacial ice-contact deposits. Portions of the sand and gravel were sometimes recognized as weathered bedrock. West of the site in the Kill-

buck Creek Valley, and to the north of the site, the sediments are sand and gravel outwash deposits. The soil types are predominantly fine to coarse sands with occasional fine to coarse gravel zones 11 ft to 40 ft thick. The surficial deposits south of the site are predominantly a silty clay till up to 24 ft thick.

Bedrock

The unconsolidated sediments in the region are underlain unconformably by the dominantly carbonate rocks of the Galena-Platteville Groups (Ordovician System). The bedrock surface elevation is highly variable due to paleo-erosional features. Regional information indicates the thickness of these groups is expected to range from 250 ft in the bedrock upland east of the WRL to 100 ft in the adjacent bedrock valley⁵. The bedrock near the WRL is composed of dolomite, with chert layers or nodules commonly noted throughout the dolomite. Shale partings and coatings were noted only below 695 ft MSL. The dolomite generally is fractured throughout the total depth sampled. The fractures are dominantly horizontal bedding planes, frequently cross-cut by high angle or vertical fractures. Vugs (void spaces) are consistently found throughout the dolomite, with their presence ranging from slightly vuggy to very vuggy. Cavernous zones were not noted. The Rock Quality Designator (RQD) of dolomite core samples ranged widely from zero to 100%, averaging 52.5%, with a standard deviation of 28.9%. These data provide an indication of the variably fractured nature of dolomite. An up to 27 ft thick zone of highly fractured, soft dolomite was encountered in the near surface bedrock during exploratory drilling in the vicinity of the northern intermittent creek on the Acme site, where the RQD ranged from "too soft to core" to 28%. Highly fractured zones (low RQD) also were found between rocks containing few fractures (high RQD), indicating rock competence did not generally improve with depth.

Groundwater

The uppermost aquifer encountered in the vicinity of the WRL changes in character due to the abrupt sloping of the bedrock surface beneath the site. East of the WRL, and below its eastern third, the water table occurs within the dolomite bedrock. From this boundary to the west, the water table is present in unconsolidated materials. Regardless of the type of matrix material, the uppermost saturated unit in the immediate vicinity of the WRL is under water table conditions. The water table also occurs in the silty, clayey till to the south of the site. The sand and gravel and/or dolomite aquifer beneath the till appears

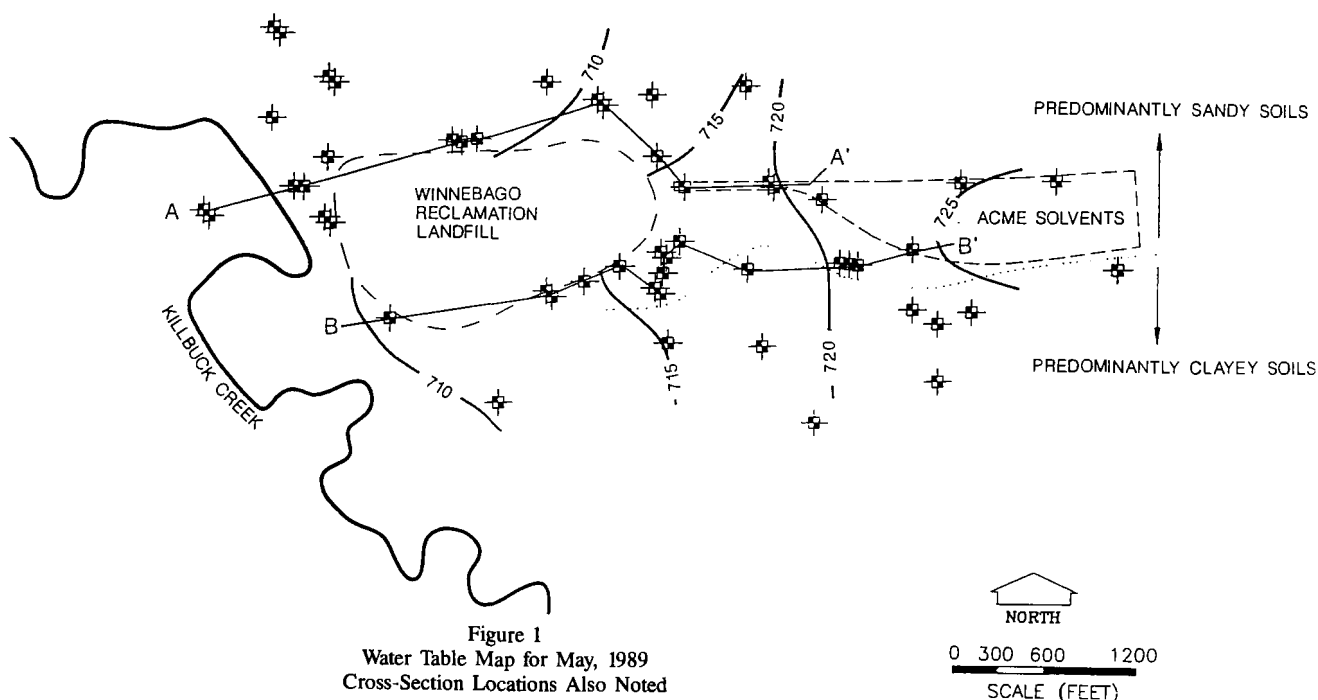


Figure 1
Water Table Map for May, 1989
Cross-Section Locations Also Noted

to be under semi-confined conditions.

Ground water generally flows from the uplands east of the WRL to the Killbuck Creek valley, but precise flow configurations within the fractured dolomite are likely to be more complex in detail (Fig. 1). East of the WRL, the water table is a subdued expression of the bedrock topography; the water table slopes outward to the west, northwest and to southwest from a generally east-west trending groundwater "high" in the vicinity of the northeast-southwest trending dolomite bedrock ridge (Fig. 1). The water table in the unconsolidated sediments gently slopes towards the Killbuck Creek floodplain to the south and west of the landfill.

A groundwater mound has been observed seasonally in the vicinity of the northern intermittent creek, east of the WRL. It is thought the mounding is due to higher recharge rates localized in this area. As discussed earlier, sandy sediments are underlain by highly weathered dolomite bedrock perhaps enhancing the potential for recharge there.

RESULTS AND DISCUSSION

Table 1 contains a summary of the leachate inorganic chemistry data developed in this study. The leachate is dominated by high chloride content as well as high sodium and potassium content. The leachate also has high alkalinity and specific conductance. Figure 2 is a trilinear plot of the major cations: calcium, magnesium and sodium plus potassium for groundwater and leachate samples as percent milliequivalents per liter. The data plot generally along a line from the endpoints

Table 1
Leachate Inorganic Analytical

Chloride	17,300	3,740	3,630	2,720	2,490
Alkalinity	11,200	9,090	8,520	7,860	6,060
Specific Condition	>50,000	27,100	26,200	24,200	19,900
(umhos/cm)					
pH	7.27	7.54	7.75	7.66	7.54
Sodium	10,200	1,620	1,440	1,090	968
Potassium	1,750	1,220	1,300	710	608
Calcium	241	40.3	37	29.9	93.1
Magnesium	812	136	70.8	57.1	110

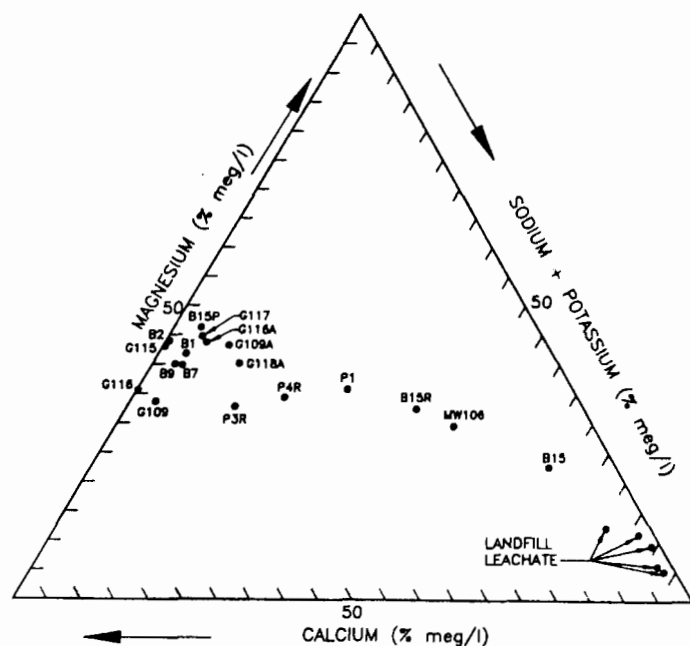


Figure 2
Trilinear Plot of Groundwater and Landfill Leachate Data
Showing Trend From Leachate to Leachate-Affected Wells
To Unaffected Wells

of leachate samples and upgradient water samples, indicating that leachate samples and groundwater samples can be discriminated on this basis.

The plot of chloride versus sodium plus potassium exhibits a strong linear relationship ($R^2 = 0.998$) indicating that chloride, too, can be used to discriminate between leachate and groundwater samples (Fig. 3). Chloride is generally considered to be non-reactive in groundwater systems⁷⁸ and so is very useful as a groundwater tracer. Alkalinity often is useful in discriminating between leachate and groundwater, but a plot of log alkalinity versus sodium plus potassium shows a less strong positive linear relationship ($R^2 = 0.82$), indicating the potential for sources of alkalinity other than leachate (Fig. 4).

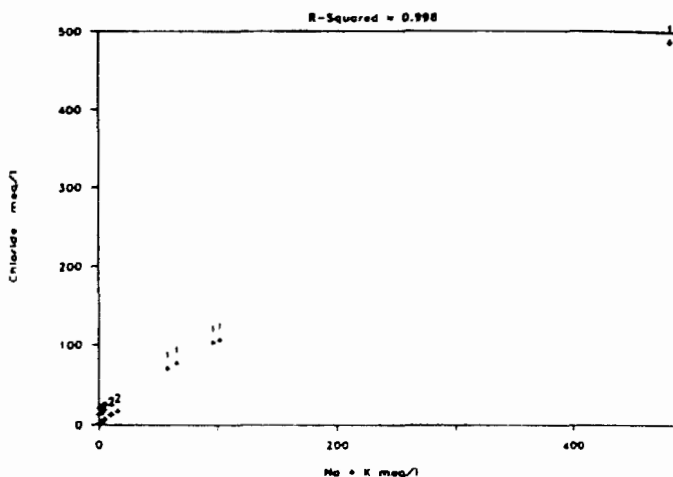


Figure 3
Plot of Chloride (mg/L) Versus Sodium Plus Potassium (mg/L) for
Leachate Samples¹ and Groundwater Samples²
Note Strong Positive Correlation

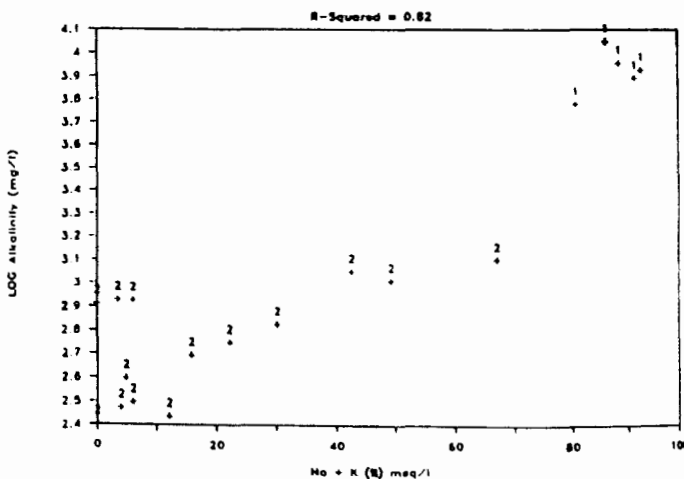
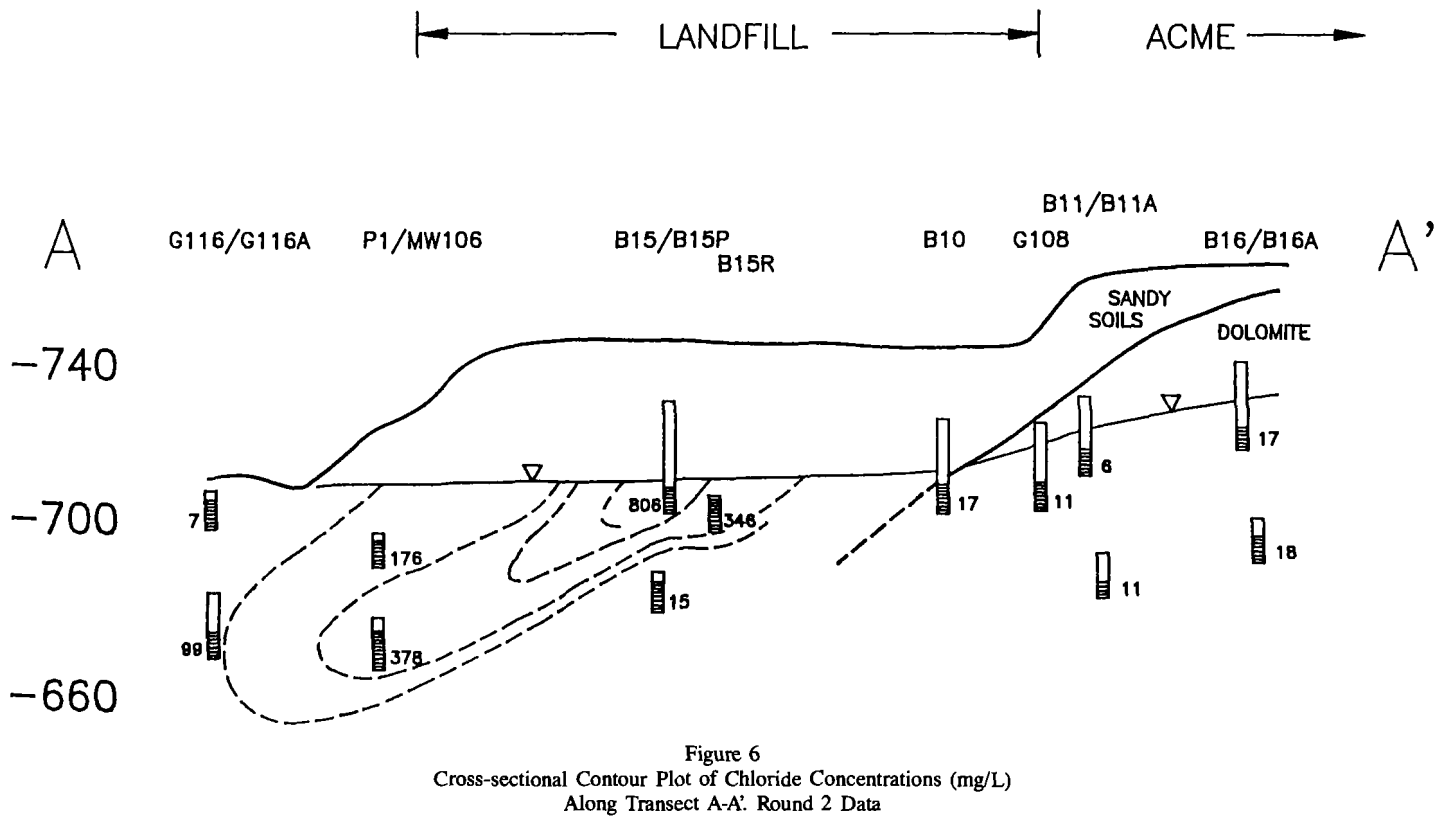
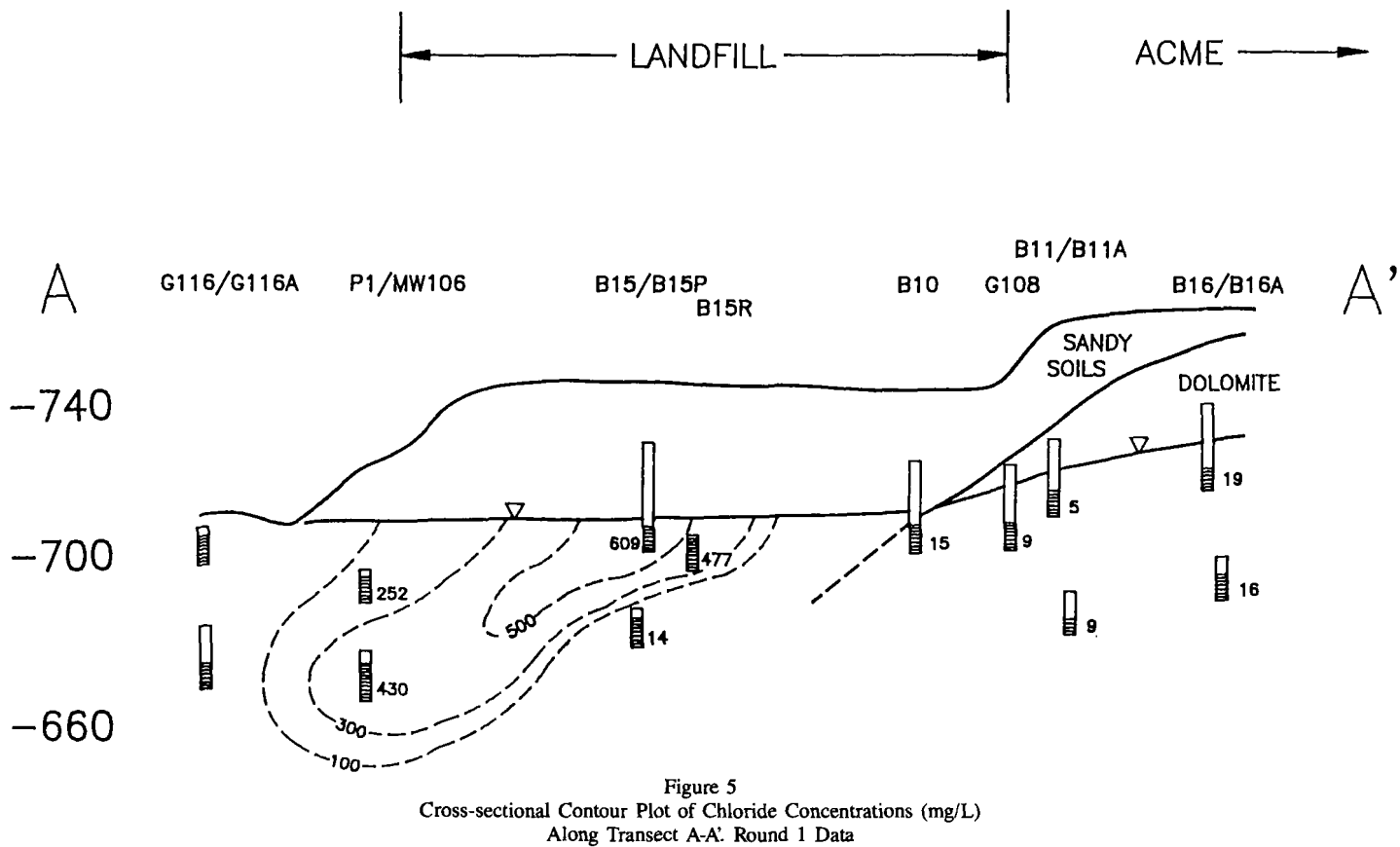


Figure 4
Plot of Log Alkalinity (mg/L) Versus Sodium Plus Potassium (% meq/l)
for Leachate Samples¹ and Groundwater Samples²
Note Variation in Groundwater Samples

Chloride concentrations are contoured on cross-sections along transect A-A' for two separate sampling events (Figs. 5 and 6). Both plots depict a chloride plume originating from the landfill and extending just past the downgradient edge of the landfill. Downgradient movement is evident from the increased chloride concentration in the deeper well in the distal well nest between the two monitoring periods. It is also evident that the deeper well (B15P) in the well nest where the plume appears to originate is unaffected by leachate since it has low chloride concentrations consistent with upgradient well concentrations.



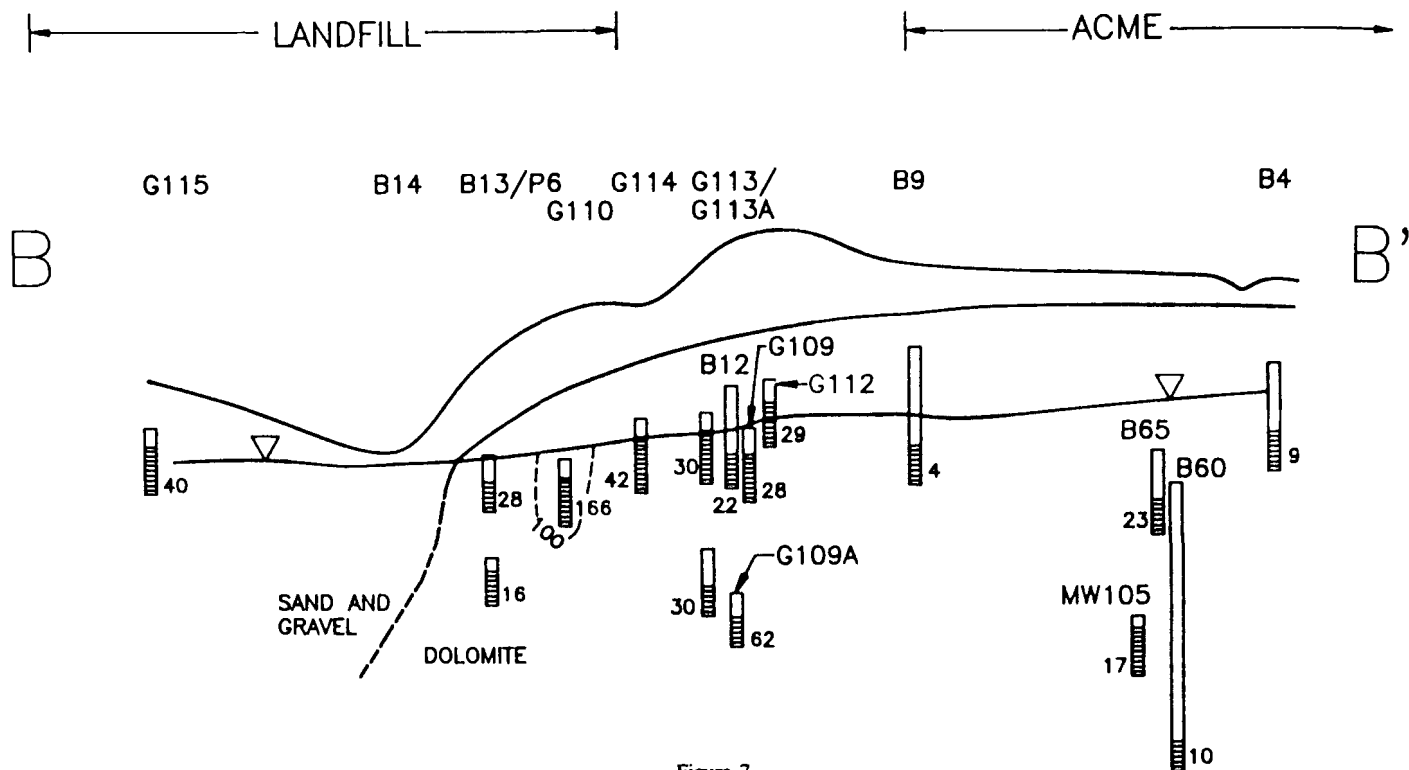


Figure 7
Cross-sectional Contour Plots of Chloride Concentrations (mg/L)
Along Transect B-B'. Round 1 Data

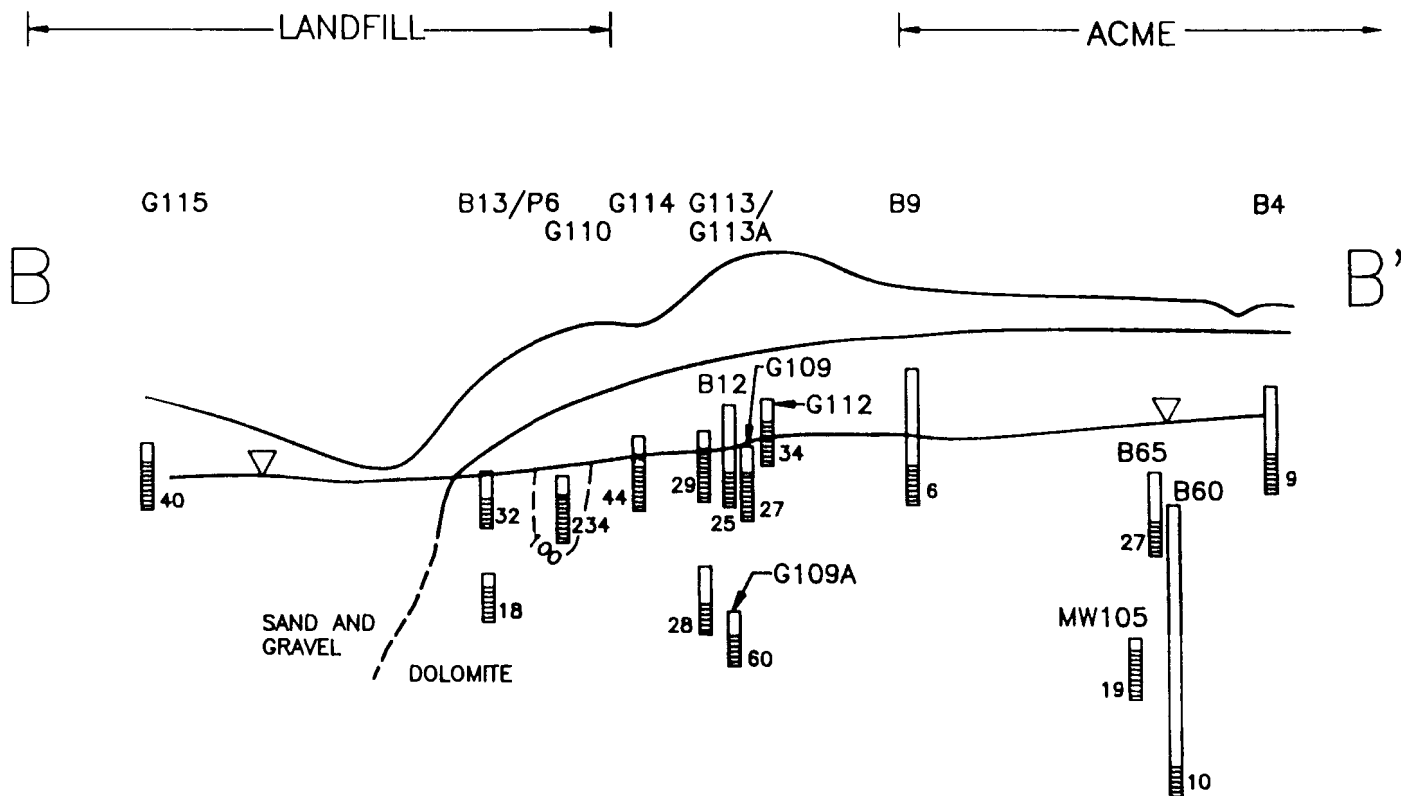


Figure 8
Cross-sectional Contours of Chloride Concentrations (mg/L)
Along Transect B-B'. Round 2 Data

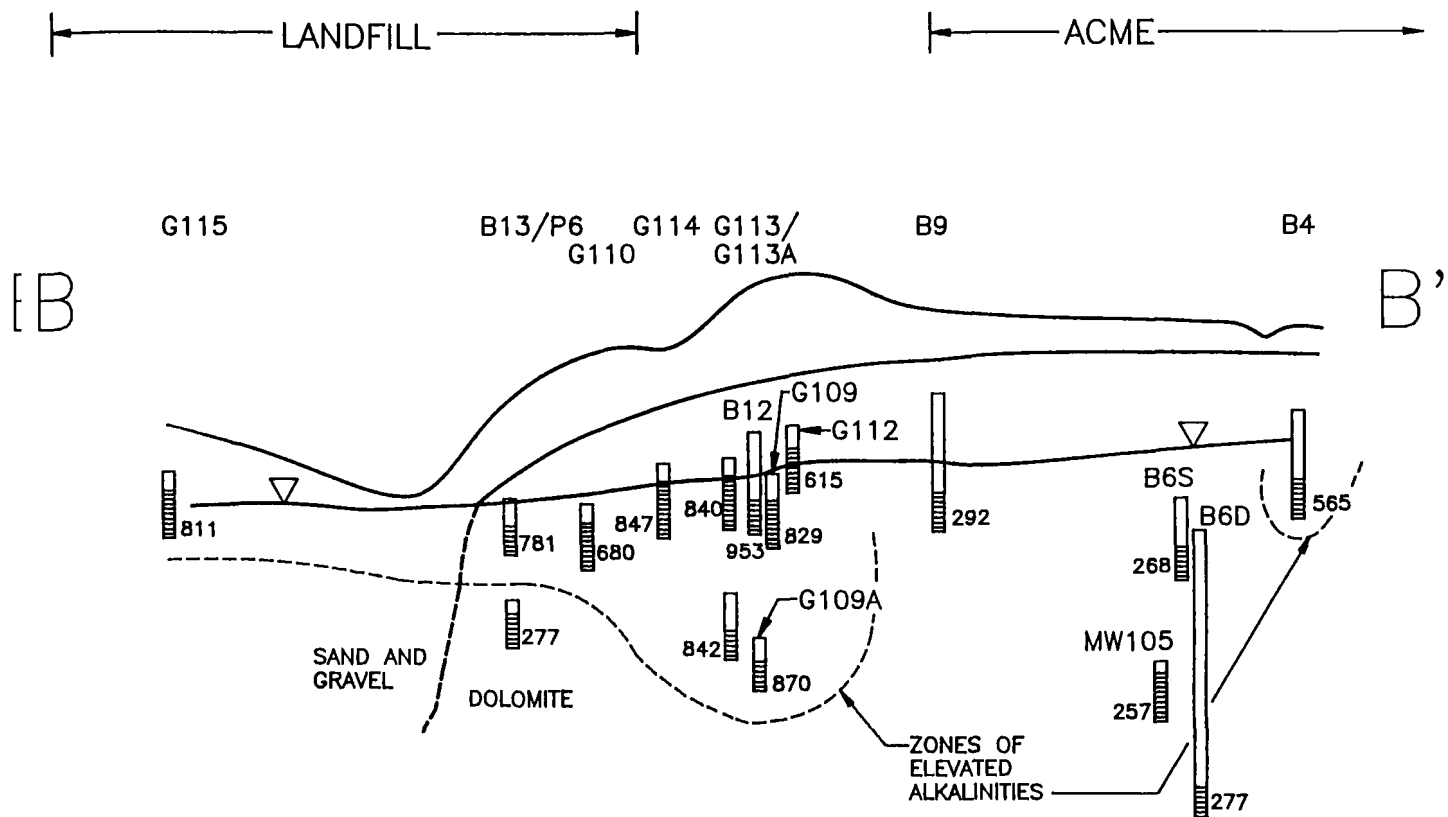


Figure 9
Alkalinities (mg/L) Along Transect B-B'. Round 2 Data

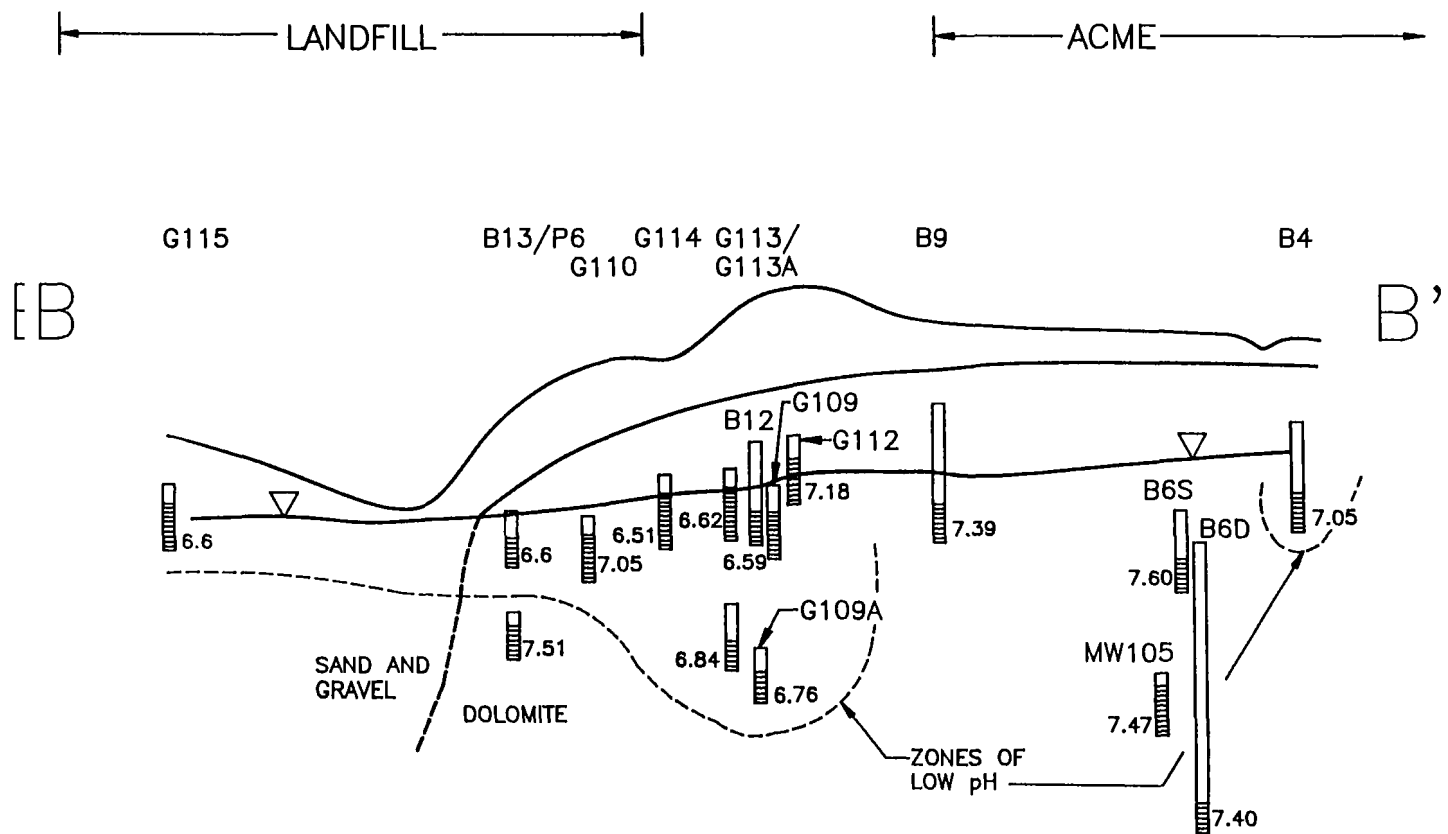


Figure 10
Zones of Low pH Along Transect B-B'. Round 2 Data

Chloride concentrations are contoured on cross-section B-B' for both rounds of groundwater samples (Figs. 7 and 8). These cross-sections indicate that chlorides are elevated in the vicinity of only one well (G110). This indicates that the chlorides at G110 are an anomaly and not characteristic of a plume. This previously was attributed to intermittent surficial leachate seeps currently under control. More recently it was reported that this area was used to load trucks for off-site shipment of leachate for treatment and disposal. Given that chloride is a good indicator of the presence of leachate, it appears that a well developed landfill leachate plume is not present at the southern margin of the landfill.

Inspection of plots of alkalinities on these same cross-sections indicates there are two zones of elevated alkalinities; one at Acme (B4) and one at the southeastern margin of the landfill (Fig. 9). A similar pattern exists for pH (Fig. 10). It is evident that landfill leachate is not responsible for patterns of alkalinities and pH since chlorides, a reliable indicator of landfill leachate, are not increased as would be expected if landfill leachate were present.

VOCs found at highest concentration in groundwater samples collected during this study were chlorinated ethenes, perchloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (DCE), vinyl chloride (VC) and chlorinated ethanes (1,1,1-trichloroethane, 1,1-dichloroethane and chloroethane). Within each grouping, these compounds may biodegrade through loss of a chlorine atom^{9,10}. Wood, et al. and Vogel and McCarty found that PCE degraded to TCE to DCE to VC¹¹. Wilson, et al., and Barrio-Lage, et al., also found that DCE degraded to VC¹². Barrio-Lage, et al., additionally determined that the cis-isomer of DCE degraded to chloroethane as well as to VC¹². The degradation product of trichloroethene is dominantly the cis-isomer of 1,2 dichloroethene¹. The degradation process is biologically mediated and occurs under anaerobic conditions. The potential for degradation of chlorinated compounds and the less widespread use of less chlorinated compounds, indicates the presence of less chlorinated species in groundwater result from the degradation of a more chlorinated parent compound.

The percent of PCE and VC relative to the total concentration of ethenes in selected groundwater samples collected during this study exhibits a general trend towards decreasing proportion of PCE and increasing proportion of VC from east to west (Table 2). This finding and the fact that almost all 1,2-dichloroethene detected in these groundwater samples was the cis-isomer suggests that degradation is affecting

Table 2
Percent of Total Ethenes in Groundwater at Various Well Sites

	PCE	TCE	DCE	VC
B4	42.3	18.3	39.3	0.1
B16	12	14.3	73.7	1.3
G108	32.5	23.1	43.1	1.3
G109	18.3	6	55.8	19.9
B12	5.7	6.6	80.2	7.5
G113	22	4.6	63.4	10
G111	16.6	11.6	71.8	0
G114	0	7.4	42.4	50.2
G110	2	7.6	13	77.4
B13	8.2	15.3	72	4.5
B15R	8.1	23.2	52.6	16.1
G115	0	0	29.2	70.8
MW106	3.6	31.6	50.2	14.6
P3R	0	13.2	71.2	15.6
G116	0	0	0	0
B16A	5	5.5	89.5	0
B11A	34.1	15.9	50	0
G109A	6.6	26.1	59.1	8.3
G113A	14.1	30	53.4	2.5
P6	19.4	22.5	58.1	0
P4R	15.7	15.7	66.5	2
P1	0	16.7	62.9	20.4
G116A	19.6	14.9	65.5	0

the distribution of ethenes in groundwater. (Note that chloroethane was not included in these calculations because a specific concentration of chloroethane as a degradation product of cis-1,2-DCE could not reliably be assigned since chlorinated ethanes are also present.) The distribution of total ethenes in the groundwater is illustrated in Figure 11. The highest concentration of ethenes was observed at location B4 (1912 ug/l), on the ACME site. Concentrations generally decline moving westward in

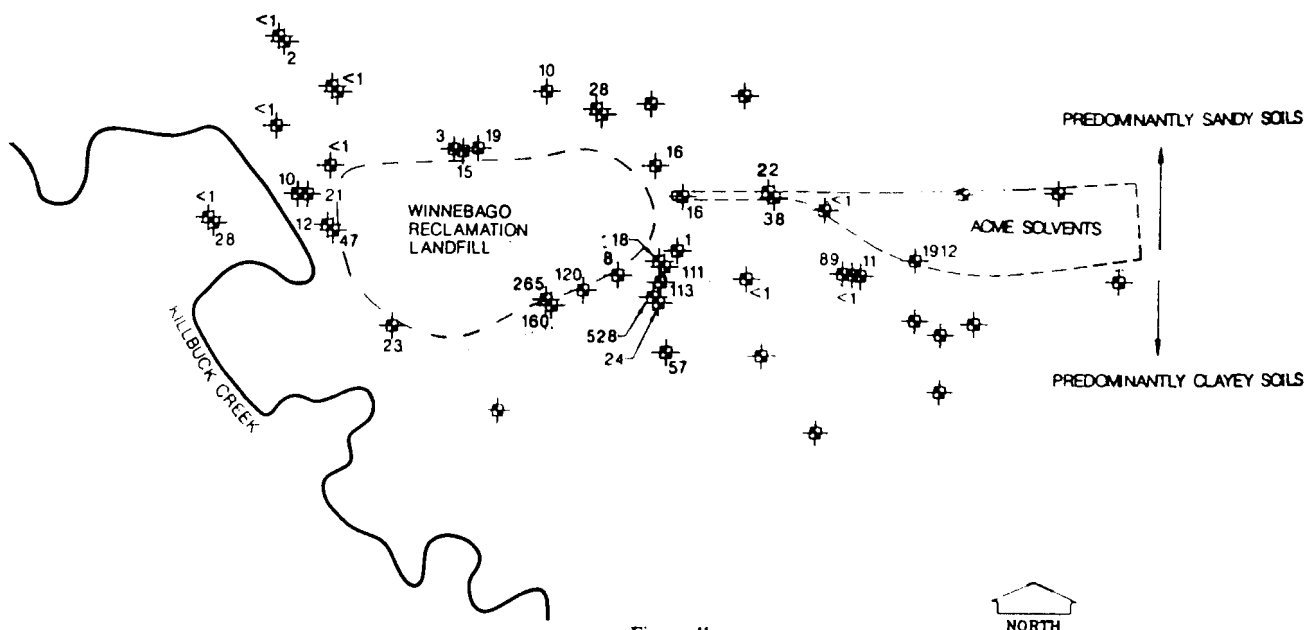


Figure 11
Numbers Adjacent to Wells refer to the Sum of the Perchloroethene, Trichloroethene, CIS 1,2 Dichloroethene and Vinyl Chloride Concentrations ($\mu\text{g/l}$).
Note That Highest Concentration is Located East of the Landfill on the Acme Site

the general direction of groundwater flow (Figure 11). Figure 12 is a cross-sectional contour plot of total VOCs in wells along cross-section A-A' which shows that VOCs are present both inside and outside of the chloride plume.

CONCLUSION

The leachate plume from the landfill is well defined by the chloride content and begins in the center of the landfill and extends to just past the downgradient edge of the landfill. Chlorinated ethenes are present inside and outside of the landfill leachate plume, indicating that the leachate plume is mixing in a preexisting VOC plume (Figs. 5, 6 and 12). The presence of VOCs at the east end of the landfill is not attributed to the presence of landfill leachate since the chloride concentrations are not increased as would be expected if leachate were the source and the area is hydraulically upgradient of the landfill.

The bimodal distribution of VOCs in this area may be due to one or more of the following possibilities:

- The wells between Acme and the landfill simply may not intersect a flow path through the fractured dolomite that is responsible for the transport of VOCs from Acme. Indeed, the Illinois State Geological Survey concluded that this dolomite is difficult to monitor because adjacent wells may be finished in fractures that are not connected to each other¹³. The southeast margin of the landfill has a high density of monitoring wells in comparison with other areas on the bedrock upland increasing the chances of intersecting a VOC flow path from Acme.
- The bimodal distribution could be the result of intermittent and spatially variable recharge. This spatially variable intermittent recharge could dilute the VOC plume resulting in variable VOC concentrations, perhaps resulting in the appearance of a bimodal distribution.
- Biodegradation may also play an important role in explaining the appearance of the bimodal distribution of VOCs. Biodegradation could increase the concentration of less chlorinated species which could give the appearance of a bimodal distribution of VOCs.

A leachate plume from the landfill has been identified by the chloride content and is mixing in a pre-existing VOC plume. Landfill leachate is not responsible for the groundwater chemistry anomalies

at the southeast margin of the landfill due to the lack of elevated chloride content and this area is upgradient of the landfill.

REFERENCES

1. Jordan, E.C., Acme Solvents Superfund Site, Winnebago County, Illinois, Technical Report, Sep., 1984.
2. Cline, P.V., and Viste, D.R. "Migration and Degradation Patterns of Volatile Organic Compounds," *Waste Man. Res.*, 3, pp. 351-360, 1985.
3. Wood, P.R., Lang, R.F. and Payan, I.L. *Anaerobic Transformation, Transport and Removal of Volatile Organics in Groundwater*, Drinking Water Research Center, Florida International University, Miami, FL, 1981.
4. Leighton, M.M., Ekblaw, G.E. and Horberg, L. Physiographic Divisions of Illinois, *J. of Geol.*, 56(1), p. 16-33, 1948.
5. Hackett, J.E., *Groundwater Geology of Winnebago County, Illinois*, Illinois State Geological Survey Report of Investigations 213, Champaign, IL, 56 pp., 1960
6. Berg, R.C., Kempton, J.P., and Stecyk, A.N., *Geology for Planning in Boone and Winnebago Counties*, Illinois State Geological Survey, Champaign, IL, Circular 531, 69 p., 1984
7. Bentley, H.W., Phillips, F.M., Davis, S.N., Habermehl, M.A., Airey, P.L., Calf, G.E., Elmore, D., Gove, H.E. and Torgersen, T. "Chlorine 36 Dating of Very Old Groundwater 1., The Great Artesian Basin, Australia," *Water Resources Res.*, 22(13), pp 1991-2001, 1986.
8. Freyberg, D.L., "A Natural Gradient Experiment on Solute Transport in a Sand Aquifer, 2. Spatial Moments and the Advection and Dispersion of Nonreactive Tracers," *Water Resources Res.*, 22(13), pp 2031-2046, 1986.
9. Vogel, T.M., Criddle, C.S. and McCarty, P.L. "Transformation of Halogenated Aliphatic Compounds," *Environ. Sci. Tech.*, 21 pp. 722-736, 1987.
10. Bouwer, E.J. and McCarty, P.L. "Transformers of 1- and 2- Carbon Halogenated Aliphatic Organic Compounds Under Methanogenic Conditions," *Appl. Environ. Microbiol.*, 45, pp 1286-1294, 1983.
11. Vogel, T.M. and McCarty, P.L. "Biotransformation of Tetrachloroethylene to Trichloroethylene, Dichloroethylene, Vinyl Chloride and Carbon Dioxide under Methanogenic Conditions," *Appl. Environ. Microbiol.*, 49, pp 1080-1083, 1985.
12. Barrio-Lage, G., Parsons, F.Z., Nassar, R.S. and Lorenzo, P.A. "Sequential Dehalogenation of Chlorinated Ethanes," *Environ. Sci. Tech.*, 20, pp 96-99, 1986.
13. Herzog, B.L., Hensel, B.R., Mehnert, E., Miller, J.R. and Johnson, T.M. *Evaluation of Groundwater Monitoring Programs at Hazardous Waste Disposal Facilities in Illinois*, Environmental Geology Notes 129, Illinois State Geological Survey, Champaign, IL, 1988.

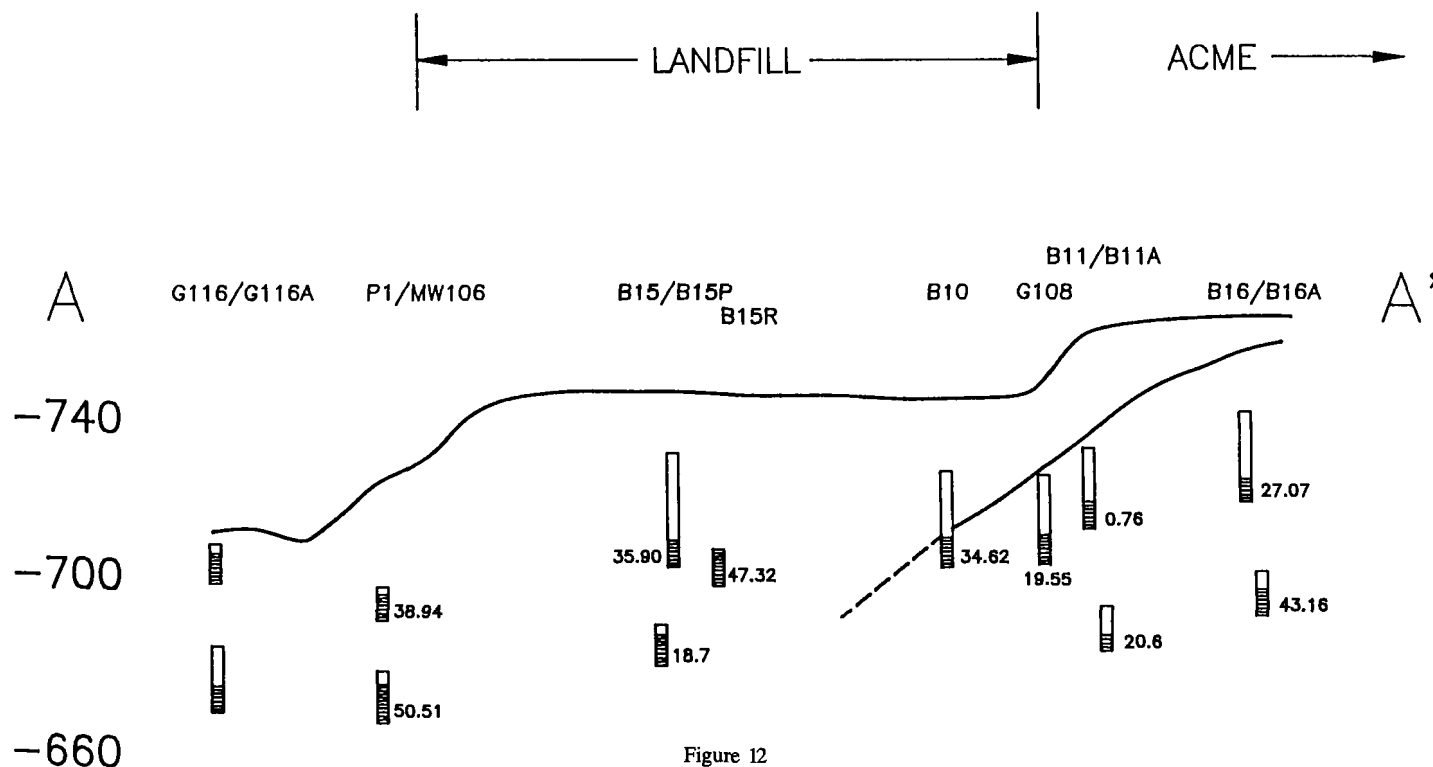


Figure 12
Total Concentration of Volatile Organic Compounds (μ/l) for
Wells Along Transect A-A'. Round 2 Data

Predicting Environmental Effects in a Puget Sound Embayment

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ABSTRACT

An RI/FS is being performed at the Wyckoff/Eagle Harbor Superfund site, which includes Eagle Harbor itself. This is an embayment located on the east side of Bainbridge Island in central Puget Sound. The harbor area was first settled in the 1870s. Current and historical

operations are being evaluated as potential sources of contamination.

Several recreationally harvested fish species are found in Eagle Harbor. National Oceanic and Atmospheric Administration research has shown the strong relationship between polynuclear aromatic hydrocarbons (PAH) in sediment and impacts on English sole, including

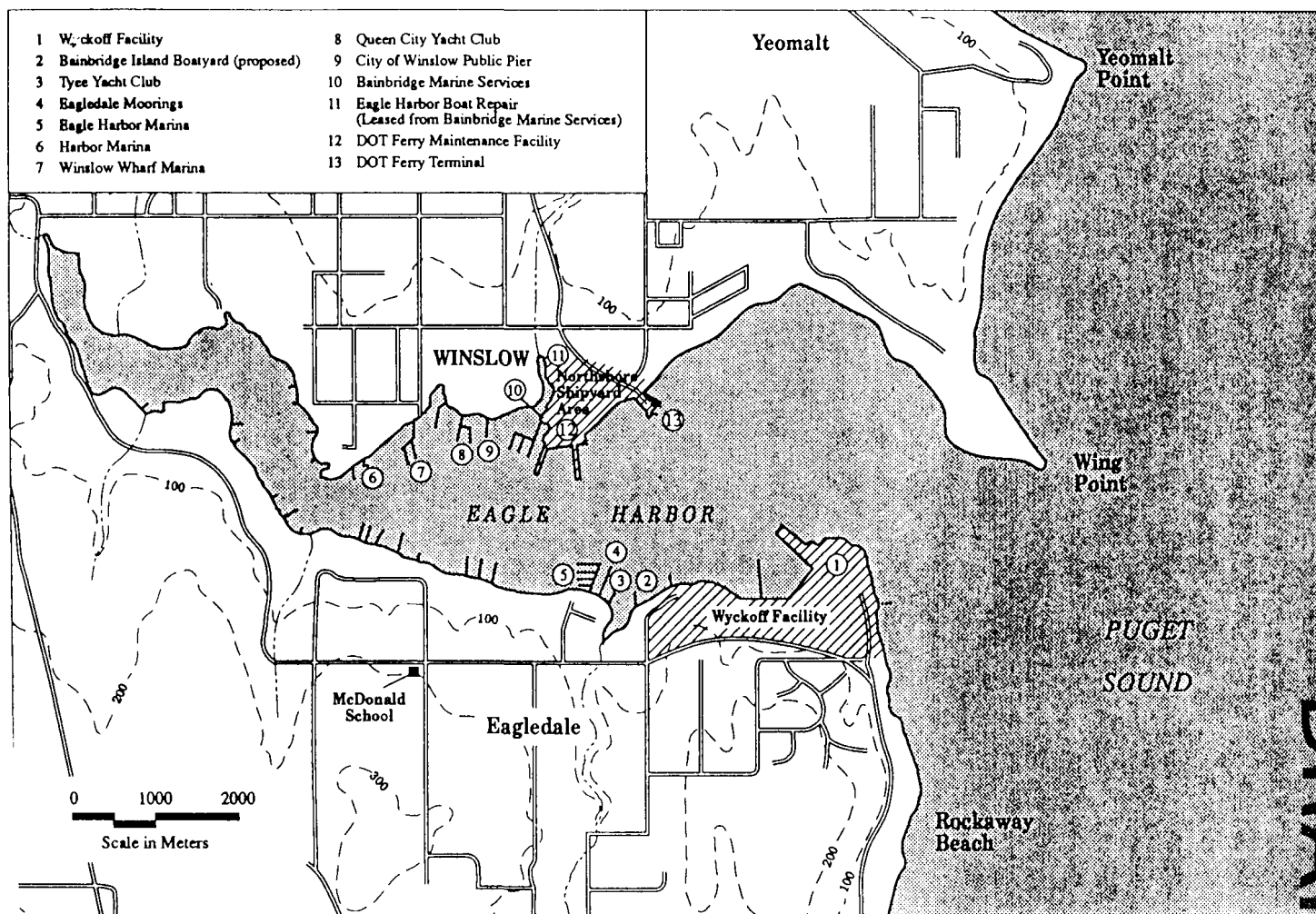


Figure 1
Location of Industrial and Commercial Facilities and
Operable Units Along Eagle Harbor

inhibition of ovarian development. The ecological effects portion of the RI/FS for Eagle Harbor attempted to better define the areas where ecological effects were likely, to determine what the sources of contamination were and to estimate whether existing levels of contamination were likely to continue.

During the RI/FS, a variety of effects were identified. Sediments in large areas of the harbor have been shown to be toxic to marine organisms. The use of benthic taxonomic evaluation provided some additional supportive information.

An evaluation of GC/MS results indicated that the sources of the PAHs in sediment are mostly of creosote type origin.

Three distinct transport features appear to dominate the overall movement of sediment associated contaminants. These are, in order of importance: (1) remobilization of bottom sediments by vessel propeller induced currents; (2) near surface and possibly subsurface flow of dense non-aqueous phase liquid (DNAPL) from the wood treatment facility and (3) the potential movement of material from Rockaway Beach to the north and into the harbor.

Future depositions of sediments are expected to be significantly lower than in the past because of blocking of natural sediment sources, particularly shoreline armoring. This implies very little potential for burial of existing contaminated material in subtidal areas. The potential for future flow of DNAPL to the harbor is still being evaluated.

INTRODUCTION

Eagle Harbor is a small embayment located in Central Puget Sound on the eastern border of Bainbridge Island. The harbor area was first settled in the 1870s. Historical operations along the harbor have included shipbuilding during World War II as well as wood treatment operations. Current operations now include ship repair and maintenance facilities, a wood preserving plant and several marinas. Figure 1 shows Eagle Harbor along with the major current operations.

Previous investigations by the National Oceanic and Atmospheric Administration (NOAA)^{5,6}, Washington State Department of Ecology^{9,11} and the U.S. EPA have shown that sediments and clams in the harbor are contaminated with polynuclear aromatic hydrocarbons (PAHs). NOAA found lesions and PAH accumulation in liver tissue in English sole collected during trawls of the harbor, as well as impacts on ovarian development, indicating possible impacts on future populations. In 1985, the Bremerton-Kitsap County Health Department issued a health advisory against eating shellfish from Eagle Harbor.

The Wyckoff wood treatment facility and Eagle Harbor were proposed as a Superfund site in 1987. The U.S. EPA has since contracted CH2M Hill to conduct an RI/FS on the harbor. As part of its focus, the study has attempted to answer a number of questions including the following:

- What are the ecological impacts of sediment contamination in Eagle Harbor?
- How large is the impacted area?
- Where has the contamination originated from?
- What are the major routes by which the contamination is moving around within the harbor?

ECOLOGICAL ASSESSMENT

General Ecological Characteristics

Eagle Harbor is inhabited by at least 18 species of fish. The harbor provides nursery and adult habitat for a variety of invertebrate species. Important fish and invertebrates include rockfish, cod lingcod, cancrinid crabs and pandalid shrimp. Several shellfish species are also present in the intertidal areas of the harbor.

Most of the subtidal area in Eagle Harbor has sediment that is composed of sandy silt to silty sand. Previous investigations of Eagle Harbor have shown elevated abundances of polychaeta—a pollution-sensitive group. The active biological zone in Eagle Harbor sediments is considered to be the upper 10 to 20 cm.

Like the subtidal fauna, the nature of the intertidal fauna is determined in part by substrate (mud, sand or cobble). Intertidal communities within Eagle Harbor and the surrounding area have not been

extensively evaluated. The absence or near absence of macro-invertebrates has been noticed in the immediate vicinity of oily seeps around the Wyckoff facility¹⁰

Ecological Study Methods and Results

Previous NOAA research has focused on identifying a variety of environmental effects in the harbor. The ecological effects portion of this study focused on identifying those portions of the harbor that were most likely to be producing those effects. The approach taken was modeled after the triad method for evaluating environmental effects⁴. This approach involves evaluating three components of sediment quality—chemistry, toxicity and benthic effects. The toxicity of the sediments is determined through bioassay tests in contaminated and reference areas. Benthic impacts are determined by evaluating the abundances of major groups of benthic animals compared with those values found in reference areas. In this approach to impact analyses, an area is considered impacted if one or more of the biologic tests shows a significant effect.

To evaluate sediment toxicity amphipod and oyster larvae bioassays were performed at 45 stations in Eagle Harbor as well as 10 reference stations. Statistical comparisons were then performed between Eagle Harbor stations and reference stations to determine whether a statistically significant effect was observed in the Eagle harbor station.

One factor that has complicated the statistical comparison of stations is the high mortalities that were found at some of the reference stations. An evaluation of the data indicates that a likely reason for higher mortality at a reference station is the higher level of silt content. Higher mortality occurred only at reference stations with sediment containing 30% or more silt/clay (primarily silt).

Each station from Eagle Harbor was compared individually with a group of reference stations with similar silt content using a pairwise "t test." There were three possible positive end-points for the bioassays: (1) mortality of amphipods, (2) mortality of oyster larvae and (3) abnormality of oyster larvae. Ten stations in Eagle Harbor had mortalities of amphipods that were significantly higher than their respective reference stations (Fig. 2 - PAH concentrations are shown in Fig. 3). Eleven stations had mortalities of oyster larvae that were significantly greater than reference, while nine stations showed significant levels of live oyster larvae abnormality. All three bioassay responses were significant at four stations.

A benthic assessment was performed using counts of total crustacea, mollusca, polychaeta and amphipoda, as well as presence or absence of Phoxocephalid amphipoda. In Puget Sound, degraded areas generally are characterized by a high proportion of polychaeta and mollusca, a low proportion of crustacea and a general absence of certain amphipod families such as Phoxocephalids. However, benthic assessments are also confounded by the high station to station variability within impacted or non-impacted areas. Causal connections are also complicated by the variety of factors (biological competition, sediment characteristics and physical disturbances) that can impact community structure.

At the stations sampled in Eagle Harbor, polychaeta and mollusca comprised more than 75% of the fauna at 15 of the 42 stations sampled (Fig. 4). The percentage of benthic fauna that were crustacea was less than 25% at most stations in Eagle Harbor. Statistical analyses were also performed in comparing benthic results with sediment physical characteristics and contaminant levels. Polychaeta were found to correlate positively and significantly with HPAH and TPAH concentrations.

One additional affect was noted as part of the ecological assessment. During the collection intertidal shellfish samples to evaluate PAH levels, an absence of shellfish was seen in areas where intertidal seeps occurred on the shoreline around the Wyckoff facility, and on the north shore near the ferry maintenance facility and ship repair yard, similar to the observations noted by Word, et al.¹⁰

FATE AND TRANSPORT MODELING

Potential Sources

Possible scenarios for contaminant transport to Eagle Harbor include:

- Atmospheric deposition

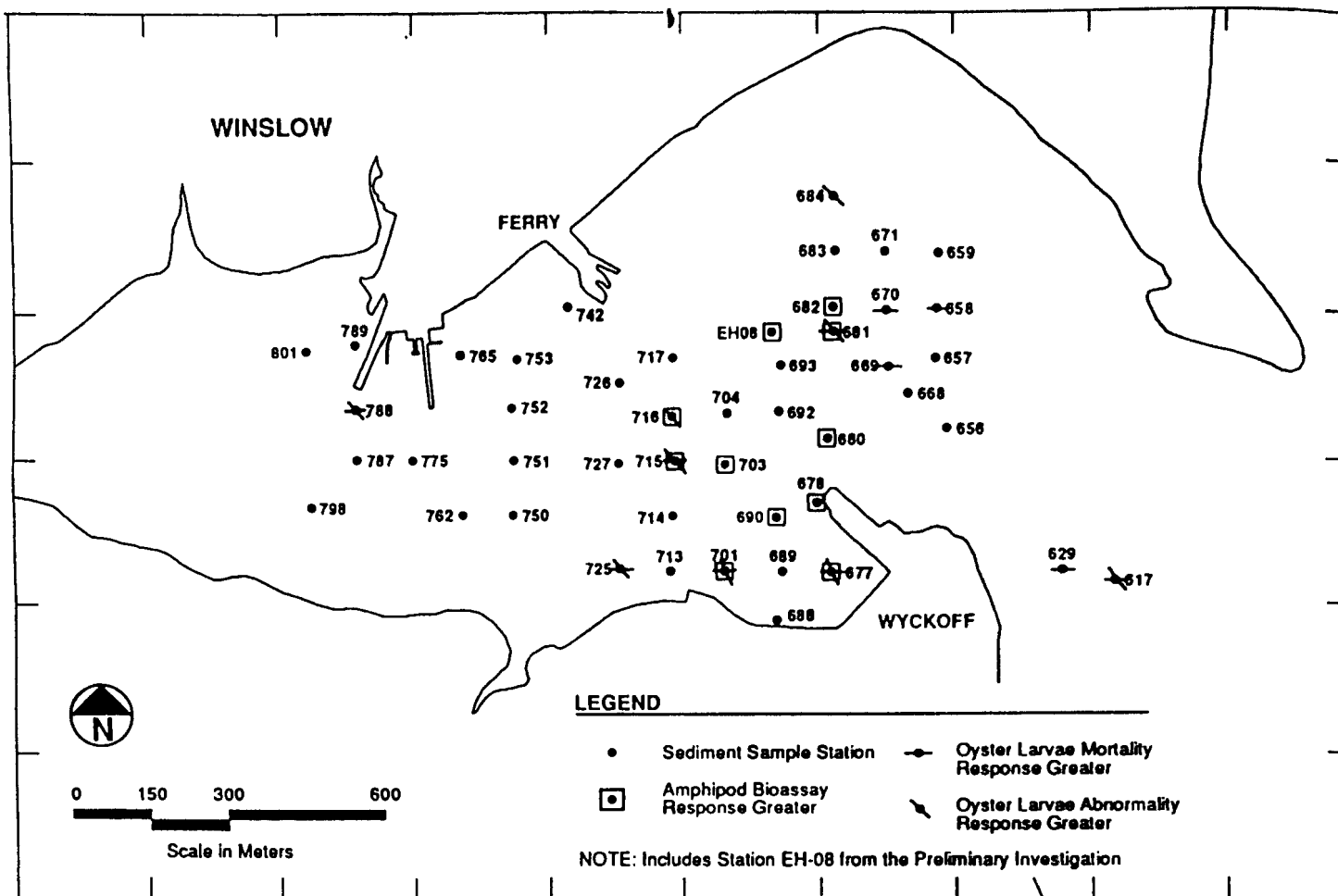


Figure 2
Stations Where Bioassay Responses Were Significantly
Greater than All Other Stations

- Spills or dumps and subsequent redistribution by bottom currents
- Intertidal and subtidal seeps from the Wyckoff facility
- Longshore processes that would carry contaminated sediments from the Wyckoff facility
- Seepage of creosote from pilings

An ocean sediment transport model was used to identify possible as well as unlikely paths for contaminated sediments, identify possible areas of sediment deposition and erosion for both contaminated and uncontaminated sediments and provide semiquantitative estimates of rates for sediment transport and accumulation.

Chemical Fingerprinting

AH sediment chemistry results were evaluated in an effort to determine whether PAH in a given sediment was due to fuel oil or creosote. All samples were analyzed for PAH concentration by an HPLC procedure. Target compounds included the 16 PAH compounds on the Priority Pollutant list. Samples also were analyzed for nitrogen-containing aromatic compounds (NCAC) by GC followed by alkalitipped flame ionization detection (AFID). Target NCAC compounds included: carbazole, quinoline, benzothiazole, benzonitrile, isoquinoline, indole, benzoquinoline, acridine and methylcarbazole. Confirmation of these analyses was performed on 25% of the samples using GC/MS. The GC/MS analyses also allowed for source identification and tracing via analyses of tentatively identified compounds.

PAHs constitute a variety of compounds that vary in their physical and chemical properties. PAH compounds are a major component of both creosote and fuel oil, which are the suspected sources of contamination in Eagle Harbor. Creosote, which may be approximately 90% PAHs, is a viscous liquid. Fuel oil typically contains 2 to 20% PAHs.

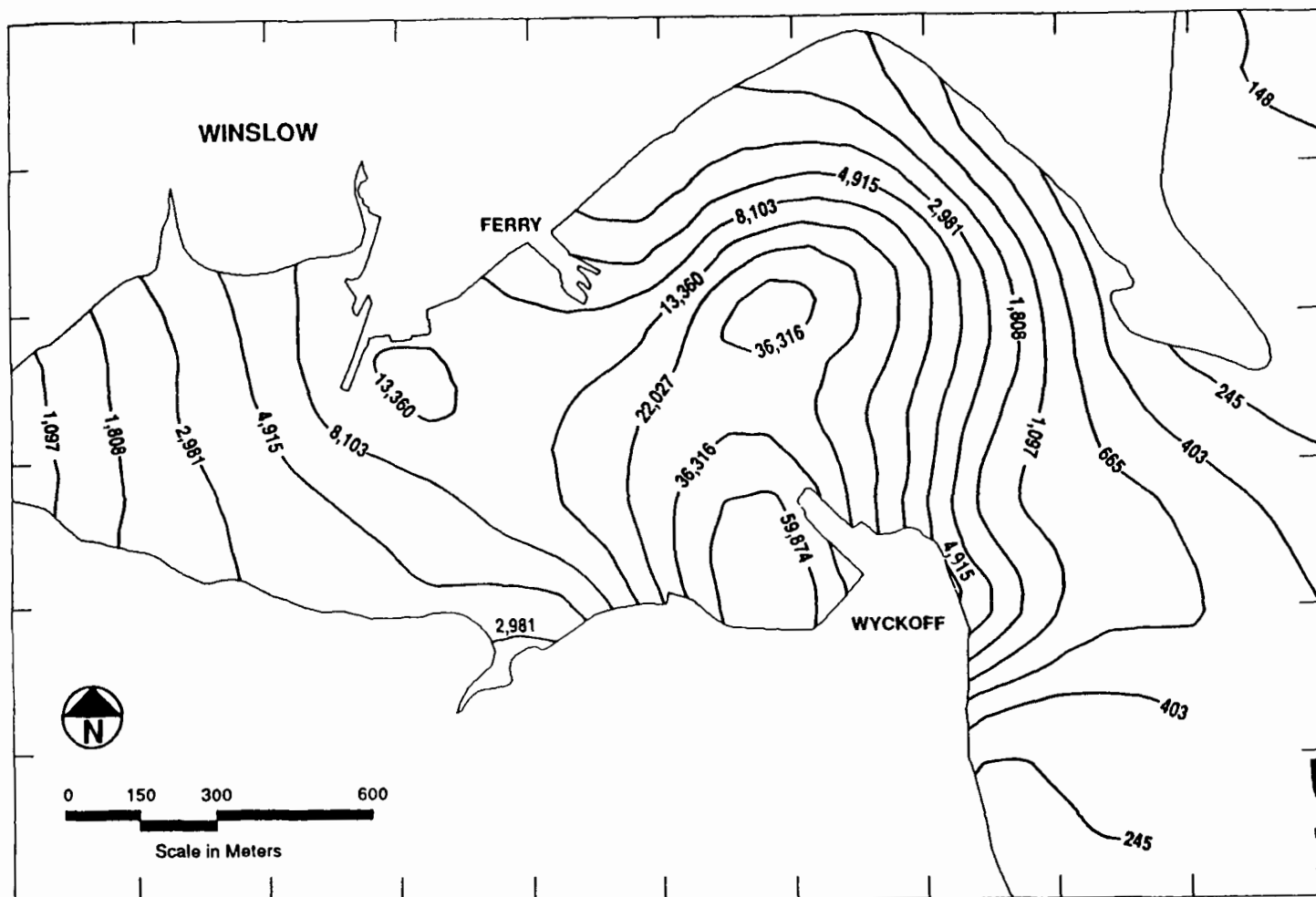
One feature of PAH chemistry that complicates the task of separating past from present effects is that PAH mixtures in the environment change over time. As lower molecular weight and more soluble components dissolve, vaporize or degrade, the remaining resistant components become relatively more abundant.

The NCAC levels, relative amounts of paraffins and ratios of individual PAH compounds are useful indications of sources of contamination. Comparison of samples from Eagle Harbor with suspected source materials indicates the presence of contaminants from creosote in the central harbor and on both the north and south shoreline. Other hydrocarbons are present in greater proportion along the north shoreline and at greater distance from the Wyckoff facility. Contamination near the Wyckoff facility closely resembles creosote or wood preservative wastewater and sludges. Figures 5 and 6 show this comparison for PAH ratios. The ratios for fuel oil and bunker oil are from Neff⁷, the ratios for the "low naphthalene" creosote are from Ingram² and the creosote multi-component standard is from Nestler⁸.

Sediment Transport

The model development involved the following elements:

- A numerical model that computes the spatial and temporal distribution of the velocity field from the known geometric and tidal boundary conditions
- A numerical model that computes the velocity field generated in response to surface wind stress
- A calculation technique that uses a number of model applications to predict alongshore transport
- A computer model that predicts the velocity fields (and critical grain size for movement) generated by vessel propeller action



NOTE: Includes intertidal sediment stations and PI data (Tetra Tech, 1986b)

Figure 3
Average Concentrations of TPAH Calculated by Kriging (ug/kg)

- A set of criteria that evaluates the potential for sediment erosion, transport and deposition

Tidal circulation was simulated with a vertically integrated, two-dimensional finite difference model; wind driven circulation was simulated with the same type of model. Vessel effects were assessed by using a far-field velocity prediction routine for propeller induced, jet-like flows. The overall circulation of the harbor was predicted by taking a linear superposition of the results of each of the above models.

Oceanographic studies were performed to support this modeling effort. These include:

- Bathymetric, hydrographic and water level measurements and data processing
- Compilation and processing of existing wind data
- Wave climate predictions
- Current speed and direction measurements
- An evaluation of the potential for sediment movement and deposition

Examination of velocities in the harbor, based on the model results, indicates that only a small interval of grain sizes will be subject to deposition. Very fine sand and coarse silt, if available, can be deposited throughout most of the harbor. Coarser material cannot be transported within the harbor, and finer material will not be deposited but will be flushed out by tidal currents. This phenomenon is shown schematically in Figure 7.

Depositional areas in Eagle Harbor include deeper parts of the inner harbor, the shoal northwest of the Wyckoff facility and the immediate vicinity of streams entering the harbor (Fig. 8). Sediment probably does

not accumulate in the area of the PAH "hot spot" in the central harbor because of the lack of source of coarse grained materials that could be deposited there. Ferry propwash prevents deposition of the finer sediment in the central harbor that has accumulated in other parts of the harbor.

In summary, three distinct transport features appear to dominate the overall movement of sediment in the harbor:

- The potential movement of material from Rockaway Beach to the north and into the harbor
- Remobilization of bottom sediments by vessel propeller induced currents (Fig. 9)
- Deposition of fine grained material in selected areas of the harbor

Sedimentation rate studies using lead 210 data indicate deposition rates of 1.0 to 1.7 mm/yr³ at three locations in the harbor. This result is based on cores dating back to approximately 200 to 300 yr. However, the sediment load from the watershed and shoreline sources to the harbor may have varied significantly from the long-term average in recent years due to land cover changes and land use practices in the watershed and the construction of shoreline protective structures.

Although the lead 210 data may be expected to reflect past sedimentation rates, future rates are expected to be much smaller than in the past. Typically, 75% of the particulate load to Puget Sound is from river-line and shoreline sources. There is no reason to expect this deposition rate to be different for Eagle Harbor. An analysis of watershed processes and soil loss estimates, and the nearly total armoring of the shoreline of the harbor and adjacent Rockaway Beach, indicate that the major

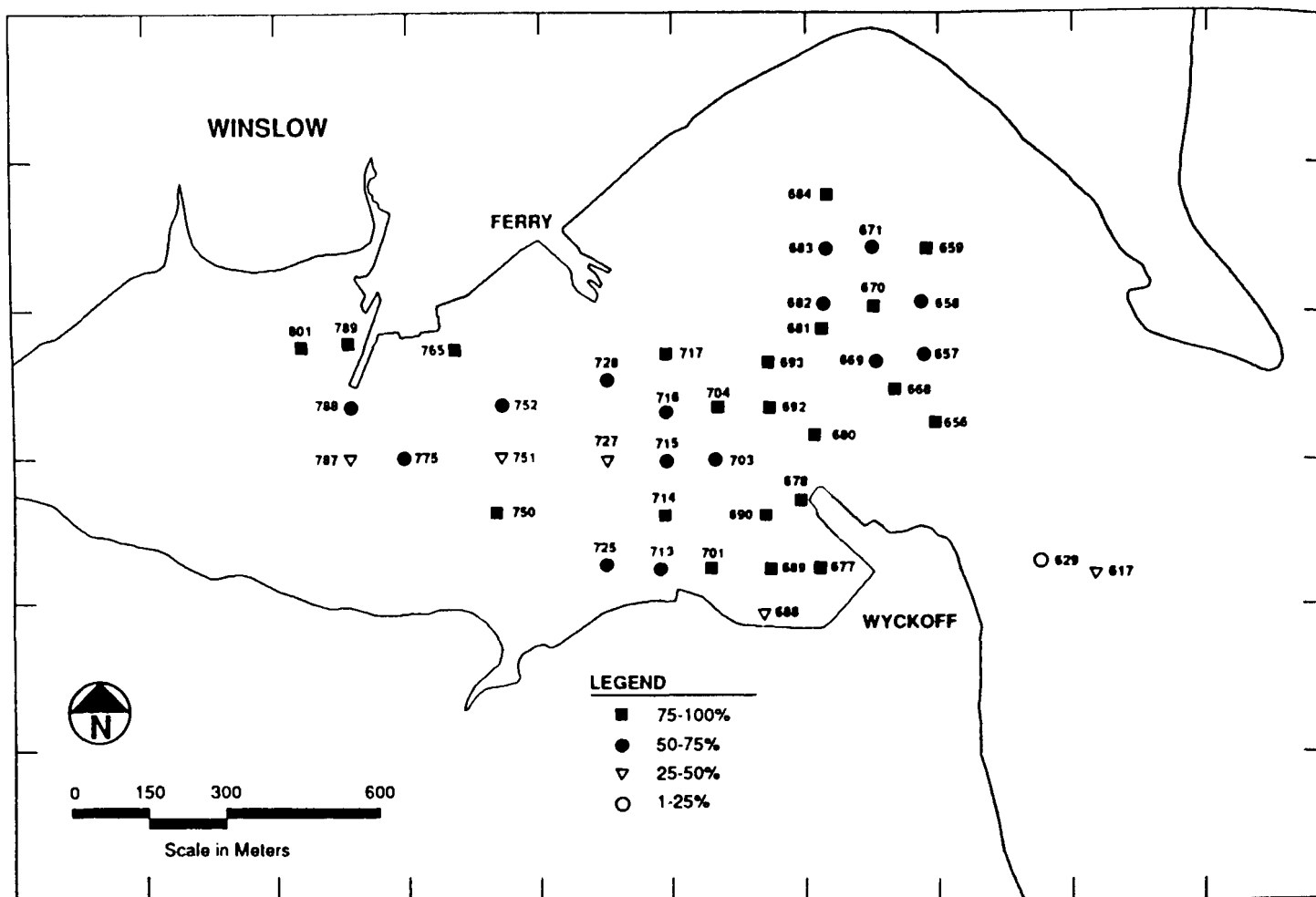


Figure 4
Relative Percent Polychaeta and Mollusca for
June 1988 Subtidal Samples

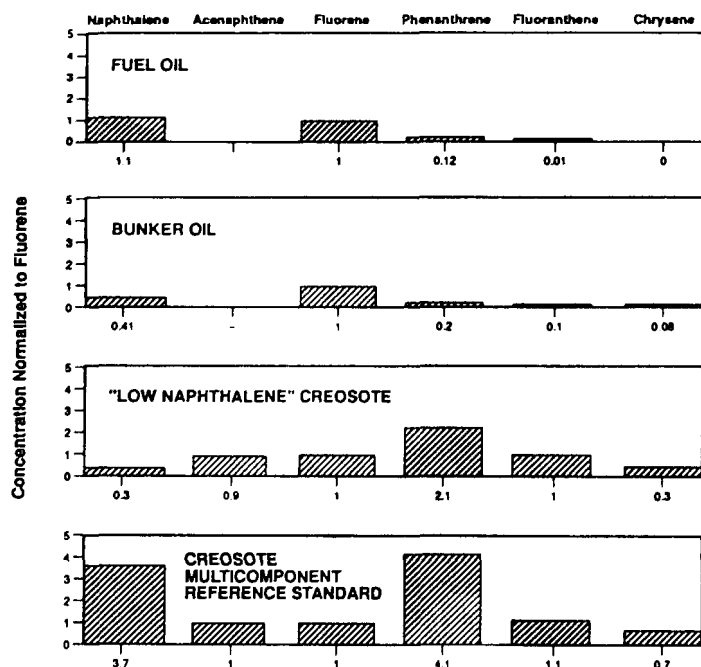


Figure 5
PAH Composition in Potential Source Materials
For Eagle Harbor

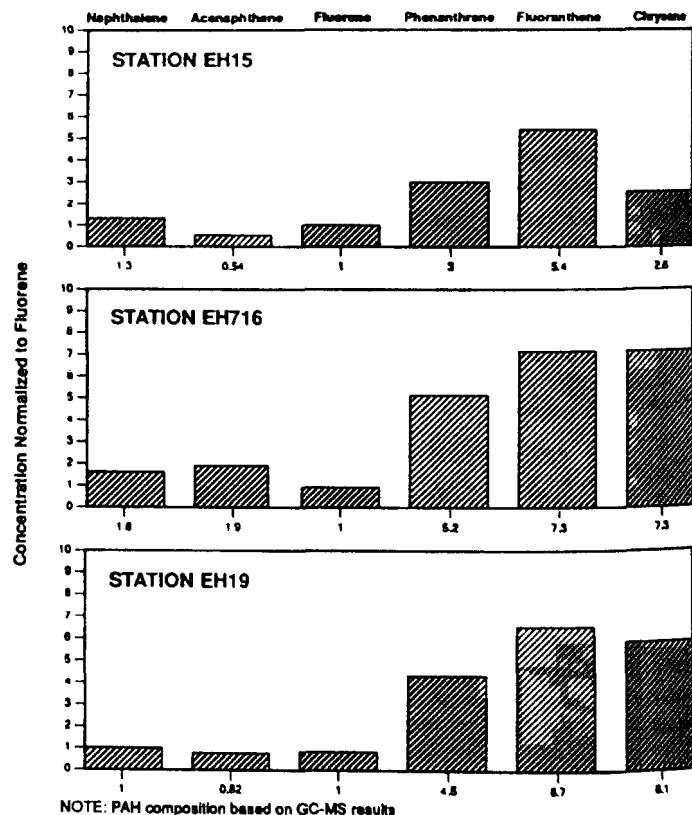


Figure 6
PAH Composition in Sediments from Central Harbor

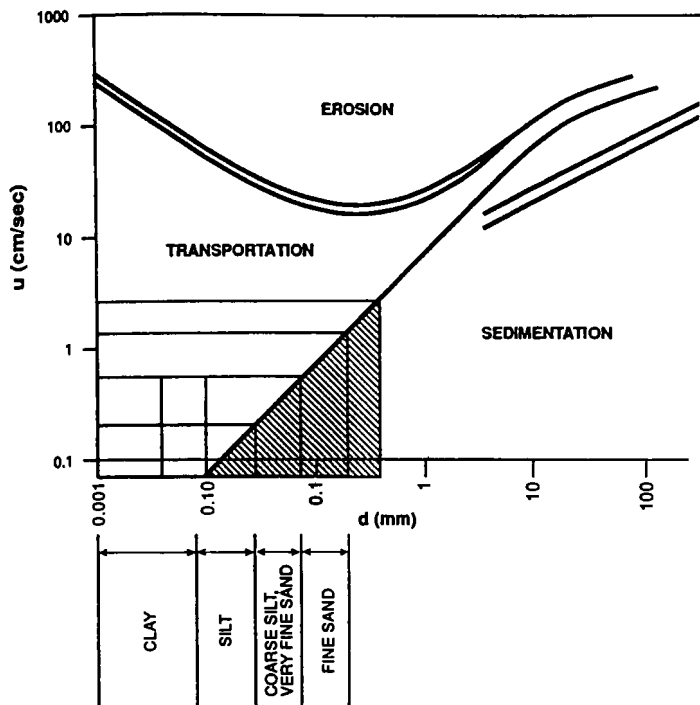


Figure 7
Sediment Sizes Sub to Deposition

sources of sediment have been effectively reduced or eliminated. Future sedimentation rates in the harbor will quite likely will be an order of magnitude less than in the past.

PAH Fate and Transport

The physical and chemical properties of PAH suggest that they are strongly absorbed to particulate surfaces. However, the relation between PAHs and particle size fraction is not clear-cut. Many organics are strongly associated with fine fractions. However, PAH compounds in Washington coastal sediment often have been associated with larger, low density particles.

Groundwater transport of PAH compounds in creosote and fuel oil is also complex. As these products migrate through the saturated zone, PAH compounds can occur in three phases: floating, soluble and sinking. Seeps of floating product have been observed from the shoreline surrounding the Wyckoff facility.

Transport of PAHs in Eagle Harbor probably involves three primary mechanisms: (1) absorption to sediment particles and transport or deposition of those particles; (2) solution and transport in water; and (3) separate flow of nonaqueous phase liquid. Results of sediment transport modeling suggest that removal or movement of PAH absorbed to sediment is likely to be slow. Rates of solution and transport in the water column cannot be predicted from existing data, but are likely to be very slow, especially for HPAH.

Movement of NAPL may affect distribution and redistribution within the harbor, but is not likely to be a loss mechanism except for floating NAPL. Flow of NAPL is a continuing source of PAH via intertidal seeps and is a possible continuing source to subtidal sediments, either

LEGEND

- 0.01 - 0.03 mm (Silt)
- 0.03 - 0.075 mm (Coarse Silt to Very Fine Sand)
- > 0.075 mm (Fine Sand)

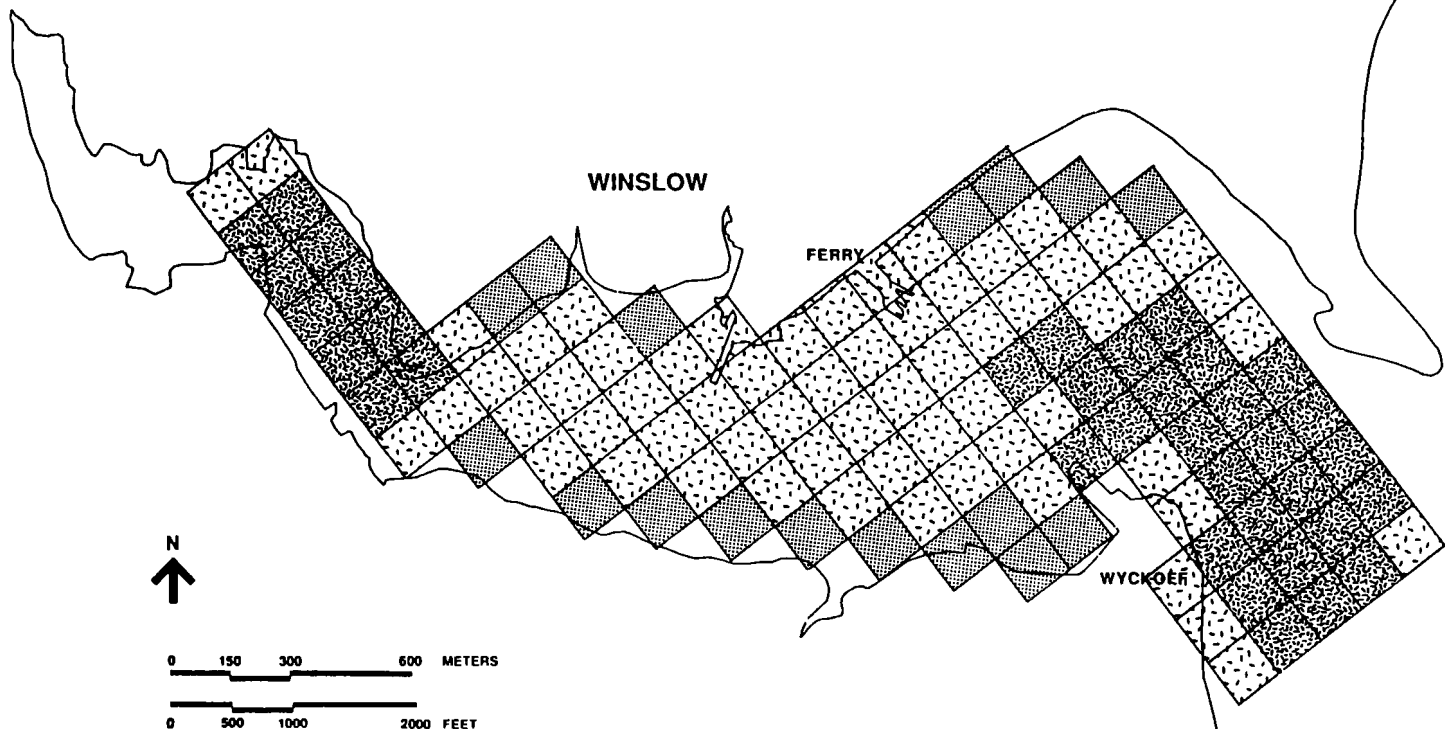


Figure 8
Areas of Potential Deposition for Fine-Grained Sediment as
Predicted by Transport Model

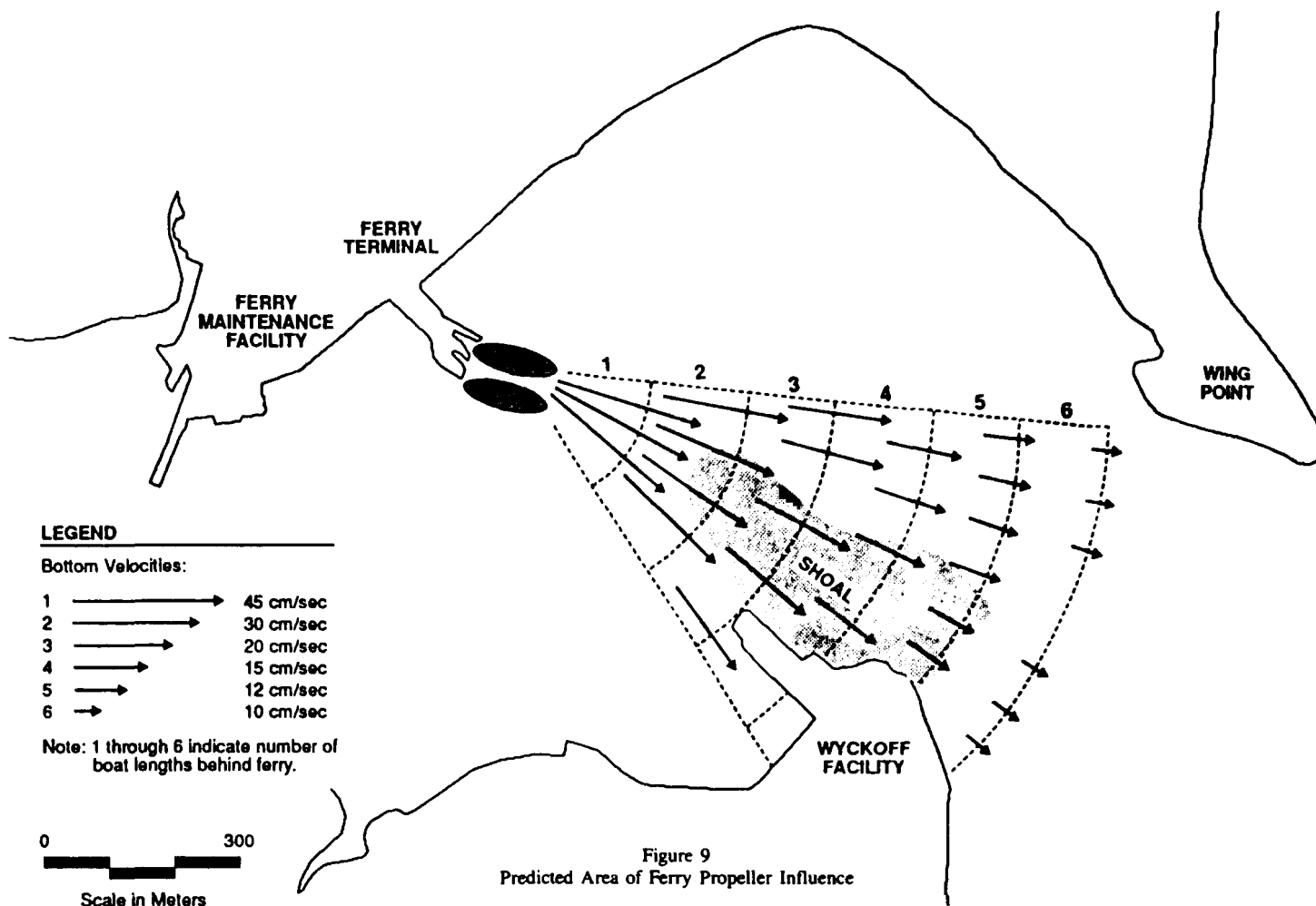


Figure 9
Predicted Area of Ferry Propeller Influence

through near-surface or subsurface flow.

Processes that effect the persistence of PAH in the biological zone of sediments in the harbor are biodegradation, photo-oxidation and volatilization. LPAHs generally are more likely to be dispersed from discharge areas by solution in water and volatilization to the atmosphere. HPAHs are lost by biodegradation and photo-oxidation, but are generally very persistent in aquatic sediments. Of these processes, only biodegradation is considered to have an impact on PAH persistence.

Another process that can have a significant impact on PAH values in the biological zone is natural recovery or burial. Based on the sediment transport assessment presented earlier, it appears that PAHs associated with bottom sediments: (1) will not be transported out of the harbor and will not be rapidly dispersed within the harbor and (2) will not be rapidly buried by clean sediment. In addition, reduced sedimentation may enhance concentrations of PAH arriving from the watershed.

CONCLUSIONS

Available data do not permit us to determine whether the PAH present in percent amounts in the central harbor are there as a result of past discharges or spills are as a result of possible continuing discharges of DNAPL. Some suspension or resuspension of PAH-contaminated sediment may occur in areas affected by ferry propeller wash, but transport away from the areas of higher level contamination may be inhibited by the low bottom velocities and the grain size of the affected sediment. Separate phase flow of DNAPL contaminants may occur over short distances in areas of the harbor where hydraulic gradients are present. Additional studies are being planned to evaluate the potential for DNAPL transport to the harbor.

REFERENCES

1. Gilchrist, C.A., Lynes, A., Steel G. and Whitham, B.T., "The Determination of Polycyclic Aromatic Hydrocarbons in Mineral Oil by Thin-layer Chromatography and Mass Spectrometry," *Analyst*, 97 pp. 880-888, 1972.
2. Ingram, L.L., et al., "Migration of Creosote and Its Components from Treated Piling Sections in a Marine Environment," *Proc. American Wood-Preservers' Association*, 78, pp.120-128, 1982.
3. Hart Crowser, *Contaminant Deposition and Sediment Recovery, Eagle Harbor Site, Kitsap County, Washington*. Draft Report prepared for Washington State Department of Transportation, Mar., 1989.
4. Long, E.R., and Chapman, P.M., A Sediment Quality Triad; Measurement of Sediment Contamination, Toxicity and Infaunal Community Composition in Puget Sound. *Mar. Poll. Bull.*, 16, pp.405-415, 1985.
5. Malins D.C., *Summary Report on Chemical and Biological Data from Eagle Harbor*, National Marine Fisheries Service, Seattle, WA, 1984.
6. Malins D.C., et al., "Toxic Chemicals in Sediments and Biota from a Creosote-polluted Harbor: Relationships with Hepatic Neoplasms and Other Hepatic Lesions in English Sole," *Carcinogenesis*, 6, pp.1463-1469, 1985.
7. Neff, J.M., *Polycyclic Aromatic Hydrocarbons in the Aquatic Environment: Sources, Fates and Biological Effects*, Applied Science Publishers, Essex, England, 1979.
8. Nestler, F.H.M., *Characterization of Wood Preserving Creosote by Physical and Chemical Methods of Analysis*, USDA Forest Services Research Paper FPL 195, US Department of Agriculture, Forest Products Laboratory, Madison, WI, 1974.
9. Tetra Tech, Inc., *Preliminary Investigation, Eagle Harbor, Bainbridge Island, Washington*, Prepared by Tetra Tech, Inc. and Black and Veatch for the Washington Department of Ecology, Nov., 1986.
10. Word, et al., *Reconnaissance Survey of Intertidal Property Owned by Wyckoff Company in Eagle Harbor*, Memorandum from Battelle Northwest Marine Research laboratories to Darrel Palmer, Wyckoff Company, 1986.
11. Yake, et al., *Chemical Contaminants in Clams and Crabs from Eagle Harbor, Washington State, with Emphasis on Polynuclear Aromatic Hydrocarbons*, Washington State Department of Ecology, Water Quality Investigation Section, Oct., 1984.

Considerations for Discharge of Contaminated Groundwater To a Municipal Sewer System and POTW

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INTRODUCTION

The remediation of contaminated groundwater at hazardous waste sites often involves alternatives for its extraction, treatment and disposal. One alternative that may be considered is discharge of contaminated groundwater to a municipal wastewater collection system for conveyance to a publicly owned treatment works (POTW). This paper presents observations made during extended use of a city's municipal wastewater collection system and POTW for discharge of trichloroethylene (TCE)-contaminated groundwater during aquifer and pilot testing for an NPL site in Missouri.

As part of the Remedial Investigation (RI) conducted at the site, aquifer testing was planned for a deep bedrock aquifer to evaluate its hydrogeologic properties¹. The deep bedrock aquifer was one of three area aquifers, and only it produced an adequate quantity of water for a drinking supply. It presently serves as the city's municipal water supply. The city's wastewater collection system and POTW were proposed for disposal of groundwater from the aquifer tests.

Information for this paper was gathered from three studies; a study which examined the feasibility of using the existing sewer system and POTW for discharge, the RI and the FS². Data from these studies were organized in two phases for this paper: (1) an evaluation of the capacities and background contaminant levels of the existing sewer system and POTW; and (2) an extended pilot testing program which monitored TCE removal by air strippers, levels of TCE discharged to the sewer from the air strippers and from an off-site well, and TCE levels of the POTW influent and effluent.

To effectively and economically implement a remedial action for the site, numerous site hydrologic characteristics were investigated during the RI, including the extent of influence of recovery well pumping. To characterize this information, aquifer tests were conducted at selected on-site monitoring wells and abandoned Municipal Well No. 1 located off-site. The aquifer tests consisted of pumping the wells at various rates and measuring the water levels in surrounding wells to define the cone of depression associated with potential operation of the recovery well.³

The proposed method for disposal of TCE contaminated groundwater generated during aquifer and pilot testing was discharge to the city's municipal sewer system and treatment at the POTW. This method was agreed to by the Missouri Department of Natural Resources (MDNR) and the city, subject to pretreatment limits to be discussed later. The following goals and objectives were developed to answer questions associated with the use of the municipal sewer system and POTW for possible extended disposal during remedial actions.

- Evaluate the capability of the POTW to remove TCE contamination
- Establish the POTW's National Pollutant Discharge Elimination System (NPDES) permit limitations or requirements

- Determine the flow capacity of the sewer system
- Determine existing TCE concentrations in the collection system flow path from near the site to the POTW
- Determine if TCE volatilization or dilution were occurring in the collection system
- Document the effectiveness of air strippers in removing TCE during aquifer testing and conformance to pretreatment requirements
- Evaluate any health risks associated with TCE vapors in the collection system or emissions from the POTW

SITE INFORMATION

The city is located in Missouri and has a population of approximately 6,000 people. Figure 1 shows the location of the site in the city. A former industrial and manufacturing site, it had been leased and operated by a number of business concerns through the years. The site consists of a 21,000 ft² lot enclosed within a 6-foot high chain-link fence. A former plant building, constructed before 1902, stood on the site. In 1979, the northern portion of the building was destroyed by fire. The fire-damaged portion of the structure was demolished and the debris was pushed into the basement under that portion of the building.

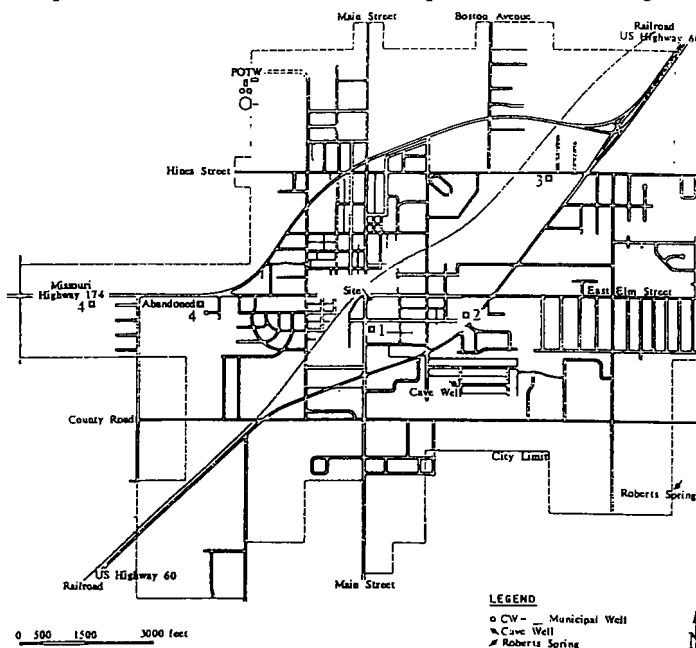


Figure 1
Location Plan

In June, 1982, MDNR and the U.S. EPA selected the city's municipal water supply wells for random sampling and analysis for volatile organic compounds as part of U.S. EPA's National Synthetic Organic Chemicals Survey. The locations of the municipal wells are shown in Figure 1. TCE was detected at 15 mg/L in samples collected from Municipal Well No. 1. This value was below Missouri's health-based criterion which, at that time, was 27 mg/L. Additional samples from all three city wells were collected in March, 1983. A TCE level of 10 mg/L was detected in Municipal Well No. 1 while none (at a detection limit of 10 mg/L) was detected in Municipal Wells No. 2 and 3.

During the subsequent RI, volatile organic compounds, primarily TCE, were detected in on-site subsurface soils and groundwater of the three separate aquifer systems: the unconsolidated materials/fractured shallow bedrock system, unfractured shallow bedrock system and deep bedrock system. The unfractured shallow bedrock system is a minor aquifer. The deep bedrock system is a major aquifer capable of yields as high as 2,000 gpm. All of the city's municipal supply wells are located in the deep bedrock aquifer. TCE contamination detected in the deep bedrock wells varied, depending on the location of the well in relation to the contaminant plume. TCE concentrations ranged from non-detectable for most off-site wells, up to 200 mg/L for Municipal Well 1, and up to 18,000 mg/L for on-site wells. Aquifer tests and pilot tests were proposed for the deep bedrock wells to determine their hydro-geologic properties for development of remedial pumping strategies.

BACKGROUND CONDITIONS

Based on historic data, it was anticipated that the aquifer testing and pilot testing would generate up to 200 gpm of potentially TCE-contaminated groundwater. Therefore, it was necessary to ensure that the groundwater generated during these activities be properly controlled,

treated and discharged in a manner which met all RCRA, state and local requirements. Because of the need for a readily available means of discharge, the city's wastewater collection system and POTW were proposed for discharge of the groundwater from aquifer testing. Before initiating discharge to the sewer, the feasibility of conveying test flows through the sewer system as well as the potential effects on the POTW and its anticipated performance were evaluated. The existence of any background levels of contaminants in both the sewer system and POTW also was established.

Sewer System

An evaluation of the sewer system was performed to determine if TCE-contaminated groundwater could be discharged to the system. The objectives of the evaluation were to determine the following:

- The presence of TCE in the sewer system
- The ability of the sewer system to convey the additional flows

Once the presence of TCE contamination in the sewer system was established, other objectives were added.

- Determine if volatilization or dilution of TCE from the wastewater was causing a reduction of TCE levels in the system
- Determine the possible effects of discharging untreated or treated TCE-contaminated groundwater to the sewer system, such as TCE vapor build up, creation of health hazards to sewer maintenance workers, or development of explosive atmospheres

Sewer System Description

A layout of the sewer system, sewer flow direction and year of sewer construction are shown on Figure 2. Flows discharged from the site would be conveyed to the POTW through both gravity sewers and force

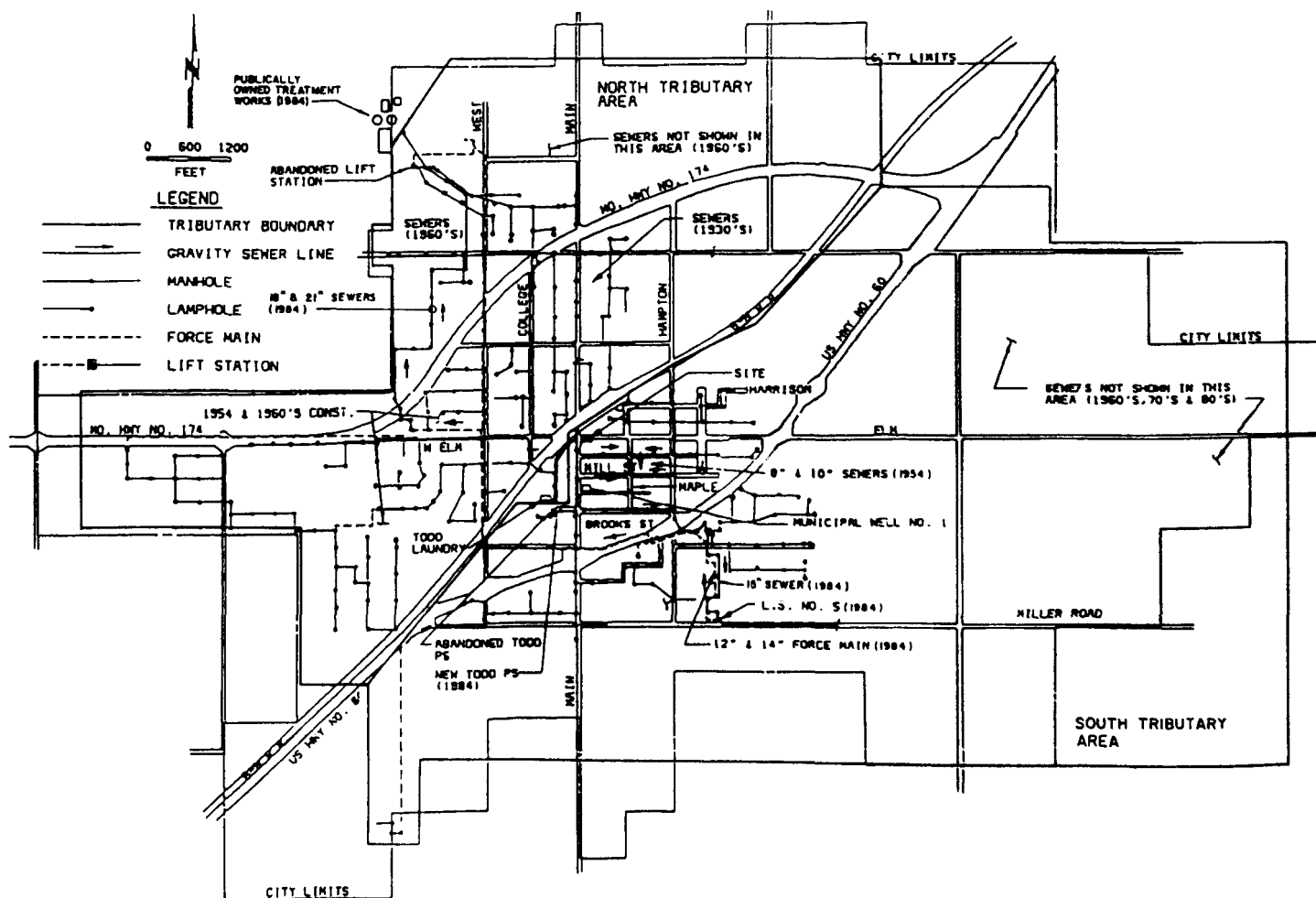


Figure 2
Existing Sewer System

mains. From the site, wastewater flows in 8- and 10-in. vitrified clay pipe (VCP) sewers, constructed in the mid-1950s, and continues in a 15-in. reinforced concrete pipe (RCP) to the lift station, both constructed in the 1980s. From the lift station the flow is conveyed in a force main to 18- and 21-in. diameter gravity sewers leading to the POTW.

The condition of the sewer system had been evaluated during an earlier infiltration/inflow (I/I) study⁴. The I/I study found the existing sewers flowing at less than half capacity during normal conditions, but surcharging during rainfall events. Infiltration/inflow was found to be excessive in the older sewer sections. The sewers near the site were found to surcharge during rainfall events. The I/I study recommended that a sewer system evaluation survey (SSES) be conducted to further evaluate the condition of the sewer system. The SSES included a physical survey, television inspection and smoke testing of selected portions of the system. The television inspection revealed that the condition of lines near the site varied. As would be anticipated for VCP sewer lines constructed in the mid-1950s, many leaking joints and root intrusions were observed. A sewer system rehabilitation program was conducted in 1984 to reduce I/I sources.

Sewer System Background Sampling

In December 1986, and January, 1987, the MDNR collected water samples in Southwestern Bell Telephone manholes near the site and found trichloroethylene (TCE) and other volatile organics. The detection of these chemicals suggested the introduction of contaminated shallow groundwater into the sewer system. Wastewater was sampled from selected manholes and analyzed for priority pollutant volatile organics to establish background conditions. In addition, wastewater flow was measured when the samples were collected using a calibrated V-notch weir. The sampling was conducted on three occasions: June, 1987; July, 1987; and May, 1988. Sampling point locations and TCE concentrations are shown in Figure 3.

The wastewater in manholes on the gravity sewer leading away from the site contained TCE in various concentrations. In general, the TCE concentrations decreased with distance from the site, as would be expected, because of dilution by incoming wastewater from downstream branches.

The decrease in TCE concentrations away from the site raised two questions. Was the decrease caused by dilution or volatilization in the turbulent wastewater flow? If significant volatilization was occurring, could vapor build up to levels which might present a health hazard to sewer maintenance workers? To determine whether dilution or volatilization was causing the decrease in TCE levels, instantaneous flow measurements taken during the June, 1987 sampling period were examined. TCE concentrations, flow rates and TCE mass loads for three manholes where flow was measured are listed in Table 1. The manhole numbers correspond to those on Figure 3.

Table 1
TCE Concentrations and Flow Rates in Sewers
(June 1987 Sampling)

Manhole No.	TCE (ppb)	Flow (gpm)	TCE Mass (pounds/day)
5	230	12	0.033
9	17	98	0.020
10	16	101	0.019

The decrease in TCE mass loading in downstream manholes indicated that volatilization may occur within the sewer system. However, the concentration of volatile organic vapors was measured before entering the manholes but organic vapors were not detected above background levels.

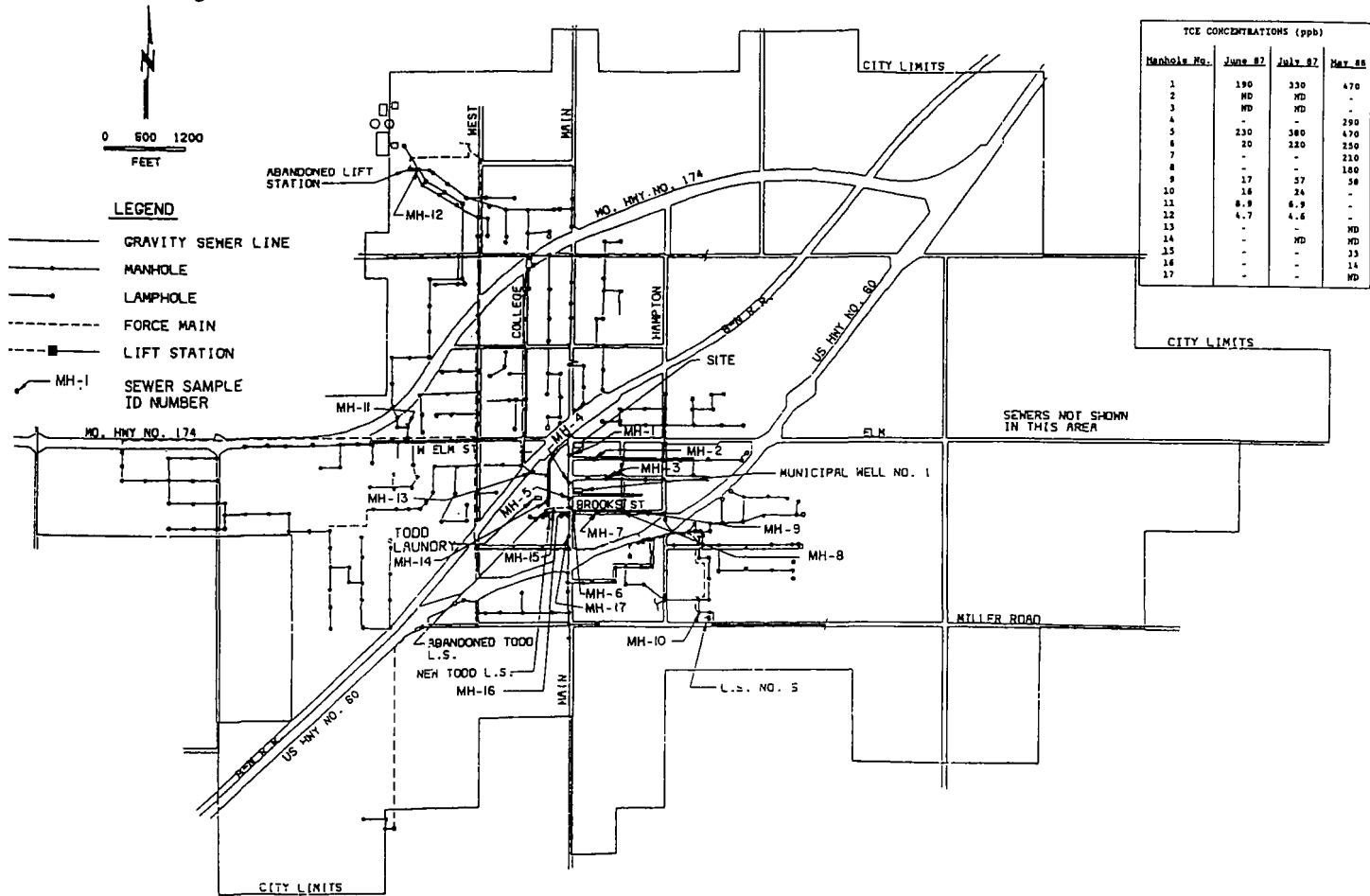


Figure 3
Sewer System Sample Points and TCE Concentrations

Sewer System Evaluation

The flow capacities of the newer sections of the sewer system were calculated from construction drawings. Flow capacities of the older sewer sections, for which no construction drawings were available, were established by a field survey to obtain pipe diameters and invert elevations. The sewers had adequate capacity to simultaneously carry peak domestic wastewater flows and aquifer test flows. However, the sewers are known to surcharge during heavy rainfalls, which would prevent discharge of aquifer test flows during these periods.

POTW

The POTW was evaluated to determine if TCE-contaminated groundwater could be discharged to it. The objectives of the evaluation were to determine the following:

- The presence of TCE in the POTW influent, effluent or sludge
- The ability of the POTW to remove TCE from groundwater
- The capacity of the POTW to handle the additional flows
- Any adverse impacts the TCE might have on plant operations or performance

POTW Description

As shown on Figure 4, the POTW is an activated sludge plant using brush rotor aerators and mixed media filters. The design average flow was 926,880 gal/day or 644 gpm, and the hydraulic capacity was 7.34 mgd (5,070 gpm). The plant is governed by a MDNR NPDES permit which stipulates monthly average limits of 10 mg/L for biochemical oxygen demand (BOD) and 15 mg/L for suspended solids (SS). The permit stipulates a monthly average TCE discharge limit of 2 mg/L, to be measured once every 6 mo.

Raw wastewater enters the POTW through a manually cleaned bar screen and is pumped by two enclosed 54-in. screw pumps. The flow is measured by a Parshall flume before it enters a multiple channel aeration basin. Aeration and mixing in the basin are accomplished by brush surface aerators. Next the flow enters two 55-ft diameter clarifiers. The clarifier effluent flows to filters equipped with an automatic traveling bridge backwashing mechanism. Filtered effluent passes through a chlorine contact basin and is discharged to a reaeration structure.

POTW Background Sampling

A background sampling program was conducted at the POTW to determine TCE concentrations in the plant influent, effluent, and sludge. The sample numbers and locations are shown in Figure 4. Samples were collected on June 11 and 12, and on July 14, 1987; the results are summarized in Table 2. During the June sampling period, influent and effluent samples were collected at different times of the day to determine diurnal variations in TCE concentrations.

Table 2
POTW Influent, Effluent and Sludge Samples

Sample Number	Location	Date	ANALYTES				
			(1)	(2)	(3)	(4)	(5)
			(ppb)	(ppb)	(ppb)	(ppb)	(ppb)
TP1	Influent	6/11/87	3.1	3.9	7.0	ND	ND
TP3	Effluent	6/11/87	ND	ND	ND	ND	ND
TP2	Influent	6/12/87	9.8	ND(6)	38.0	4.6	ND
TP2A	Influent	6/12/87	10.0	2.2	38.0	5.0	ND
TP4	Effluent	6/12/87	ND	ND	ND	ND	ND
TP5	Sludge	6/12/87	ND	27,000	ND	ND	ND
TP1	Influent	7/14/87	ND	15.0	ND	ND	ND
TP3	Effluent	7/14/87	ND	ND	ND	ND	ND
TP3A	Effluent	7/14/87	ND	ND	11.0	ND	4.5
TP5	Sludge	7/14/87	ND	4,800	6.8	ND	ND

Note: Concentrations below the detection limit of 2 ppb are indicated by ND.

- (1) - Trichloroethylene
- (2) - Toluene
- (3) - Chloroform
- (4) - trans-1,2-Dichloroethene
- (5) - 1,1,1-Trichloroethane

The background TCE concentrations in the plant influent ranged from non-detectable to 10 mg/L. TCE concentrations in the plant effluent were below detection limits. There were no detectable TCE concentrations in the plant sludge samples; however, toluene was detected at a concentration up to 27,000 ppb.

TCE was detected in the POTW influent but it was below detectable levels in the POTW effluent. The POTW apparently could reduce influent TCE at the concentrations received during sampling to less than the 2.0-mg/L discharge limit. From this evidence the ability of the POTW to treat higher levels of TCE could not be determined. It also appears that at the influent TCE levels found during sampling, there is no TCE carryover to the sludge.

Evaluation of POTW Treatment Potential

The potential of the POTW to remove the TCE that exceeded background levels and to meet the 2 mg/L discharge limit was evaluated. A literature search was conducted to review the biological treatment of TCE from contaminated groundwater. POTWs have reported significant removals of volatile organic carbon (VOC) by various treatment processes¹⁻⁴. These reported removals include secondary treatment processes such as activated sludge plants using surface aeration, diffused air and pure oxygen; trickling filters; aerated lagoons; rotating biological contactors; air strippers; and advanced wastewater treatment systems which incorporate tertiary treatment, such as mixed media filtration.

The principal mechanisms involved in TCE removal at air activated sludge plants are air stripping, adsorption on the microbial growth and biodegradation. Volatilization by air stripping was reported to be the primary mechanism involved in removal of TCE in activated sludge plants. TCE can be volatilized into the atmosphere in the plant collection system, wet wells, grit chambers, aeration basins and post-aeration devices (weirs). TCE removal efficiency values in activated sludge processes reported in a U.S. EPA study² ranged between 68 and 90% and were up to 97% when followed by tertiary treatment such as effluent filtration. The wide range of removal efficiencies underscores the fact that removal estimation requires plant-by-plant evaluation. The removal capacities of individual plants are found to be strongly influenced by physical configuration.

The POTW average design flow was 926,800 gpd (0.93 mgd), however, it was determined that the POTW could handle a flow of 1.46 mgd at the design per capita organic and solids loadings. The POTW has a hydraulic capacity of 7.34 mgd and the capacity of the clarifiers, at normal design loading rates, is 2.9 mgd. Flows from aquifer testing, which have no organic or solids loadings, were not expected to affect plant performance or its ability to meet NPDES requirements.

EXTENDED AQUIFER TESTS - RESULTS

Based on the background samples gathered from the sewer system, the POTW and other information, MDNR, the pretreatment authority for the city's POTW, recommended the following discharge limits for the sewer system and the POTW which were adopted by the city:

Table 3
Pretreatment Discharge Limits

Monitoring Point	Allowable TCE Concentration Limit (ppb)
Sewer Discharge	200
POTW Influent	10*
POTW Effluent	2*

* Established by the POTW NPDES permit.

The city agreed to allow discharge of fluids into the sewer system and the POTW. The agreement allowed up to 200 gpm of groundwater meeting the established limits to be discharged.

Groundwater was discharged to the sewers from two sources, untreated groundwater from Municipal Well No. 1 and treated groundwater from onsite wells. Groundwater from Municipal Well No. 1 was generated

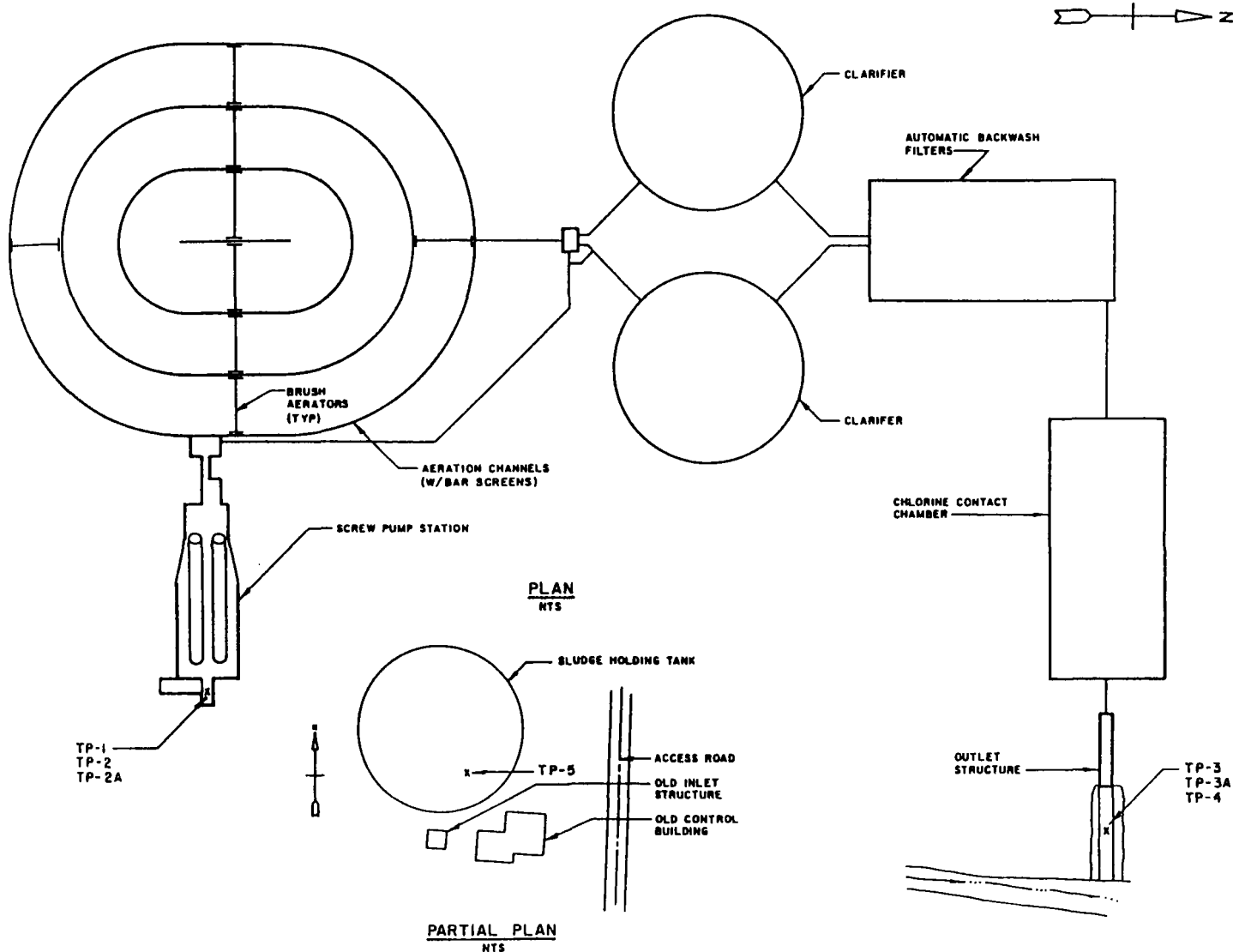


Figure 4
POTW and Sample Locations

during long-term aquifer testing. TCE concentrations in groundwater from Municipal Well No. 1, located approximately 500 ft south of the site, were below the 200 mg/L limit; therefore, no treatment was required. Discharge of groundwater from Municipal Well No. 1 to the sewer commenced in August, 1987, and was periodic through January, 1988 and then essentially continuous from January, 1988 through January, 1989. The concentration of TCE during this period is shown in Table 4. Until March, 1988, samples from Municipal Well No. 1 were taken at least once per day. After that date, the frequency was changed to once every 2 wk with the city's approval since the TCE levels in Municipal Well No. 1 were shown to be consistent.

Groundwater which was generated from on-site wells during the remedial investigation contained TCE concentrations significantly higher than the 200 mg/L sewer discharge limit. Two air strippers, with a flow capacity of 150 gpm and operating in series, were constructed to reduce groundwater TCE concentrations to acceptable levels. The air strippers were operated intermittently for two periods: in September and October, 1987; and January through March, 1988. TCE concentrations in the air stripper Tower 1 influent, Tower 1 effluent/Tower 2 influent, and Tower 2 effluent/sewer discharge, including the total TCE removals, are shown in Table 5. The frequency of collecting samples from the Air Stripper No. 2 effluent/sewer discharge was one or more times per day.

Concurrently with the discharge of groundwater to the sewers, the POTW influent and effluent TCE concentrations were monitored. POTW sampling began in June, 1987 and continued until January, 1989.

The POTW influent and effluent TCE levels are listed in Table 6. The frequency of collecting POTW influent and effluent samples was once per day until March, 1988, when the frequency was changed to once every 2 wk. The City approved the request to decrease the frequency for this sampling also because the TCE concentrations were shown to be consistent.

Figure 5 shows the relationship between TCE concentrations in the discharges from Municipal Well No. 1 and Air Stripper No. 2 to the sewer and the corresponding POTW influent and effluent TCE concentrations. Based on expected sewer flow quantities, the travel time from the discharge point of Municipal Well No. 1 or Air Stripper No. 2 to the POTW would be approximately 2 hr. Based on measured flow rates, the average hydraulic retention time at the POTW during the pumping was approximately 40 hr.

Air samples were taken from the sewers and at the POTW during air stripper operation on Feb 3 and June 16, 1988 to determine the presence and/or concentration of VOCs in the air. The chemicals present were qualitatively identified using a portable gas chromatograph. Results of the samples are shown on Table 7. The sewer air samples were taken at Manhole MH-6, as identified on Figure 3, and the POTW air samples were taken downwind of the aeration basin channels.

EXTENDED AQUIFER TESTS—DISCUSSION

During extended pumping of Municipal Well No. 1, the groundwater TCE concentrations became stabilized in the range of 40 to 80 mg/L,

Table 4
TCE Concentrations in Groundwater From Municipal Well No. 1

SAMPLE DATE	TCE CONCENTRATION (PPB)	SAMPLE DATE	TCE CONCENTRATION (PPB)
08/10/87	32	01/01/88	76
08/10/87	44	02/04/88	20
09/02/87	180	02/27/88	27
09/02/87	110	03/01/88	43
09/03/87	200	04/15/88	57
09/03/87	106	05/15/88	52
09/03/87	117	06/02/88	48
09/03/87	87	06/15/88	40
09/03/87	140	07/15/88	43
09/03/87	150	08/01/88	48
09/03/87	89	08/15/88	46
09/03/87	99	09/01/88	27
09/12/87	150	09/15/88	51
10/24/87	93	10/14/88	52
10/25/87	100	11/01/88	53
10/26/87	88	11/15/88	58
10/27/87	110	12/01/89	69
10/28/87	99	12/15/88	57
10/29/87	78	01/01/89	29
10/29/87	67		
11/04/87	60		
11/04/87	76		
11/05/87	64		
11/06/87	76		
11/07/87	127		
11/08/87	83		
11/08/87	86		
11/09/87	80		
12/15/87	40		
12/16/87	57		
12/17/87	55		
12/18/87	71		

Table 5
Air Stripper Influent and Effluent TCE Concentrations

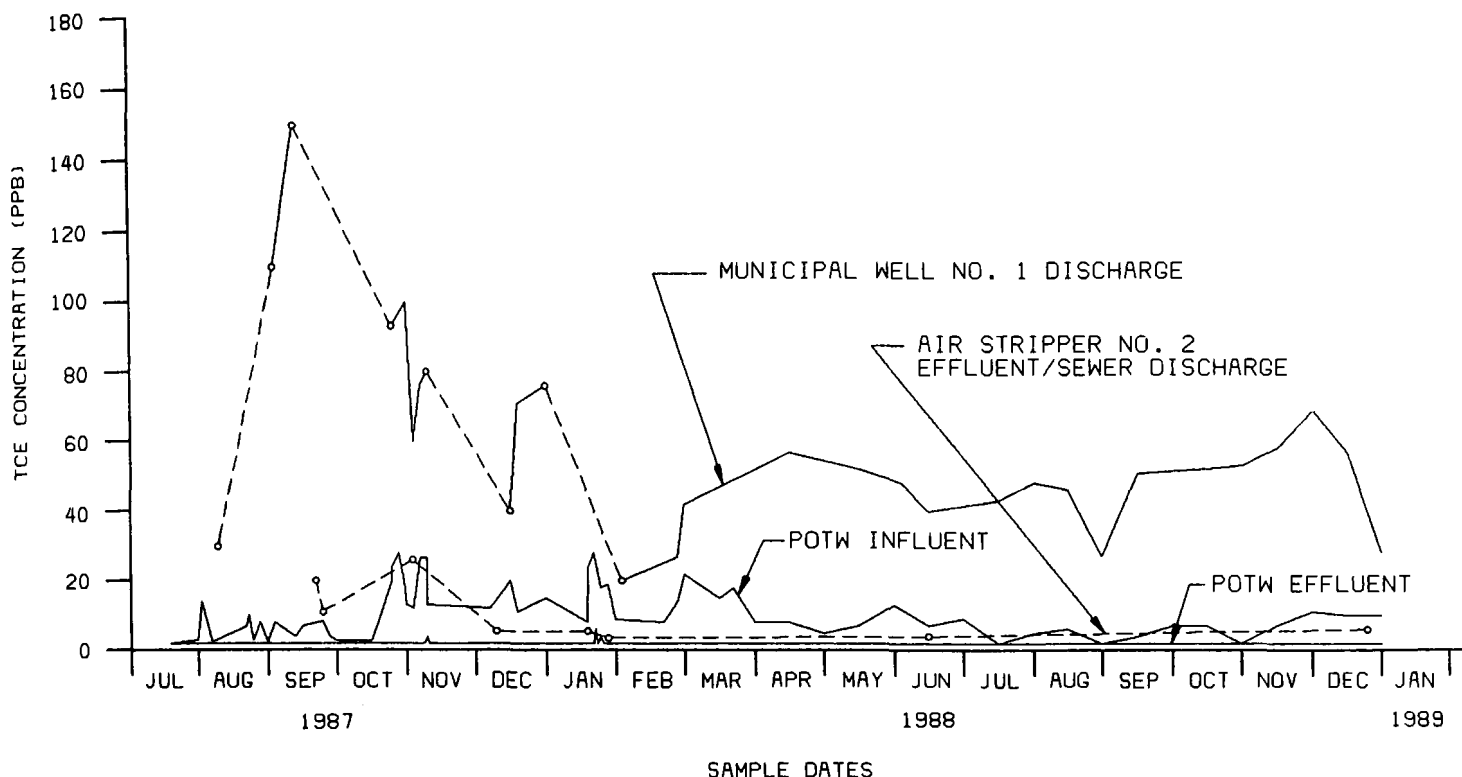
DATE	TOWER 1 INFLUENT TCE (PPB)	TOWER 1 EFFLUENT TCE (PPB)	TOWER 2 EFFLUENT SEWER DISCHARGE TCE (PPB)	TOTAL TCE REMOVAL (%)
09/21/87	8800	280	3.3	99.95
09/21/87	1800	76	21	98.83
09/21/87	260	11	8.0	96.92
09/24/87	830	160	11	98.67
09/24/87	780	140	-	-
09/24/87	6700	570	5.8	99.91
10/16/87	360	ND	2.8	99.22
11/03/87	-	110	26	-
12/10/87	99	33	5.7	94.24
01/18/88	3800	430	4.7	99.88
01/19/88	3200	440	5.7	99.82
01/20/88	4400	370	6.0	99.86
01/21/88	4800	250	6.0	99.88
01/22/88	4000	320	5.9	99.85
01/23/88	3700	230	5.3	99.86
01/24/88	3300	300	4.6	99.86
01/25/88	4900	240	4.6	99.91
01/26/88	3200	470	6.3	99.80
01/27/88	3600	240	3.8	99.89
01/30/88	2100	46	ND	99.90
02/03/88	2500	-	-	-
06/18/88	4200	110	4.2	99.90
12/23/88	3800	150	6.2	99.84
12/23/88	3900	160	6.4	99.84

Table 6
POTW Influent and Effluent Concentrations

SAMPLE DATE	INFLUENT (PPB)	EFFLUENT (PPB)	SAMPLE DATE	INFLUENT (PPB)	EFFLUENT (PPB)
7 / 17 /87	ND	ND	11 / 6 /87	15	ND
7 / 17 /87	ND	ND	11 / 6 /87	27	ND
7 / 18 /87	2.7	ND	11 / 7 /87	27	ND
7 / 19 /87	4.4	ND	11 / 8 /87	28	ND
7 / 29 /87	ND	ND	11 / 8 /87	27	4
7 / 30 /87	ND	ND	11 / 9 /87	13	ND
7 / 31 /87	2.3	ND	11 / 10 /87	14	ND
8 / 1 /87	2.8	ND	12 / 5 /87	13	ND
8 / 2 /87	14	ND	12 / 16 /87	20	ND
8 / 5 /87	4.8	ND	12 / 17 /87	15	ND
8 / 8 /87	ND	ND	12 / 18 /87	11	ND
8 / 10 /87	ND	ND	1 / 1 /88	15	ND
8 / 10 /87	2.5	ND	1 / 18 /88	8.1	ND
8 / 12 /87	ND	ND	1 / 19 /88	24	ND
8 / 20 /87	7	ND	1 / 20 /88	26	ND
8 / 20 /87	10	ND	1 / 21 /88	28	ND
8 / 21 /87	3.4	ND	1 / 22 /88	15	6.1
8 / 22 /87	2.7	ND	1 / 23 /88	21	ND
8 / 23 /87	3.3	ND	1 / 24 /88	18	ND
8 / 24 /87	2	ND	1 / 25 /88	8.3	ND
8 / 46 /87	ND	ND	1 / 26 /88	16	2.2
8 / 47 /87	8.3	ND	1 / 27 /88	19	3.8
8 / 49 /87	7.8	ND	1 / 30 /88	9.5	ND
8 / 31 /87	4.2	ND	2 / 22 /88	7.8	ND
9 / 1 /87	2	ND	2 / 27 /88	14	ND
9 / 2 /87	ND	ND	3 / 1 /88	22	ND
9 / 3 /87	8.1	ND	3 / 15 /88	15	ND
9 / 12 /87	3.8	ND	3 / 21 /88	18	ND
9 / 17 /87	ND	ND	4 / 1 /88	8.6	ND
9 / 17 /87	6.6	ND	4 / 15 /88	8.9	ND
9 / 18 /87	4.4	ND	5 / 1 /88	5.3	ND
9 / 18 /87	4.4	ND	5 / 15 /88	6.4	ND
9 / 24 /87	8.4	ND	6 / 2 /88	13	ND
9 / 25 /87	2.8	ND	6 / 15 /88	6.8	ND
9 / 28 /87	5.5	ND	7 / 1 /88	9.2	ND
9 / 29 /87	2.7	ND	7 / 15 /88	ND	ND
9 / 30 /87	3	ND	8 / 1 /88	4.7	ND
10 / 1 /87	ND	ND	8 / 15 /88	6	ND
10 / 2 /87	ND	ND	9 / 1 /88	2	ND
10 / 16 /87	ND	ND	9 / 15 /88	3.8	ND
10 / 24 /87	24	ND	10 / 1 /88	7.3	ND
10 / 25 /87	29	ND	10 / 15 /88	7.4	ND
10 / 26 /87	28	ND	11 / 1 /88	ND	ND
10 / 27 /87	19	ND	11 / 15 /88	7.5	ND
10 / 28 /87	18	ND	12 / 1 /88	11	ND
10 / 29 /87	15	ND	12 / 15 /88	9.5	ND
11 / 3 /87	2.1	ND	1 / 1 /89	9.7	ND
11 / 4 /87	12	ND			

Table 7
Constituents Detected in Air Samples

Volatile Organics (ppb)	POTW		Manhole MB-6	
	02/03/88	06/16/88	02/03/88	06/16/88
Benzene	ND (25)	ND (1.0)	290	ND (1.0)
Methylene Chloride	5000	NA	11000	NA
Tetrachloroethene	ND (50)	ND (5.0)	720	ND (5.0)
1,1,1-Trichloroethane	NA	ND (100)	NA	ND (100)
Trichloroethene	ND (25)	1.0	770	1.0



LEGEND

- TCE CONCENTRATIONS DURING CONTINUOUS DISCHARGE
- TCE CONCENTRATION FROM SINGLE SAMPLING EVENT-
CONNECTED FOR CLARITY

Figure 5
Ice Concentrations for Discharges from Municipal Well No. 1,
Air Stripper No. 2, and POTW Influent and Effluent

below the 200 mg/L discharge limit. Flow quantities from this well ranged from 50 to 75 gpm which did not exceed the flow capacity the sewer system at any time.

The two air strippers operating in series effectively reduced TCE concentrations in on-site wells below the 200 mg/L discharge limit. During September, 1987, a period of intermittent air stripper operation, the total TCE removal was greater than 94%. During January, 1988, a period of continuous air stripper operation, the average total TCE removal was 99.8% or more, and TCE concentrations in the water discharged to the sewer system were consistently below 10 mg/L. Flow quantities from the air strippers ranged from 50 to 100 gpm which did not exceed the sewer system flow capacity at any time.

Flows from Municipal Well No. 1 were not discharged to the sewer during the January 1988 operation of the air strippers. However, it is anticipated that even with a combined discharge from Municipal Well No. 1 and the air strippers, the sewer capacity would not be exceeded at any time except possibly during heavy rainfall events. During heavy rains, groundwater pumping could be temporarily halted to prevent surcharging the sewers.

Background TCE concentrations in the POTW influent ranged from nondetectable to 10 mg/L. During the period from August, 1987 to January, 1989, when groundwater from Municipal Well No. 1 and treated groundwater from the air strippers were discharged to the sewer system, TCE concentrations in the POTW influent ranged from non-detectable to 29 mg/L. Ninety-five samples were collected during this period and the number and the percentage of samples which exceed selected TCE concentration ranges are shown in Table 8.

Table 8
Influent POTW Flows

TCE Concentration Range (ppb)	Number of Samples	Percent (%)	Cumulative Percent (%)
21 - 30	12	13	100
11 - 20	22	23	87
ND - 10	61	64	64
Total	95	100	--

Sixty-four percent of the samples did not exceed the highest TCE background level of 10 mg/L and 87% were below 20 mg/L. Only 36% of the samples exceeded the background levels. Peak TCE concentrations in the POTW influent appeared to increase slightly during discharge from either Municipal Well No. 1 or the air strippers.

Background TCE concentrations in the POTW effluent were consistently below the detection level of 2.0 mg/L, which is the NPDES discharge limit for TCE measured once every 6 mo. During the period when groundwater from Municipal Well No. 1 and treated groundwater from the air strippers were being discharged to the sewers, 95 POTW effluent samples were taken. In general, the POTW effectively removed TCE to below detection limits. Four effluent samples did exceed the detection limit of 2.0 mg/L. The TCE concentrations in these four samples were 2.2, 3.8, 4.0 and 6.1 mg/L. Possible reasons why these

samples exceeded detection limits were examined.

Three of the POTW effluent samples above 2 mg/L were obtained between Jan 18 and Jan 30, while the air strippers were being operated. Groundwater from Municipal Well No. 1 was not being discharged to the sewers at the time. During this period, POTW influent TCE concentrations ranged from 8.1 to 28 mg/L. However, air stripper effluent TCE concentrations ranged from non-detectable to 6.3 mg/L. In Figure 5, it can be seen that air stripper effluent TCE levels at the time were below POTW influent TCE levels, which suggests that other sources of TCE may exist in the sewer system.

Air samples taken downwind of the POTW aeration basin contained TCE concentrations at or below detection limits which indicated that this basin was not a significant source of volatile emissions. TCE and other volatiles were detected in the one sewer manhole sampled. The concentrations of these volatiles were below the time-weighted average for normal workday exposure of 50 ppm established by the American Conference of Governmental Industrial Hygienists (ACGIH).

CONCLUSIONS

The sewer system and the POTW were evaluated for potential conveyance and treatment of TCE-contaminated groundwater generated during remedial activities at the site. Wastewater in the sewer system was found to contain TCE at concentrations which decreased with distance from the site. This decrease could not be attributed directly to either dilution or volatilization. Air measurements did not indicate any volatile chemicals in sewer manholes above background levels.

The sewers had extra capacity to convey remedial flows along with normal wastewater flows, except for periods of heavy rainfall. The POTW influent was found to contain TCE in concentrations ranging from non-detectable to 10 mg/L, and the POTW effluent TCE concentrations were below the detection limit of 2 mg/L. The POTW had adequate hydraulic capacity available to treat the increased flows.

The City agreed to allow the discharge of groundwater to the sewer system and the POTW provided the fluids met the pretreatment limits established by MDNR. TCE concentrations in groundwater from Municipal Well No. 1 became stabilized between 40 to 80 mg/L during extended pumping. These concentrations were below the 200 mg/L discharge level and thus did not require treatment. During continuous operation, the air strippers reduced groundwater TCE concentrations from onsite wells by an average of 99.8%. Air stripper effluent TCE concentrations normally were below 10 mg/L.

Peak TCE concentrations in the POTW influent appeared to increase slightly during discharge from either Municipal Well No. 1 or the air strippers. However, the TCE concentrations in 64% of the POTW influent samples were below the background TCE level of 10 mg/L. The highest TCE concentration detected in the POTW influent was 29 mg/L. The POTW effluent TCE concentrations usually were below the detection limit of 2 mg/L. Only in four of the 95 samples did effluent TCE levels exceed the 2 mg/L detection limit concentration.

TCE levels in air were measured downgradient of the POTW aeration basins. During discharge from Municipal Well No. 1 or the air stripper operation, TCE concentrations were at or below detection limits and the aeration basins did not appear to be a significant source of volatile emissions. TCE levels also were measured at one sewer manhole during discharge from the air strippers. TCE was detected in the manhole air; however at a concentration less than the level established by ACGIH for normal work day exposure.

REFERENCES

1. Geraghty & Miller, *Remedial Investigation Report*, (Final Draft), June 1989.
2. Black & Veatch, *Feasibility Study*, July, 1989.
3. Geraghty & Miller, *Pilot Program Statement of Work Remedial Investigation/Feasibility Study*, (Draft) Jan 20, 1989.
4. Hood-Rich, Architects and Consulting Engineers, *Wastewater Facilities Plan for Green County, Missouri*, Prepared for the Green County Sewer District, Feb, 1984.
5. Hanna, S., U.S. EPA, Cincinnati, OH, personal communication to J. Sandino, Black & Veatch, July 13, 1987.
6. Grady, C.P.L., Jr., *Biodegradation of Hazardous Wastes by Conventional Biological Treatment*, *Haz. Wastes and Haz. Mat.*, 3, pp. 333-365, 1986.
7. Lue-Hing, C., et al., *Effects of Priority Pollutants on the Disposal of Sludges from Publicly Owned Treatment Works*, Report No. 5-10, Dept. of Research & Development, Metropolitan Sanitary District of Greater Chicago, IL, 1985.
8. Richards, D.J. and Shien, W.K., *Biological Fate of Organic Priority Pollutants in the Aquatic Environment*, *Water Res.*, 20, pp. 1077-1090, 1986.
9. Roberts, P.V., Munz, C. and Dandliker, P., "Modeling Volatile Organic Solute Removal by Surface and Bubble Aerator," *JWPCF*, 56, p. 157, 1984.
10. Russell, L.L., Cain, C.B. and Jenkins, D.I., *Impact of Priority Pollutants of Publicly Owned Treatment Works Processes: A Literature Review, Proceedings of the 37th Industrial Waste Conference*, Purdue University, Lafayette, IN, pp. 871-833, 1983.
11. Unger, M.T. and Claff, R.E., *Evaluation of Percent Removal Variability for Priority Pollutants in POTW's, Proceedings of the 40th Industrial Waste Conference*, May 1985, Purdue University, Lafayette, IN, pp. 915-924, 1985.
12. U.S. EPA, *Fate of Priority Pollutants in Publicly Owned Treatment Works*, EPA 440/1-82/303, Sep. 1982.

Predicting the Fate and Transport of Organic Compounds in Groundwater

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ABSTRACT

The rate of migration and the concentration of hazardous chemicals in ground water is a major factor in determining potential extent of migration, in performing risk assessment and in designing remedial actions. To assess the rate of migration and concentration of chemicals in ground water requires a thorough understanding of the geochemical behavior of the hazardous chemicals in soil water systems. Organic chemicals can undergo a variety of reactions in the subsurface including hydrolysis, oxidation/reduction, volatilization, adsorption, and biodegradation. The importance of each of these processes in effecting the fate and transport of chemicals depends upon the site conditions and the specific chemical compounds of concern. Generally, adsorption and biodegradation are the major reactions effecting chemical transport in ground water.

Adsorption can be evaluated and predicted using eight methods. These include:

- Use of empirical field data
- Methods based on K_{ow}
- Methods based on water solubility
- Methods based on molecular structure
- Methods based on surface area
- Laboratory methods
- Field column devices and injection tests
- Methods based on plume location

Several of these methods require only minimal site data that can be easily obtained. As many of the methods as possible should be used depending on data availability and on the purposes of the prediction. For example, laboratory studies may be necessary when a quantitative prediction of desorption is needed to design a treatment plant in terms of concentration and design life. In all cases, the prediction should be compared to actual site data.

Of the processes which control mineralization of organic compounds in the subsurface, biodegradation is the most important mechanism in transforming short chain halogenated compounds in an anoxic environment, and in breaking one⁸ and two⁸ ring compounds under aerobic conditions. The reaction rates of these processes have been defined for both laboratory and field conditions and are usually modeled using the power rate law or the hyperbolic rate law.

Modeling contaminant transport in the subsurface relies on a large body of site specific data including that required to represent adsorption, biodegradation and dispersion of the compound of interest. Examples discussed include the lateral migration of trichloroethene and benzene in ground water, percolation of tetrachloroethene through the unsaturated zone, and volatilization of trichloroethene from the ground water surface followed by adsorption in the overlying soil profile. Where appropriate, adsorption and biodegradation are included in each simulation.

Geostatistical Decision-Making Process For Plume Modeling In Cadillac, Michigan

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ABSTRACT

A geostatistical block model of plume geometry provides a set of powerful decision-making tools for enforcement and remedial design at sites of environmental contamination. These three-dimensional block models are most effective when geologic, hydrogeologic and historic information are incorporated into the modeling of these complex sites.

The geostatistical modeling was part of an overall program to define zones of contamination and aid in a design of remedial measures for the industrial park. Data collected from various hydrogeological investigations during the last 30 yr were examined to create boundary conditions for the geostatistical evaluation. These data included MDNR- and PRP- sponsored investigations for the contamination problems that began to surface in 1978.

The MDNR investigation produced 795 vertical data points over a period of three mo. These data were subjected to quality control measures and then explored for patterns that might relate to the underlying contaminant hydrogeology. A representative and geologically realistic block model was built with geostatistical techniques. The final block model was verified by further field sampling. Thorough exploration of the sample data and an understanding of the geologic setting yielded conservative, defensible kriged estimates of contamination that were used as an enforcement tool. The results of the geostatistics provided insight into source location and further data needs.

INTRODUCTION

The city of Cadillac is located in northwestern lower Michigan in Wexford county (Fig. 1). The Cadillac Industrial Park is in the northwest corner of the city. Various facilities within the industrial park have been under investigation since the first private wells were found to be contaminated in 1978. During the subsequent 10 yr, eight sources of groundwater contamination have been discovered within an area of just over 0.5 mi². The contamination and the proximity of the municipal water supply have won the industrial park two spots on the CERCLA/SARA NPL as well as funding from the Michigan Environmental Response Act (Act 307, 1982).

In 1986, out of concern for the water supply, the Michigan Department of Natural Resources began a program to define known and suspected plumes of contamination. The major pollutant in the park is trichloroethene. A chromium plume has been defined at a separate NPL site. Over 180 wells have been drilled in an area of approximately 0.5 mi² by contractors employed by the MDNR, the PRPs.

Vertical sampling in 88 of the well borings enabled the MDNR to collect data with 795 discrete three-dimensional chemical analyses with which to analyze the contaminant distribution. Using the screened auger method¹, vertical samples were taken between 30 and 180 ft below the surface. Six contaminant plumes have been defined, one of which, the

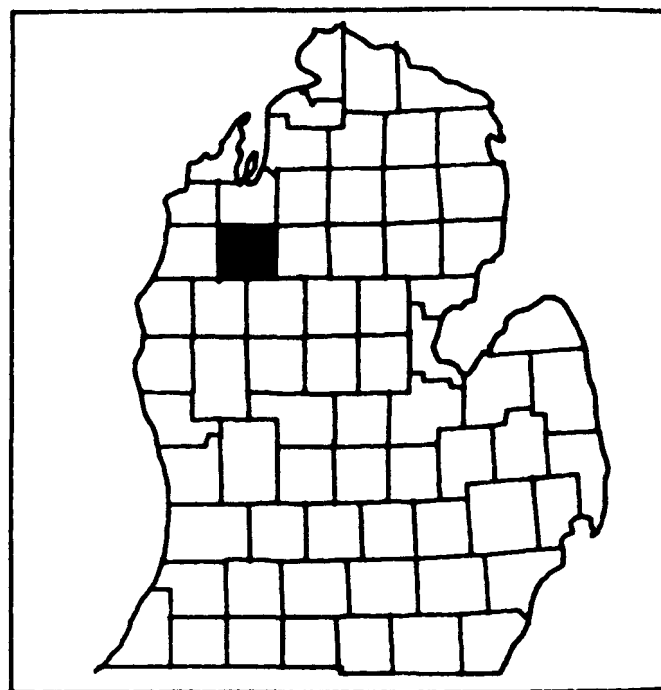


Figure 1
Wexford County, MI

East Plume, directly threatened the city well field.

These data were used to construct a three-dimensional, geostatistical model of the plume geometry for enforcement and remedial design. This study focused on the East Plume area. The East Plume data included 280 vertical samples from 27 wells.

The samples were analyzed in the field with a Photovac 10A10 portable gas chromatograph. Sample results were reported in total volatile organic carbon (VOC). Contract laboratory results showed trichloroethene to be 97 to 100% of the VOC field-reported concentration. Taylor and Serafini¹ showed the field results to be well correlated ($r^2 = 0.83$, $n = 48$ df) with the laboratory results. Their work demonstrates that the use of field screening data is applicable for the purposes of this project.

SITE GEOLOGY

Cadillac is situated on a basin of glacial origin (Fig. 2). It is located at the southern end of the Cadillac outwash plain. This outwash plain

is hemmed in to the east and south by the Valporaiso Moraine and to the north and west by the Lake Border moraine. This condition caused intermittent ponding in the south and east of the outwash plain during the Lake Border stand. The stratigraphy in Cadillac consists of outwash sands alternating with lacustrine clays. The sediments consist of alternating clays and well sorted outwash sands. Four outwash layers were described in the 290 ft maximum depth of exploration. The unsaturated zone is 30 ft thick. The two uppermost clays pinch out in the southeast half of the industrial park, resulting in the three upper outwash layers becoming one in the northeast half. The deep clay appears to be a regional till.

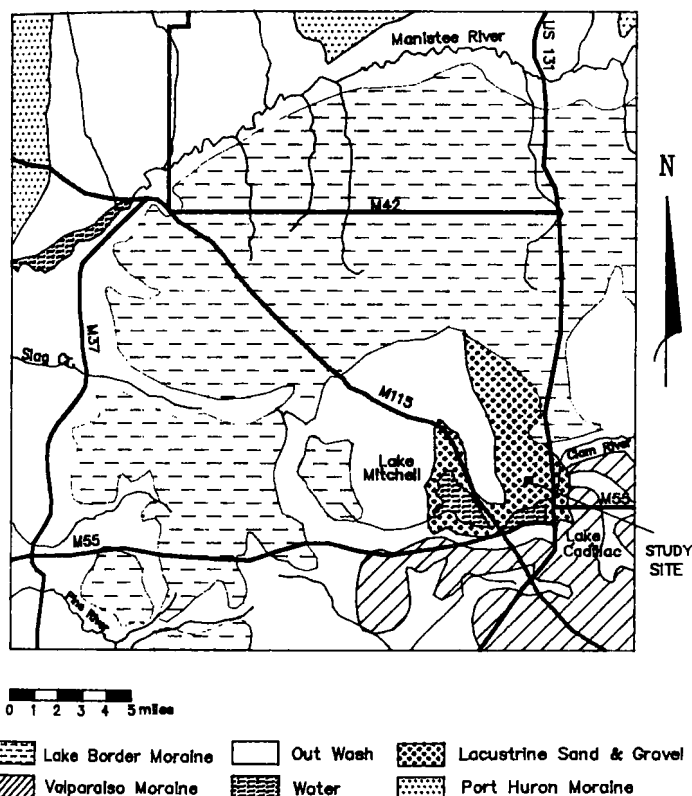


Figure 2
Glacial Geology of Wexford County

The lake clays exist as "bowls within bowls," having been formed by the infilling of the Cadillac basin. Sands filled the basin during peak glacial melting. The clays were then deposited into successively smaller lakes during times of low melt or inefficient drainage. Lakes Mitchell and Cadillac (Fig. 2) are remnants of this process. Five discrete lake clays have been observed in well logs from the Cadillac area, two of which extend into the industrial park. These two lake clays pinch out in the park on a N30W strike (Fig. 3). The shallow lake clay pinches out at an elevation of 1265 ft (MSL) and dips to the SSW at a gradient of 0.02 (Fig. 4). The deep lake clay pinches out at an elevation of 1140 ft and dips to the SSW at a gradient of 0.01. The ground surface elevation averages approximately 1295 ft. The bottom of the basin is a regional till clay at an average elevation of 1070 ft. The till lies above an older outwash sand layer that extends to at least an elevation of 945 ft. Bedrock elevation is approximately 545 ft.

The presence of sloping clay layers that pinch out in the middle of the study area makes a complex situation. The bulk of the East Plume data lay beyond the shallow clay but above the area of the lower lake clay.

HYDROGEOLOGY

The presence of two confining clay layers that both pinch out in the industrial park make a complex hydrogeologic system, as well. Where both clays exist, there are three aquifers above the regional till (Fig. 4).

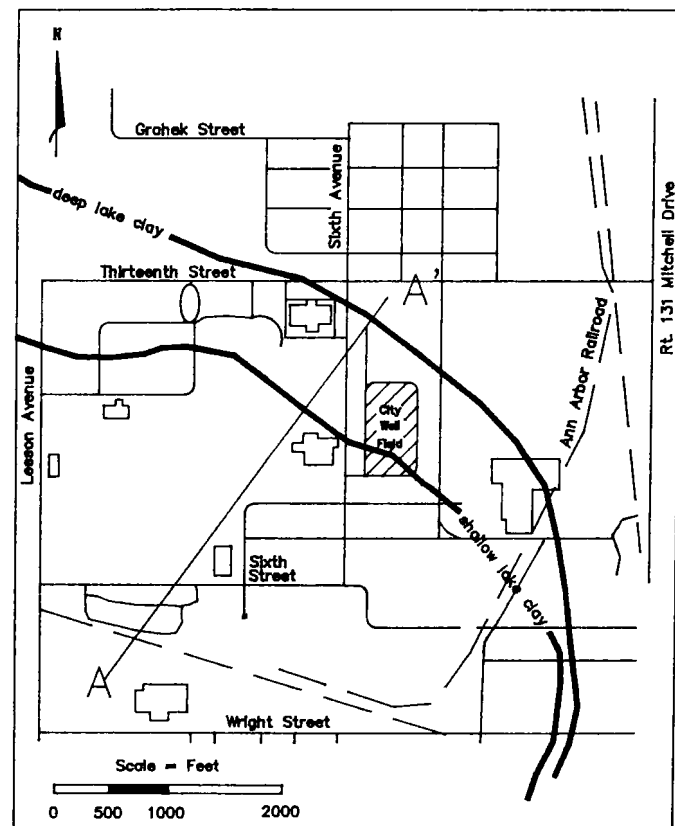


Figure 3
Cadillac Industrial Park
Northern Limit of Glacial Lake Clays

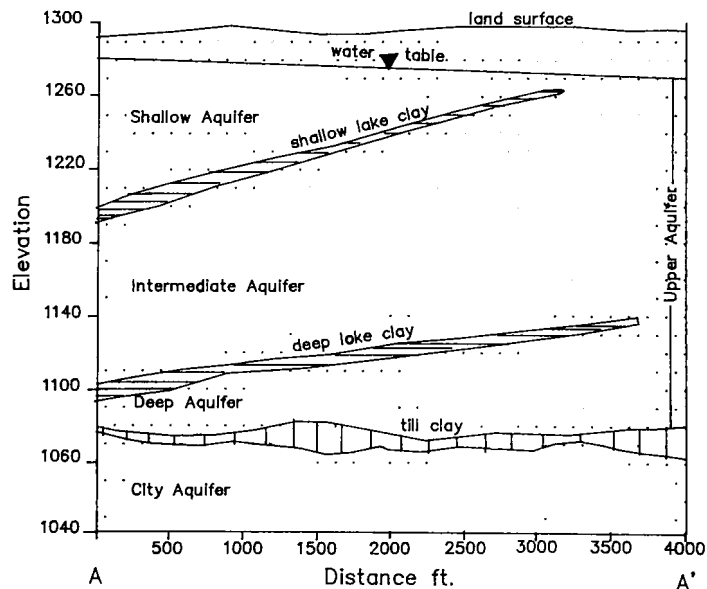


Figure 4
Cadillac Industrial Park
Glacial Stratigraphy

North of where the clays pinch out, there is only aquifer. The city well field is screened in an older outwash aquifer below the regional till. Hence, depending on location, there are from two to four aquifers to be considered. The groundwater in the uppermost aquifer flows north to northeast above the upper clay. The regional flow in all other aquifers is toward the northwest. There is a downward vertical gradient in all aquifers. Therefore, three directions of groundwater flow have to be considered.

The shallow aquifer is a water table aquifer above the shallow lake clay. There are 30 ft of unsaturated sand above this aquifer. The saturated thickness ranges between 5 and 10 ft where the clay pinches out, to 60 ft at the south end of the industrial park. Groundwater flow in this aquifer is toward the nearest edge of the clay. In the industrial park, this causes the flow to vary from north to northeast (Fig. 5). There is a downward vertical gradient in this and all other aquifers studied for this project. The decrease in saturated thickness downgradient causes an increased flow gradient to the north. The gradient increases from 0.0019 to 0.0029. With no change in hydraulic conductivity, this 65% increase in gradient does not compensate for the 600% loss of saturated thickness. It is obvious that there must be leakage through the shallow clay. Lakes Mitchell and Cadillac are the recharge areas for the shallow aquifer.

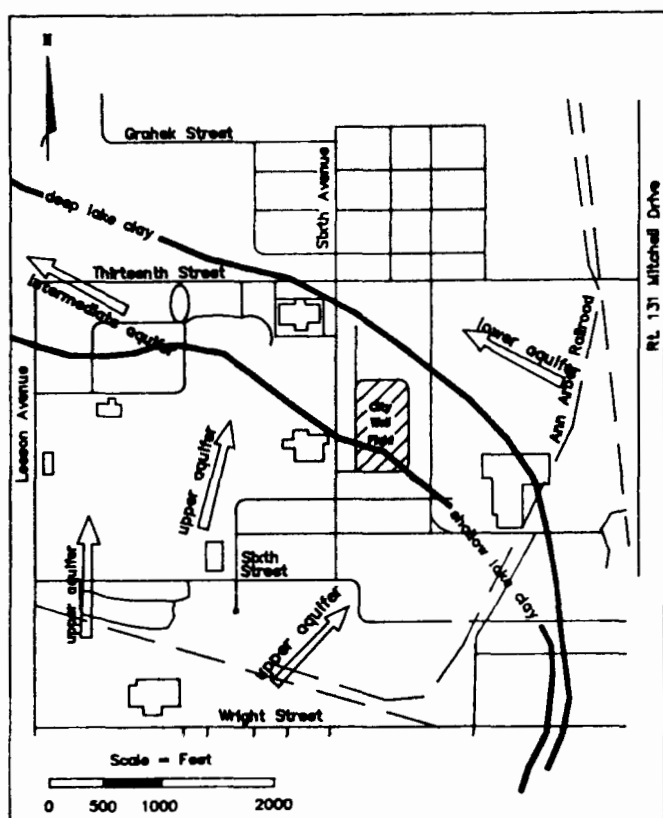


Figure 5

Groundwater Flow Directions in the Upper, Intermediate, and Lower Aquifers

The intermediate and lower aquifers lie below the shallow and lower lake clays, respectively (Fig. 4). Both aquifers flow toward the northwest. Their recharge area is the high country of the Valporaiso Moraine to the east (Fig. 2). The saturated thickness of the intermediate aquifer is approximately 130 ft. The gradient remains constant at 0.001. The lower aquifer is approximately 40 ft in saturated thickness. Its horizontal gradient is 0.001. Vertical gradients in these aquifers are also downward. The groundwater discharge area is the Manistee River, 18 miles to the northeast at an elevation of 810 ft (Fig. 2).

With the absence of the lake clays in the northeast portion of the industrial park (Fig. 4), all three of the above mentioned aquifers merge into one. Consider that there are 12 in. of recharge per year to the water table from precipitation. There is no change in aquifer thickness, hydraulic gradient or hydraulic conductivity in the northeast part of the study area. These observations alone lead to the conclusion that there is leakage through the till clay into the deep aquifer.

The city's wells are screened in the deep outwash aquifer below the regional till (Fig. 4). This aquifer is at least 110 ft thick; the bottom confining layer has not been reached by any well. The well field produces an average of 2.2 mgd with a capacity of 10.5 mgd from seven

wells. Groundwater flow is toward the well field as all monitoring wells screened there were within the pumping zone of influence. Hydraulic conductivity for all of the aquifers is in excess of 5×10^{-4} – 3 ft/sec. A pump test performed on the city well field concluded that leakage through the till contributed a significant portion of the well field pumpage. As much as 5% of the pumpage is coming through the till where it is overlain by contaminated portions of the upper aquifers (Fig. 6). When this situation came to light, it was deemed an emergency. Immediate steps were taken to further define the vertical and horizontal extent of contamination for remedial design.

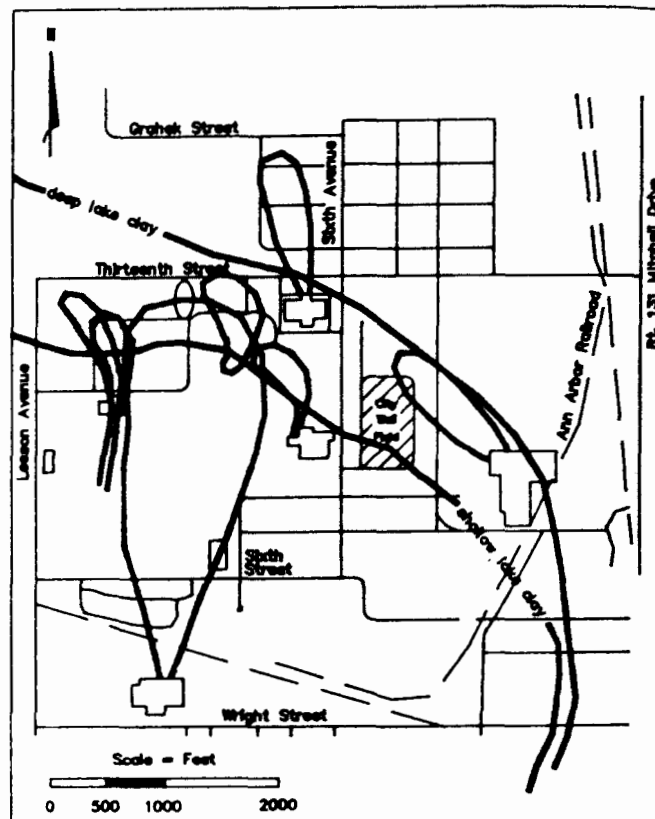


Figure 6
Location of VOC Plumes

The geostatistical study, therefore, had to consider the geological and hydrogeological parameters outlined above. That is, three directions of groundwater flow, movement through and around the confining layers and leakage within the influence of an active well field.

EXPLORATORY DATA ANALYSIS

The East Plume data were thoroughly examined prior to the geostatistical estimation. Exploratory data analysis techniques were used to identify patterns in the sample data. These patterns were compared to the current hydrogeologic visualization of site conditions. Exploring the data provides both a quality check on the data and a reality check on the modeling process itself. Insight gained during this step can be rapidly incorporated into the geostatistical block model to produce superior estimates.

The data were first explored as a single collection of measurements. A quantile plot was used to provide a picture of the distribution of the data. A plot of the ordered sample values against their reported VOC concentrations, the quantile plot highlights several patterns and groupings (Fig. 7). Roughly a third of the observed samples were below detection level or traces. These coded values are plotted in the lower left hand corner of Figure 7. Such values serve to bound the kriged estimates in the final three-dimensional block values.

The other three groupings (1 to 4 μ /L, 5 to 10000 μ /L, and >10000 μ /L) may represent factors involved with the introduction and trans-

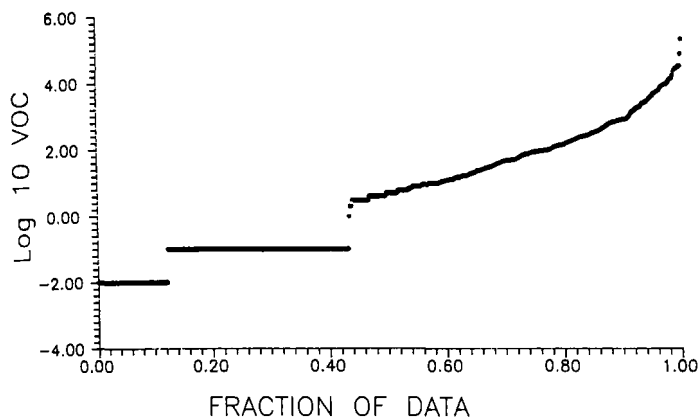


Figure 7
Quantile Plot of log 10 VOC Values

port of the contaminants. These factors include intermittent dumping, rainfall passing through contaminated soils, the descent of dense non-aqueous phase liquids (DNAPL) through the aquifer, hydrogeology and glacial stratigraphy. Each of these "post-source" sources can produce a different distribution signature in the aquifer.

The two extreme values found at the upper left of the quantile plot represent two outliers, (observations that seem to lie too far from the majority)^{2,3}. An order of magnitude greater than the other samples, these concentrations were measured in the same boring. Their impact on the spatial continuity between samples was investigated during the varicography phase of the process.

Vertical aspects of the East Plume data also were examined during this stage of the process. Samples values were collected and displayed using their elevation. Values above 1 mg/L were grouped according to their vertical location within the three-dimensional block model. The model consists of multiple levels. Each level is 10 ft thick. Levels are numbered from the top of the model down. Level 1 starts at the ground surface.

The box plot display of the \log_{10} VOC samples by levels showed an informative pattern; a cyclic pattern in median values (Fig. 8). The median is the horizontal line within each box. Two local highs are clear in this display with local maximums occurring in levels 8 and 14. This pattern may indicate a vertical clumping of high VOCs within the East Plume study area. VOC behavior can be explored further by examining how the length of the box changes by level (same figure number). The spread of the bulk of the data, the central 50%, is shown by the length of the box. Note how spread varies with depth. The middle levels exhibit much less spread in their raw data values than the upper and lower levels.

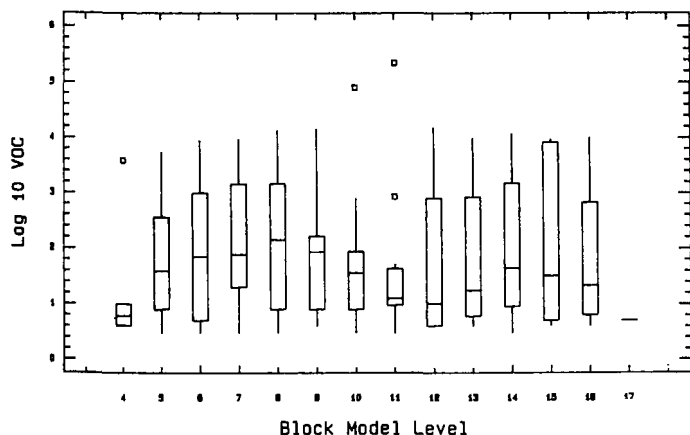


Figure 8
Box and Whisker Plot of East Plume Block Model by Level

The short box length of levels 10 and 11 also presents evidence that two of the sample values, the two extreme values mentioned above, may

be out of the ordinary for these levels. These two, represented as squares in the display, fall outside of the bulk of the data for their levels. The box plot was also used in the interpretation of the varicography.

VARICOGRAPHY

The next step of the geostatistical decision-making process is to quantify the spatial relationships that exist between sample pairs. This quantification process is done with the variogram, a basic tool of geostatistics. The variogram provides key information for the actual estimation process, kriging.

By successively using each sample as a datum, the sample variance for all predetermined intersample distance categories is calculated. Then the distance (x-axis) vs. variance (y-axis) plot, the variogram, is drawn. When the variance is calculated from data that fall within certain angular windows from the datum, quantitative changes in the trend with direction can be determined. Figure 9 shows the ideal form of a spherical model variogram⁴. The plot begins at the origin and rises until it reaches a maximum variance, the sill (C), where the variance remains constant for greater distances. The sill of the average variogram will be equivalent to the total sample variance. The distance at which the sill is attained is the range. At distances greater than the range, the relationship between samples no longer is influenced by distance.

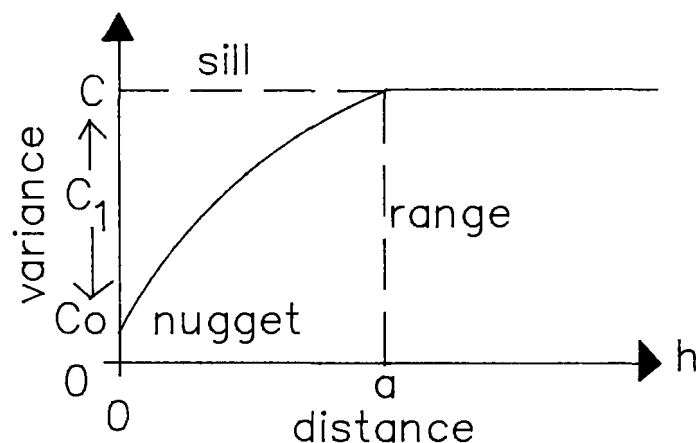


Figure 9
Idealized Spherical Model Variogram

If the plot has a Y-intercept greater than zero, that value is called the nugget (C_0). If the modeled variogram does not pass through the origin, it is indicative of a high degree of variability over short distances. This anomaly can be the result of laboratory error sampling error or the intrinsic microvariability of the environment itself.

Being directional in nature, the variogram is also an excellent tool for investigating possible anisotropic conditions at the site. Several types of variograms were calculated to verify if different measuring scales showed consistent patterns. These were the general relative and indicator variograms. By looking at the East Plume data from several different viewpoints, consistency was built into the final block model estimates.

The protocol for modeling the variograms was to first calculate and model general relative variograms for different directions. Indicator variograms using a median cut were used to temper the general relative ranges. Indicator variograms use the "cut" value as the datum by which they compare all other values. Such indicator variograms are more resistant to extreme values and thus provide a second, conservative estimate of the range.

An average general relative variogram which used all available data pairs was used to estimate the nugget (C_0) and the structured variance (C_s) (Fig. 10). Variograms were then calculated and modeled on the four cardinal directions; azimuths 0, 45, 90 and 135 degrees. Variograms were for azimuths 22.5, 67.5 and 157.5 to better investigate anisotropic conditions.

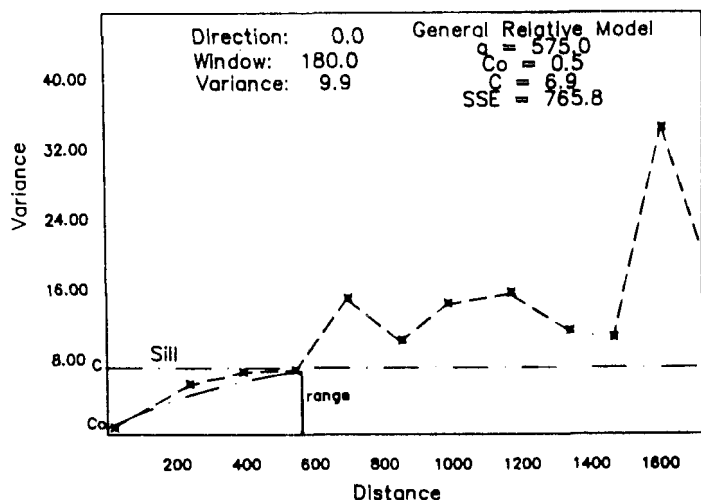


Figure 10
General Relative Variogram for East Plume

A huge general relative sill resulted. Quantile and box plot evidence gathered during the exploratory data analysis phase of the process indicated that the two largest VOC values were quite different from the other 278 sample values. Excluding these two values from the variogram calculations reduced the sill tenfold. The general relative variogram parameters used for the kriged block estimates were a nugget of 0.5 ($C_0 = 0.5$) and a structured variance of 6.9 ($C_1 = 6.9$). The modeled average variogram is given in Figure 10.

Modeled ranges demonstrated a 2:1 anisotropy present within the study area. The range rose for the East Plume shows a strong trend from the southeast to the northwest (Fig. 11). This is the predominant groundwater flow direction in this area of the Cadillac Industrial Park. This flow direction is in keeping with the hydrogeologic model of the geology. Only one horizontal flow direction is involved north of the shallow clay.

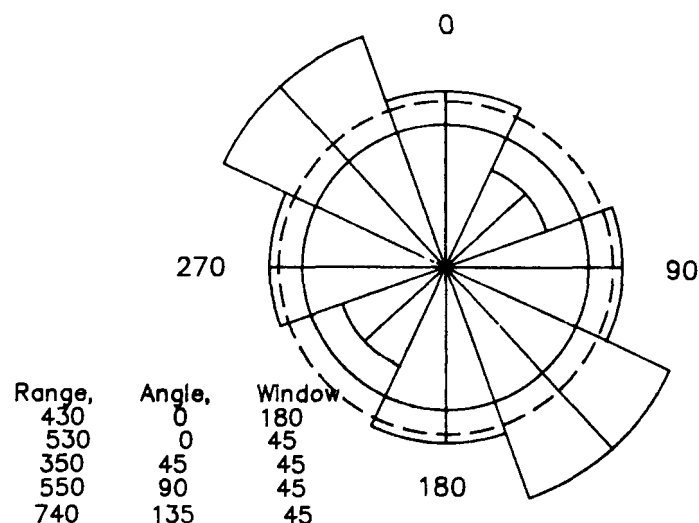


Figure 11
East Plume Range Rose

Downhole variograms were used to quantify the vertical spatial relationship between sample pairs. A distinct double structure in the cross-sectional distribution of the VOC samples is shown in Figure 12. A range of 40 ft was modeled. A striking similarity to the box plot of VOC values by level (Fig. 8) can be seen.

These two graphical data analysis displays were derived in very different ways and are not directly comparable. However, their similarity contributes to the overall understanding of site conditions. As discussed

above, more than one factor is involved in the distribution of contaminants in the aquifer, especially in the vertical distribution. It is more likely that this result may have to do with two source mechanisms as opposed to contaminant transport types. The aquifer is very uniform to about 130 ft and there do not appear to be any altered flow vectors here as exist in the southwest part of the industrial park. The modeled variogram results were incorporated into the three-dimensional block kriging estimates of VOC concentrations.

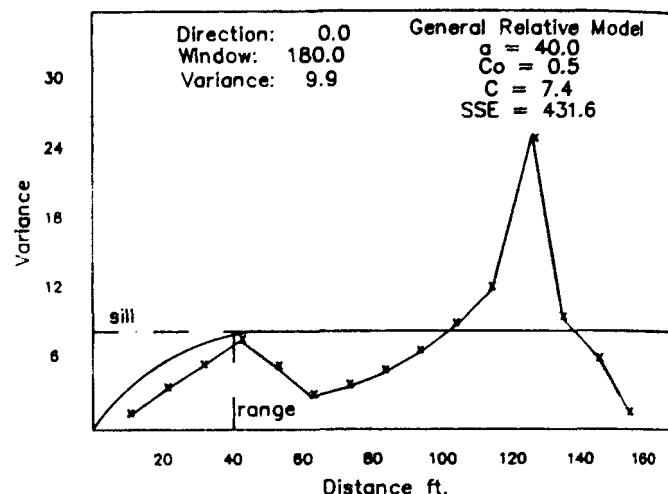


Figure 12
General Relative Vertical Variogram for East Plume

KRIGED BLOCK MODEL

Kriging is an interpolation technique for regionalized data. The technique is a best linear unbiased estimator; best being that with the smallest variance. The process uses information from the surrounding sample locations and the autocorrelation structure of the data to estimate values at unsampled locations. Block kriging, the technique used on this project, estimates the average value over the entire block. Kriging is the only known estimation technique that calculates individual interpolation errors for every estimated value. Kriging provides both an estimate of the contaminant and the reliability of the estimate. This dual result of kriging provides an objective evaluation of the modeled contaminant distribution and the adequacy of the data.

The modeled horizontal and vertical general variogram information was incorporated into the kriging equations. The kriged estimates themselves were produced using the program KRIG3 (Geostat Systems International, Inc.).

Based upon current project objectives and understanding of the geologic and hydrogeologic setting, the three-dimensional block model was defined. The conservative block dimensions selected provided the necessary resolution needed for remediation design without going beyond the information inherent in the data. Block dimensions of 50 ft by 50 ft in the horizontal and 10 ft in the vertical were used for the kriging estimates. There were 21 levels. Within this overall framework, 54,285 estimates of VOC concentration could be made. To better model the site geology, blocks that were coincident with the three-dimensional extent of the any mapped clay layers were excluded from the estimation process.

The estimated locations of the zones of highest contamination were chosen for the screened intervals for three purge wells. Kriged estimates were compared to the results of further sampling done where the plume directly overlies the city well field. These results were consistently higher than the modeled estimates. This result shows the model to be conservative and more reliable from an enforcement standpoint.

CONCLUSIONS

Geostatistics, as in any modeling technique, is enhanced by being drawn into an overall model of the geologic conditions that exist at the site. Exploring the data under the existing constraints of the system aids

in bringing out trends that might not otherwise be quantifiable. It also suppresses false trends that might appear as a result of using techniques that are not supported by the geologic model. This process, therefore, yields a more reliable variogram with which to construct the kriging estimation ellipse. The modeling methods used in this study gave conservative, defensible, kriging estimates that were used as a tool for enforcement and remedial design.

REFERENCES

1. Taylor, T. W. and Serafini, M. C., "Screened auger sampling: the technique and two case studies," *Groundwater Monitoring Rev*, 8(3), pp. 145-152, 1988.
2. Chambers, J. M., et al., *Graphical Methods for Data Analysis*, Duxbury Press, Boston, MA, 1983.
3. Gilbert, R. O., *Statistical Methods for Environmental Pollution*, 2nd ed., John Wiley and Sons, New York, NY, 1986.
4. Clark, I., *Practical Geostatistics*, Elsevier, New York, NY, 1979.

Using a Three-Dimensional Solute Transport Model to Evaluate Remedial Actions for Groundwater Contamination at the Picatinny Arsenal, New Jersey

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INTRODUCTION

The Picatinny Arsenal is located in Morris County, New Jersey, approximately 4 mi northeast of Dover (Fig 1). The installation, officially known as the U.S. Army Armament Research Development and Engineering Center, performs research on munitions and weapons. Recent investigations have found trichloroethylene (TCE) and other volatile organic solvents in groundwater. The metal plating shop in Building 24 has been identified as a possible source of contamination. TCE and other solvents were used in decreasing operations at this metal shop.

The contaminant plume was found in the water table (top) layer of a three-layer aquifer system with some evidence of minor amounts of contamination in lower layers. The objective of the study was to site wells for a proposed remedial action plan that included the pumping of contaminated groundwater and treatment in an air stripping tower. One important question was whether the wells in the water table layer of the aquifer system would effectively control gradients in the lower aquifers and stop contamination that could be in the lower aquifers from migrating off-site. To answer this question, a three-dimensional solute transport model was used.

Groundwater modeling is a powerful tool that may be used to predict contaminant transport at hazardous waste sites. One- and two-dimensional groundwater flow and solute transport models are used to predict contaminant transport. There are situations, however, where a three-dimensional simulation capability is necessary. There are a number of well-known groundwater flow models with three-dimensional capability, such as the USGS Modular Three-Dimensional, Finite-Difference Ground-Water Flow Model (MODFLOW)¹ and the Prickett-Lonnquist Aquifer Simulation Model (PLASM3D), but there are relatively few three-dimensional solute transport models.

A new three-dimensional solute transport model, RAND3D was developed as part of this project. The RAND3D model is a solute transport model utilizing the random-walk algorithm. A preprocessor code (PREMOD3D) was written to use the output of the MODFLOW model as input and create files of velocity vectors for the RAND3D model. The RAND3D model runs interactively on an IBM PC while displaying

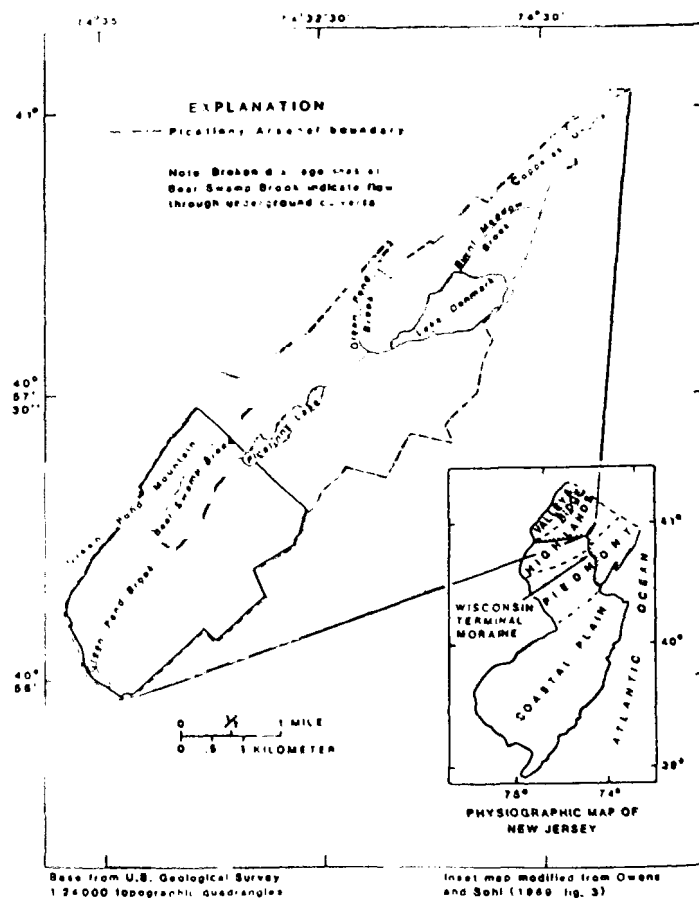


Figure 1
Location of Picatinny Arsenal

the progress of the plume graphically. Figure 2 shows the conceptual relationship between the data and computer models used on this project.

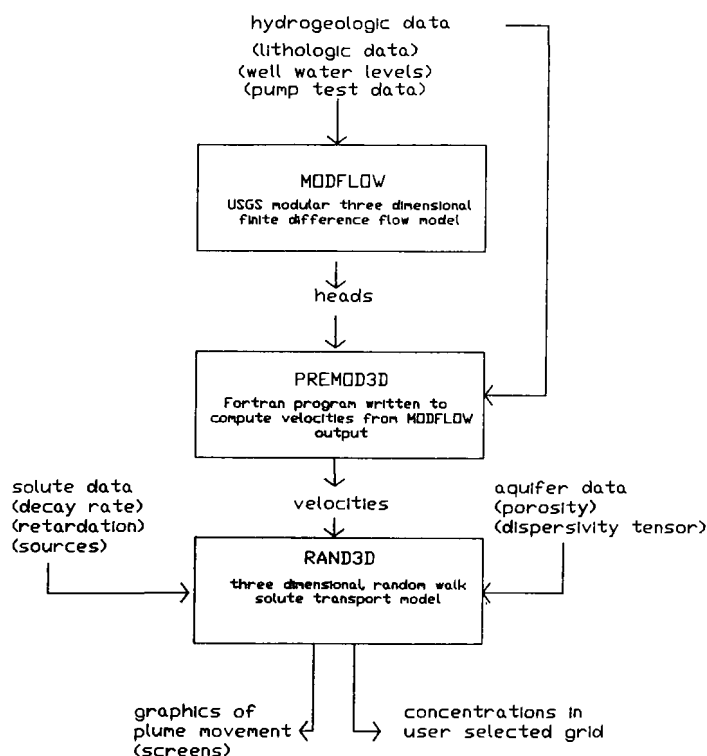


Figure 2
Conceptual Relationship Between Models and Data

RAND3D MODEL

The RAND3D program is a three-dimensional version of the random walk algorithm developed by Thomas Prickett, et al., at the Illinois Water Survey as an efficient algorithm for solving groundwater solute transport problems². The model originally was developed for two-dimensional solute transport. Thomas A. Prickett and Associates developed a three-dimensional version of the model, and further modifications and improvements were made to the model as part of this project.

The random-walk technique is based on the concept that dispersion in porous media is a random process. A particle, representing the mass of a specific chemical constituent contained in a defined volume of water, moves through an aquifer with two types of motion. One motion is with the mean flow (along streamlines determined by finite differences), and the other is random motion (governed by scaled probability curves related to flow length and the longitudinal and transverse dispersion coefficients). A sufficient number of particles are included in simulations so that their locations and density, as they move through a flow model, are adequate to describe the distribution of the dissolved constituent of interest. Each particle represents a fixed mass of solute. As more particles, with correspondingly smaller masses, are used in a given simulation, accuracy improves.

One major feature of the RAND3D model is its interactive operation on an IBM PC or compatible microcomputer. After velocity files are prepared using PREMOD3D or some other suitable procedure, the user may use this program to simulate solute transport and watch the results on the monitor. The program operates from a menu. The user is prompted for all data inputs. A major feature of the model is the ability to display geographic features on the computer screen and superimpose the plume simulation. The user may zoom in on any area of the model to see a more detailed simulation. The geographic features are input by the user in any convenient right-handed (x-y) coordinate system in ft (such as a State Plane coordinate system). These features may then be displayed on the screen as background reference for the plume simulation.

The RAND3D model includes the following features:

- Calculation of horizontal advective transport based on a four point interpolation of the input velocity vectors
- Calculation of vertical advective transport based on linear interpolation between the input vertical velocity vectors at the top and bottom of each layer
- Calculation of dispersion using constant dispersivities: longitudinal, transverse and vertical
- Calculation of first-order decay
- Calculation of linear, reversible adsorption (retardation)
- The ability to originate solute (particles) in the model as sequences of prisms, cylinders, or lines
- Calculation of solute concentrations exiting the model at sinks (wells or gaining streams)
- Mapping of solute concentration in user selected areas of the model, either plan view or cross-section concentration maps may be prepared
- Output of gridded solute concentrations by layer for plotting
- Interactive operation
- On-screen display of plume (particle) movement in user selected area
- On-screen display of user input geographic features at user selected scale as background for the plume display
- Saving and viewing of screen slides
- Saving and restart of model parameters at any time
- Transient flow simulations may be simulated by inputting a series of velocity files

The RAND3D model was designed for an IBM PC or compatible microcomputer with 640K, a numeric co-processor, a hard drive and a color monitor with a color graphics adapter. The program is written in Microsoft Quick Basic Version 3.0. Current limits in the program are:

- Maximum input grid of 45 columns, 45 rows and three layers
- Maximum number of particles is 10000
- Maximum number of sinks (wells or gaining streams) is 99
- Maximum number of special feature files is 20

SITE GEOLOGY AND HYDROGEOLOGY

The study area is located in the drainage basin of Green Pond Brook, a tributary to the Rockaway River. The Rockaway River flows into the Boonton Reservoir, a water-supply reservoir for Jersey City. Green Pond Brook runs through the middle of the Picatinny Arsenal.

The Picatinny Arsenal is located in the Green Pond syncline, a structural region within the New Jersey Highlands physiographic province. The New Jersey Highlands is comprised of a northeast-southwest system of folded and faulted Proterozoic to Devonian rocks that form a sequence of valleys and ridges. The Green Pond syncline is a narrow, northeast-trending, faulted syncline containing a thin section of Paleozoic sediments. Bedrock at the site consists of gneiss, quartzite, dolomite and conglomerate. The bedrock is overlain by approximately 200 ft of glacial deposits. The glacial deposits are stratified, consisting of sublacustrine sands and gravels, lake-bottom silts and deltaic sands and gravels³.

Groundwater flow at the site generally follows the topography; groundwater flows towards Green Pond Brook and down valley. Vertical gradients are downward except around Green Pond Brook where there is some upward movement of groundwater.

FLOW MODEL CALIBRATION

The USGS MODFLOW model was used to simulate the groundwater flow at the site. The groundwater flow system at the site was represented as a three-layer model: the first layer was the water table aquifer in the permeable glacial sediments near the land surface; and the second layer was the confined glacial aquifer. The third layer was the fractured limestone and dolomite underlying the glacial sediments. A 35 column by 43 row grid was defined as shown in Figure 3. The model was calibrated to the existing observation well data assuming steady-state conditions. Figure 4 shows the water table in the upper layer of the model generated from the calibrated model. Observation well water levels were compared to water levels predicted by the model. The average error across 41 wells was 0.12 ft and the root mean-square error was 1.76 ft.

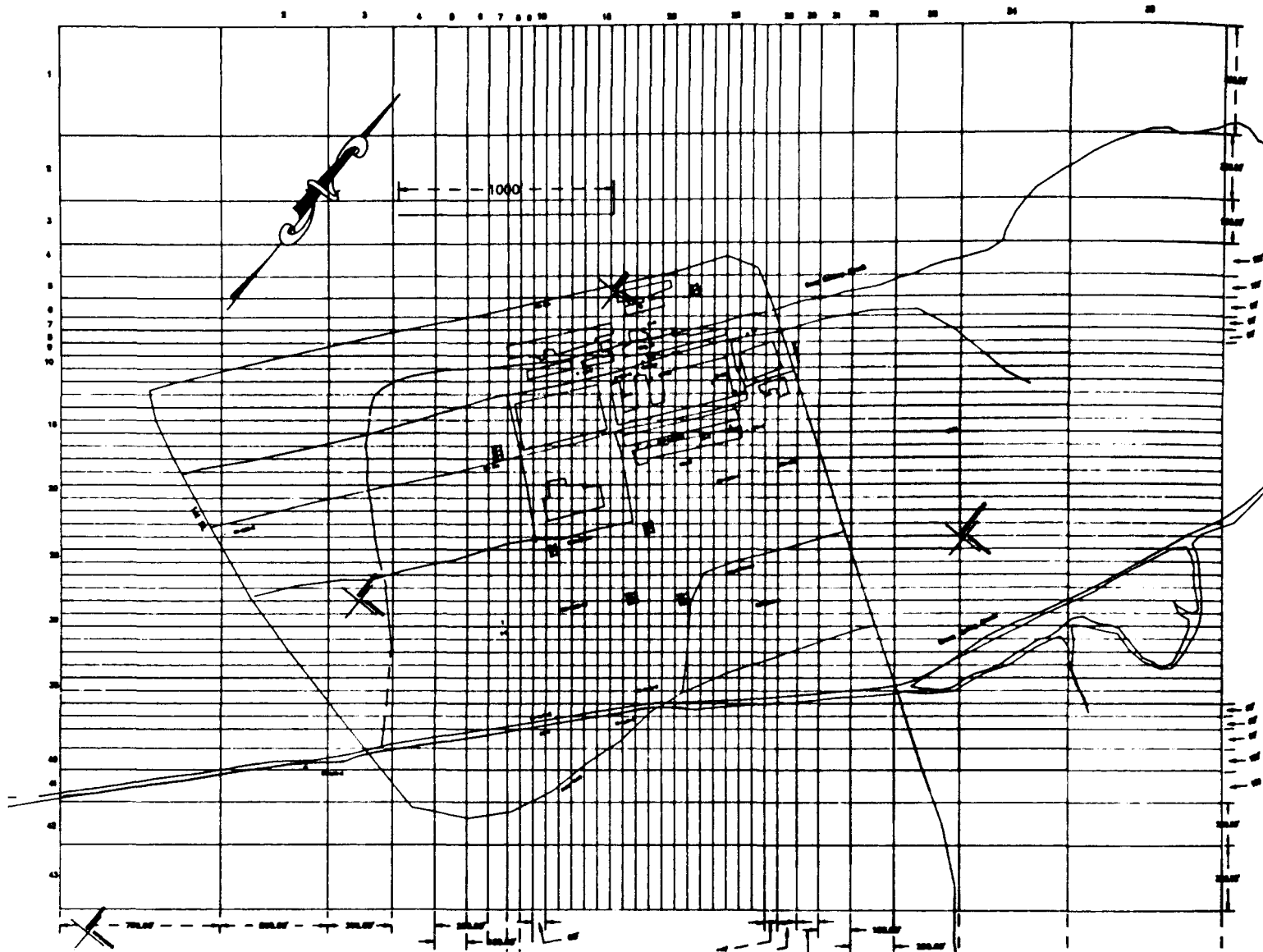


Figure 3
Model Grid

ALTERNATIVE ANALYSIS

Six different pumping schemes for remedial action were simulated using the three-dimensional solute transport model, RAND3D. The first alternative analyzed was the no action alternative. The existing position of the plume was input to the model and the movement of the plume towards Green Pond Brook was simulated for 60 yr. After 5 yr, 60% of the contamination had entered Green Pond Brook.

The first active remedial action scheme simulated was a group of three collection wells, each pumping at 36 gpm, located to create a hydraulic barrier between Building 24 and Green Pond Brook. These wells were input to the MODFLOW model, the new water table was simulated and a set of velocity files that reflect the transient conditions in the aquifers was created for input to the RAND3D model. After 6 yr of pumping, 91% of the TCE has been removed; 88% by the wells and 6% by the stream.

The third remedial action scenario simulated was the group of collection wells plus injection wells. Four injection wells were assumed to be placed on the upgradient site of Building 24 (the assumed source of the plume). Each collector well was assumed to be pumped at a rate of 72 gpm, twice that used in the collector well scenario. Of the 216 gpm to be treated, 200 gpm would be injected back into the water table aquifer. Letting some treated water discharge to surface water insures that the system as a whole (total of pumping and injection) causes a slight depression in the water table, so if the assumptions are incorrect, contamination will still remain in the area, rather than being pushed away faster than it would without injection. Each injector well would recharge 50 gpm. After 6 yr of pumping, 98% of the TCE has been removed; 94% by the collection wells and 4% by entering Green Pond Brook.

The fourth alternative simulated was using three collection wells and discharging the treated water to Bear Swamp Brook, which is upgradient of Building 24 and the contamination plume. The assumption was that by increasing the flow and depth of flow in Bear Swamp Brook, the recharge to the water table aquifer would increase. The results of this simulation indicate that this alternative is not significantly different from the three collection wells with discharge of treated water to Green Pond Brook. Infiltration to Bear Swamp Brook was small.

The fifth alternative simulated was using four collector wells. The first three wells were at the same positions as in the other pumping alternative simulations (equally spaced row between Building 24 and Green Pond Brook). A fourth well was placed adjacent to Green Pond Brook, where substantial concentrations of TCE had been measured in the water table aquifer. This fourth well was assumed to be pumped at a rate of 44 gpm for 1 yr and then turned off. After 6 yr of pumping, 94% of the TCE has been removed; with 92% by the wells and 2% by entering the stream.

The sixth and final alternative simulated was variable pumping at the three collector wells. By pumping more from wells in the middle of the TCE plume and less from wells at the edges, it was hoped that the overall efficiency of the collection and treatment system would increase. Pumping more water from the wells at early times would also capture more of the contamination that is between the collection wells and the stream. The collection well in the middle of the plume assumed to be pumped at a rate of 80 gpm for the first year, 60 gpm for the second year and 54 gpm for the third year. One well at the edge of the plume was assumed to be pumped at a rate of 18 gpm and the collection well on the other side of the plume was assumed to be pumped at a rate of 36 gpm. After six years of pumping, 95% of the TCE has been removed; 92% by the

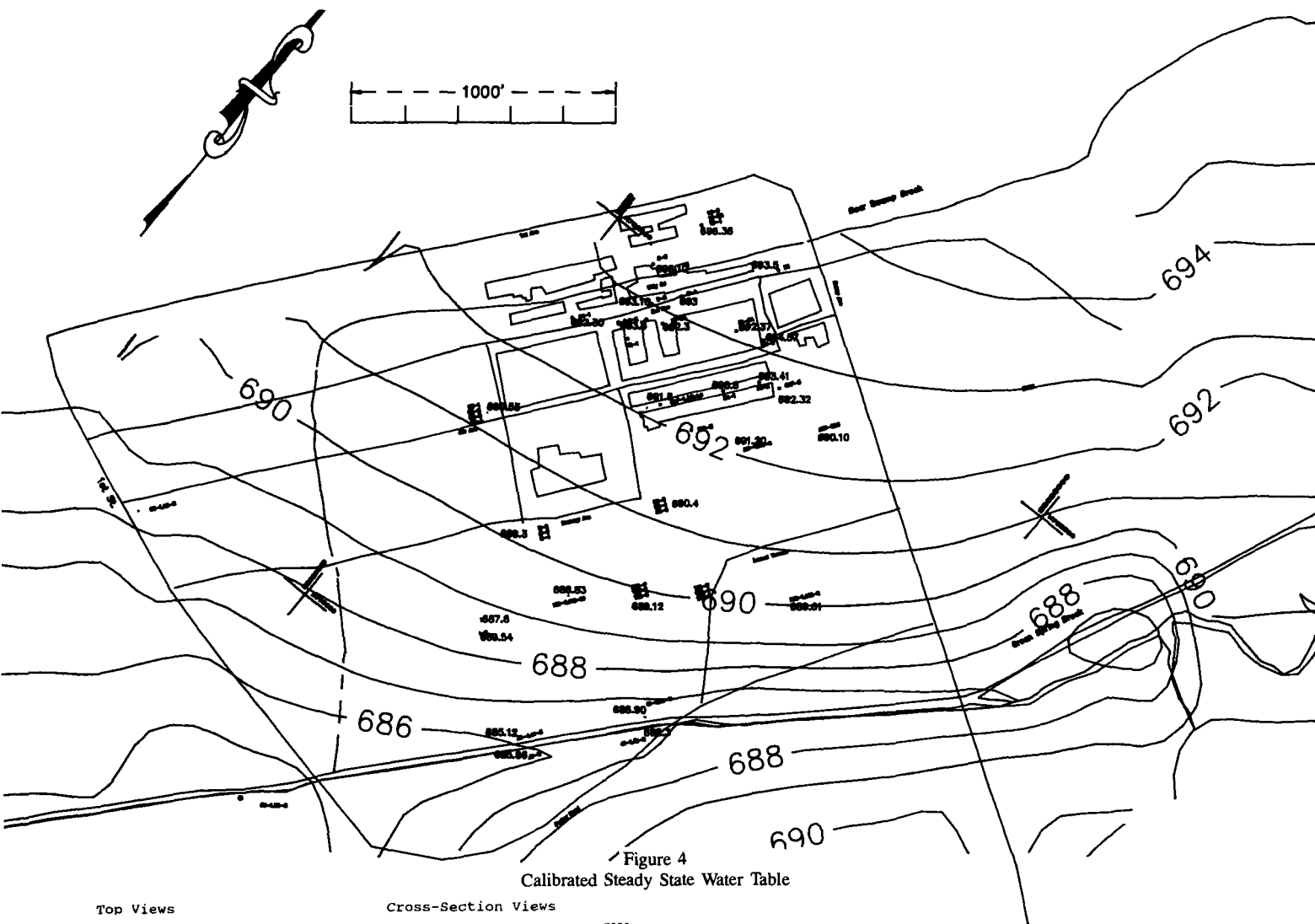


Figure 4
Calibrated Steady State Water Table

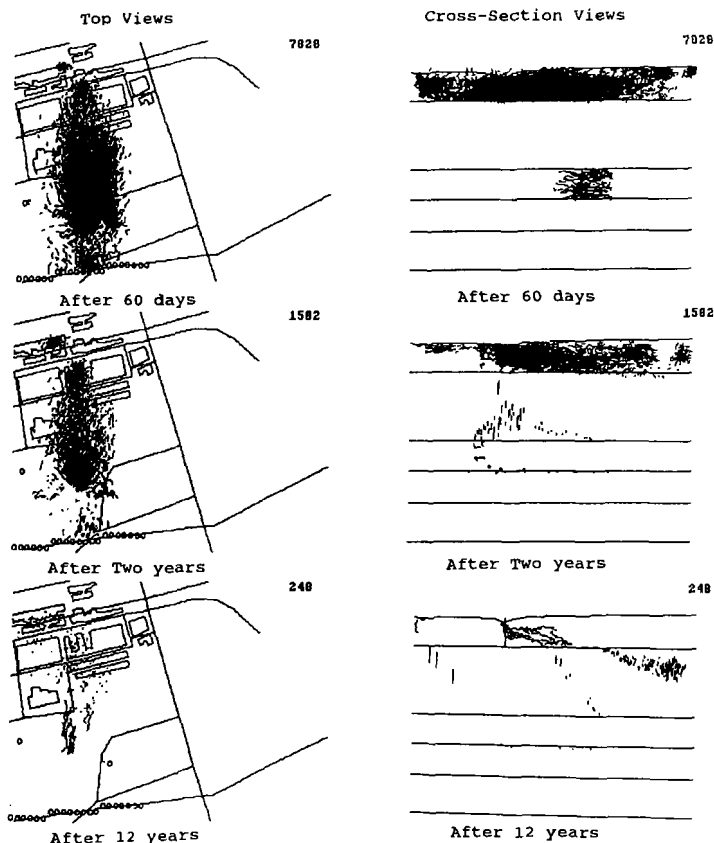


Figure 5
RAND3D Screen Graphics

wells and 3% by entering the stream.

Figure 5 shows several of the screen graphic displays generated by the RAND3D program for the variable pumping scenario. The first column of results shows the a top view of the plume after 60 days of pumping, after 2 yr of pumping and after 12 yr of pumping. The second column of results shows the corresponding cross-sectional views of the aquifer system.

Collection Wells with Variable Pumping

A sensitivity analysis was performed on the model predictions. The parameters with the greatest amount of uncertainty that also had a significant impact on the simulation results were the retardation coefficient (adsorption), the amount of TCE still leaching into the unsaturated zone to the water table aquifer over time and the amount of TCE adsorbed in the confining clay beds between aquifers. The sensitivity results indicate that the cleanup (pumping and treatment) could extend for more yr than predicted. With the maximum reasonable retardation coefficient, 90% cleanup would take approximately 15 yr. With a reasonable worst case scenario for TCE leaching into the water table aquifer from recharge, 90% cleanup would take more than 20 yr as TCE is continuously entering the aquifer. The collection of TCE that may be trapped in the confining layer takes even longer. Assuming that TCE is trapped in the confining layer near Building 24, after 50 yr of pumping and treatment, 50% of the TCE is still present in the aquifers and confining layers.

CONCLUSIONS

A practical model for simulating three-dimensional solute transport in groundwater on an IBM PC has been developed. This model uses the groundwater flow results of the MODFLOW model and simulates solute transport using the random-walk algorithm. The model operates interactively and generates graphic displays of plume movement as the

simulation takes place.

The results of the modeling of the Building 24 TCE plume at the Picatinny Arsenal indicate that there is no clearly superior pumping design for cleaning up the contaminated groundwater and preventing TCE from reaching Green Pond Brook. All of the simulated scenarios that do not include recharge wells upgradient of Building 24 achieve similar long-term removal rates. Recharge wells would speed the removal of TCE from the aquifer, but effective recharge wells may not be feasible because of a shallow water table and the likelihood of injection well clogging. The pumping plans that remove groundwater from the aquifer rapidly collect more TCE from the water table aquifer faster. All the collection well scenarios simulated effectively formed a barrier to the movement of TCE towards Green Pond Brook. Placing collector wells closer to Green Pond Brook would effectively collect more of the TCE,

reduce the amount entering Green Pond Brook, but result in larger amounts of pumpage containing lower concentrations of TCE.

REFERENCES

1. McDonald, M.G. and Harbaugh, A.W., *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*, Techniques of Water-Resource Investigations, of the United States Geological Survey, Washington, DC, 1988.
2. Prickett, T.A., Naymik, T.G., and Lonquist, C.G., *A Random-Walk Solute Transport Model for Selected Groundwater Quality Evaluations*, Illinois Water Survey Bulletin 65, Champaign, IL, 1981.
3. Sargent, B.P., Fusillo, T.V., Storck, D.A., and Smith, J.A., *Groundwater Contamination in the Area of Building 24, Picatinny Arsenal, New Jersey*, review draft, United States Geological Survey, Trenton, NJ, 1988.

Statistical Modeling of Ambient Air Toxics Impacts During Remedial Investigations at a Landfill Site

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ABSTRACT

At landfills or other waste disposal sites, the off-site impacts due to air toxics generated by intrusive activities are a principal concern. To assess these impacts, the multivariate statistical technique of canonical correlation has been applied to ambient air toxics sampling data collected during a remedial investigation of a landfill in the metropolitan area of Los Angeles, California. The goal of the analysis is to determine whether a site activity produces significant ambient air toxics impacts in the area immediately downwind of the site.

Canonical correlation analysis of the data collected at the downwind site reveals that the primary physical process occurring is dilution of contaminants by wind, with secondary slight increases in contaminant levels primarily due to boring activities. Although the canonical models are not strong enough for quantitative predictions for this data set, they do provide a realistic qualitative analysis of the physical situation.

INTRODUCTION

This paper presents the results obtained from application of canonical correlation analysis to ambient air toxics sampling data collected downwind of a landfill site during RI activities. Canonical correlation is a multivariate statistical technique that can be used to evaluate the relationship between groups of variables, in this case, meteorological conditions, site activities and ambient air toxics levels. The technique is an extension of traditional multiple regression analysis, which seeks to relate a single variable to a group of other variables.

Canonical correlation was chosen as an analytical tool because of its ability to provide information beyond the scope of traditional statistical comparison techniques, such as simple tests for equality of means or multiple correlation. The use of multivariate methods allows better resolution of the complex interactions between the atmosphere and the variety of air toxics compounds that may be present due to intrusive activities on a landfill site.

SITE DESCRIPTION

The site chosen for this study was an urban landfill located in the Los Angeles, California area. Historically, the site was used for disposal of general construction-type debris, but petroleum wastes and solvents also were potentially disposed of there. The site investigation was prompted by plans for new construction over the landfill site.

The site is located at the intersection of two major thoroughfares, with the upwind sampling location near the intersection. The downwind air sampling site was located beyond the northeast corner of the landfill area. The heavy automobile traffic around the site had a definite influence on the sampling results, particularly at the upwind site.

DATA COLLECTION

Ambient air samples were collected at the upwind and downwind

locations during the 3-wk site investigation. Wind speed, direction and air temperature data were collected concurrently with the sampling. Due to the consistent land-sea breeze circulation pattern at the site, day-time winds were most frequently from the southwest. The wind rose for the site activity period is shown in Figure 1. The upwind and downwind sampling locations were therefore the same for all samples and were chosen based on this wind pattern.

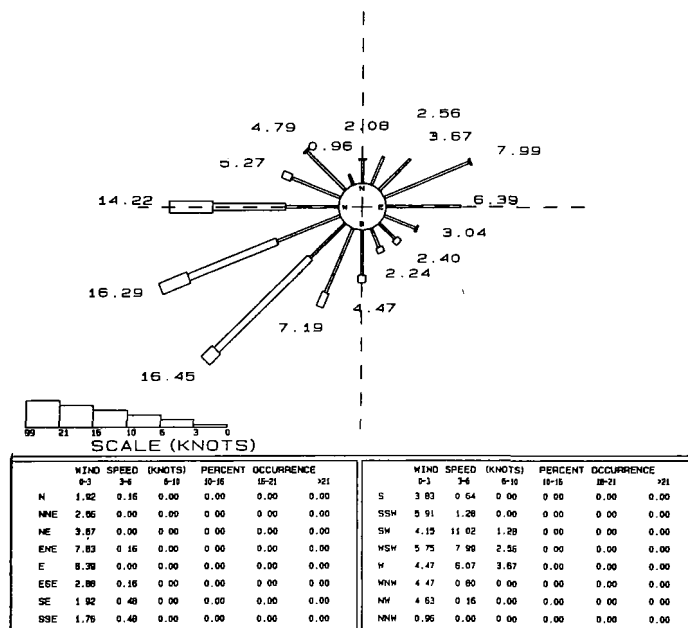


Figure 1
On-site Wind Rose Activity Period

During the activity period, 31 high-volume air samples and 33 volatile organics samples were collected. The compounds detected included eight toxic volatile organic compounds (VOCs), copper, lead, zinc and asbestos. The following eight VOCs were detected in at least 75 % of the samples;

- acetone
- benzene
- ethylbenzene
- styrene
- toluene
- xylenes
- tetrachloroethene
- 1,1,1-trichloroethane

The VOCs were collected using passivated stainless steel canisters (U.S. EPA Method TO-14) and the metals were analyzed from high-volume air samples of particulate matter. Asbestos was determined using low-volume personal pumps and filter cartridges.

Site activity was parameterized as the durations of the two principal intrusive activities: boring (soil core samples) and drilling (ground-water monitoring wells). Activity durations were obtained from the site log books.

In addition to the activity period data, background samples were collected on the 3 days immediately prior to the start of intrusive site activities. The mean contaminant levels in these three samples are used to establish a benchmark level to assist in interpreting the activity period results.

SAMPLING RESULTS

For the activity period, a complete range of descriptive statistics was calculated for the upwind and downwind locations. The statistics include the average, standard deviation, standard error, maximum, minimum, median and the 25th and 75th percentiles (lower and upper quartiles). These statistics were used to generate the box-and-whiskers plots presented in the next section, used for upwind vs. downwind comparisons.

Mean concentrations of air toxics measured during the activity period are compared to mean background concentrations for all contaminants in Figure 2 for the solid contaminants and Figure 3 for the volatile organics. Concentrations of the solid contaminants were higher during the activity period than background means in all cases except for the downwind lead and upwind zinc levels. For the VOCs, all concentrations were higher than corresponding background levels. The concentrations of acetone, styrene, toluene and xylenes during the activity period were markedly higher than their background levels at both locations.

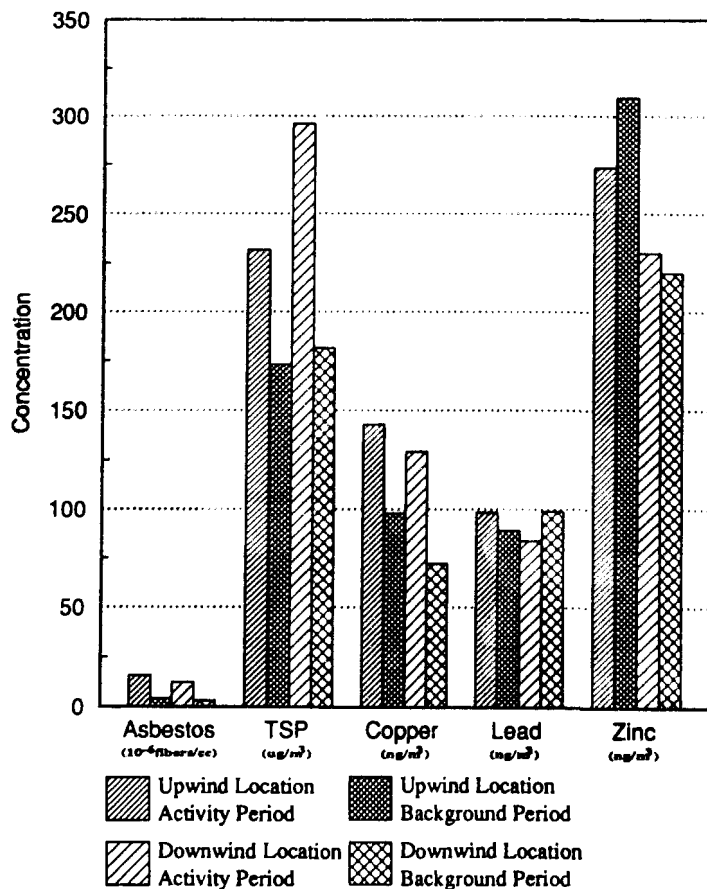


Figure 2
Comparison of Activity and Background Levels
For Solid Contaminants

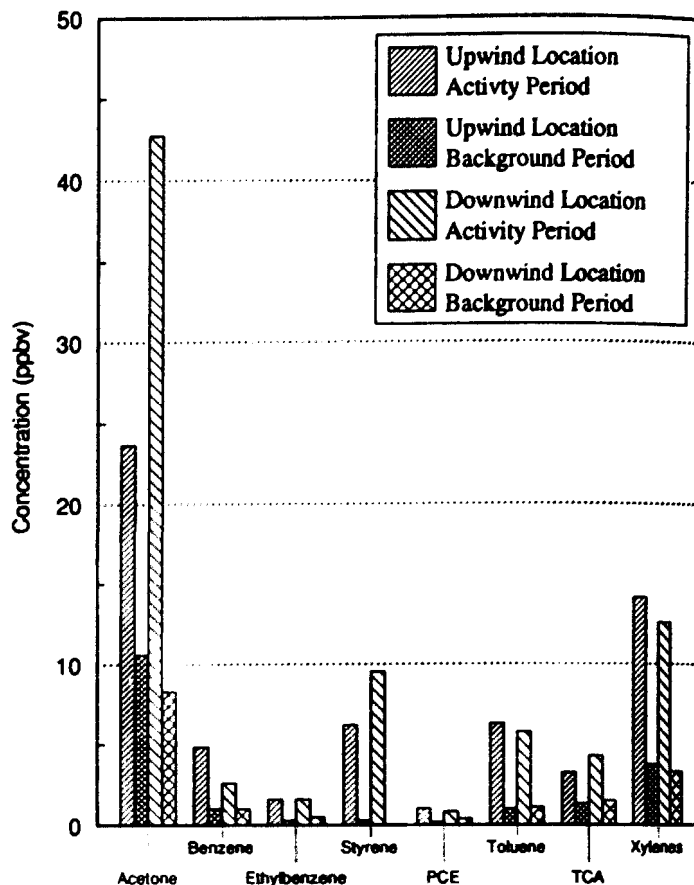


Figure 3
Comparison of Activity and Background Levels
For Volatile Organic Contaminants

UPWIND/DOWNWIND COMPARISONS

To assess the amount of contamination introduced into the ambient air by site activities, a comparison of upwind and downwind means can be used. Normally, a t-test for equality of means would be used in the comparison. However, the t-test assumes that both samples are normally distributed. This is not a reasonable assumption for the air toxics data being considered, as they tend more toward a log-normal distribution. Rather than performing the log transform to "force" the data to become normal, a nonparametric comparison of medians was performed using the Wilcoxon two-sample test for independent samples. None of the upwind/downwind pairs of medians were significantly different at the 10% level.

The upwind/downwind sample sets also were compared using side-by-side box-and-whiskers plots. A box-and-whiskers plot (or simply a box plot) is designed to display the distribution of a sample and allow visual comparison of samples. The plot consists of a box bounded by the 25th and 75th percentiles (lower and upper quartiles) of the data set, with a bar between them indicating the 50th percentile (median). The "whiskers" extend from the quartile edges of the box to the maximum and minimum values in the sample. In addition to these standard features, a circle has been added at the sample mean, along with an error bar stretching one standard error unit above and below the mean. This addition allows visualization of the skew of the distribution and allows easy comparison of means in side-by-side plots.

Interpretation of the plots is straightforward. A normally distributed sample would have a perfectly symmetric plot, with the mean and median collocated at the center of the box. Skewed samples have means above or below the median and disproportionate whiskers.

Side-by-side box plots were used to compare upwind and downwind sample sets. Figure 4 shows the data for all of the solid contaminants and Figures 5 and 6 show the VOCs in two groups. The plots are generated from the descriptive statistics for the activity period only.

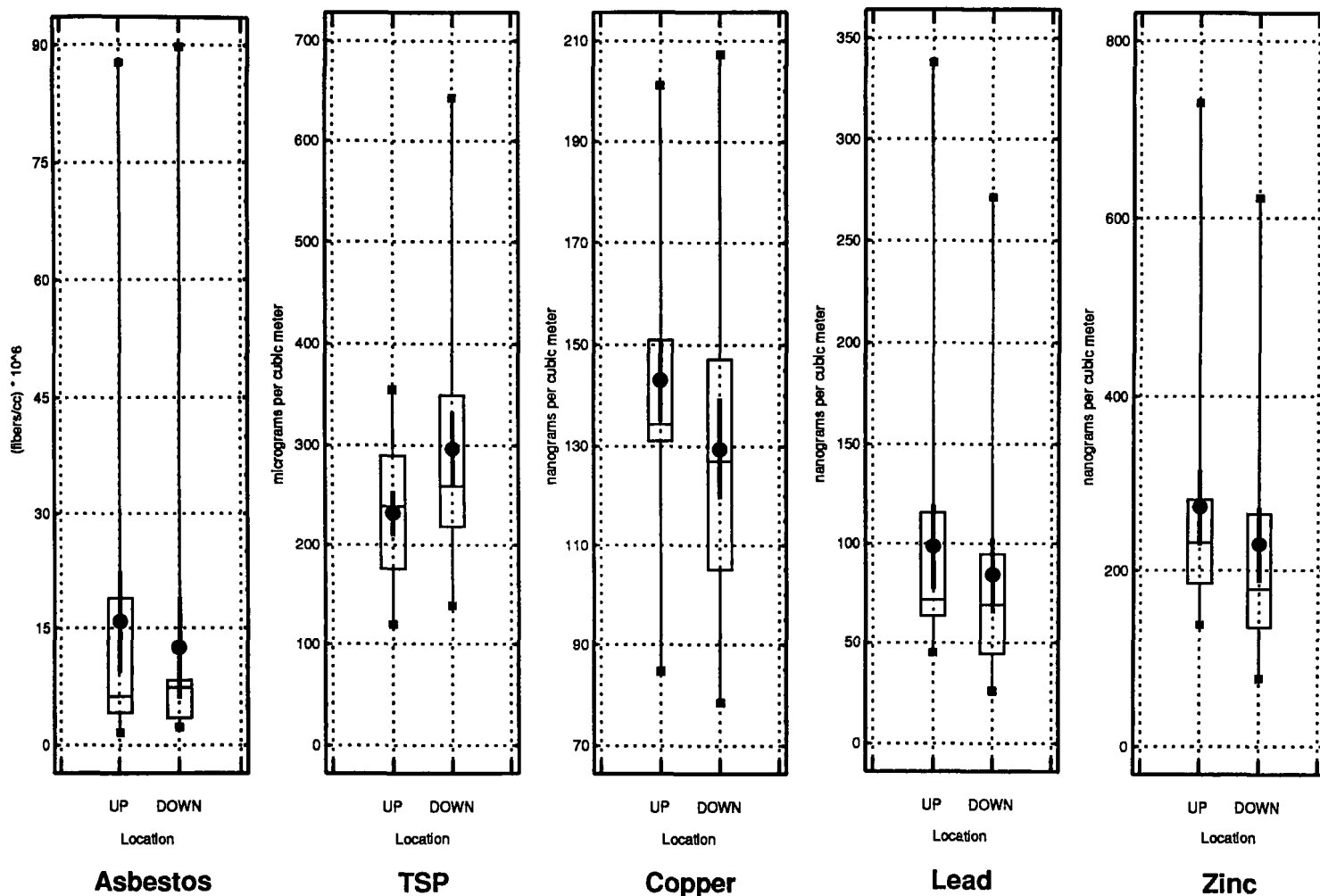


Figure 4
Box Plots for Activity Period: Solid Contaminants

These figures effectively portray the difficulty in determining whether the downwind contaminant levels are in any way distinctly greater than the upwind levels, using normal "yardsticks" such as means or medians. Using these methods of comparison would lead to the conclusion that site activities had no distinguishable impact on contaminant levels, with the apparent exception of acetone. However, the broad overlap of the box plots for acetone indicates that the two samples are not meaningfully different (a conclusion supported by the Wilcoxon test).

DOWNWIND CANONICAL CORRELATION

The primary goal of this analysis was to determine the potential impacts of site activity on nearby downwind (i.e., off-site) locations. Therefore, the remaining discussion in this paper is limited to the downwind data collected during the activity period.

The canonical correlation procedure was performed based on the correlation matrix for all contaminant variables. The northerly and easterly wind speed components were mean values covering the period from 0700-1700 L each day. The values of these variables for each day are tabulated on Table 1. Note that the vector wind components are directed to the north and to the east. Thus, a northeast wind would have both components negative, while a southwest wind would have both components positive.

Canonical correlation extends the sample correlation concept from two single variables to two sets of variables. The two sets are analogous to the dependent and independent variables in traditional regression analysis. The canonical correlation procedure finds the most highly correlated pairs of linear combinations of the variables in each set. These linear combinations are known as canonical variable scores and the sample correlation between a pair of scores is the canonical correla-

Table 1
Daily Mean Wind Components

Day	North (mph)	East (mph)
1	2.74	0.68
2	3.28	3.05
3	3.30	0.33
4	2.93	3.27
5	2.33	3.75
6	1.39	2.41
7	2.28	2.31
8	1.02	5.62
9	2.11	3.13
10	1.32	4.93
11	0.66	4.73
12	0.64	3.85
13	1.48	4.33

tion coefficient. The scores may be interpreted by examining the component variables' sample correlations with the resultant score.

Solid Contaminants

A summary of the results of the downwind canonical correlation analysis for the solid contaminants is shown on Table 2. The first two pairs of canonical variates are significant at the 10% level. The correlations of the two pairs of scores with their component variables are

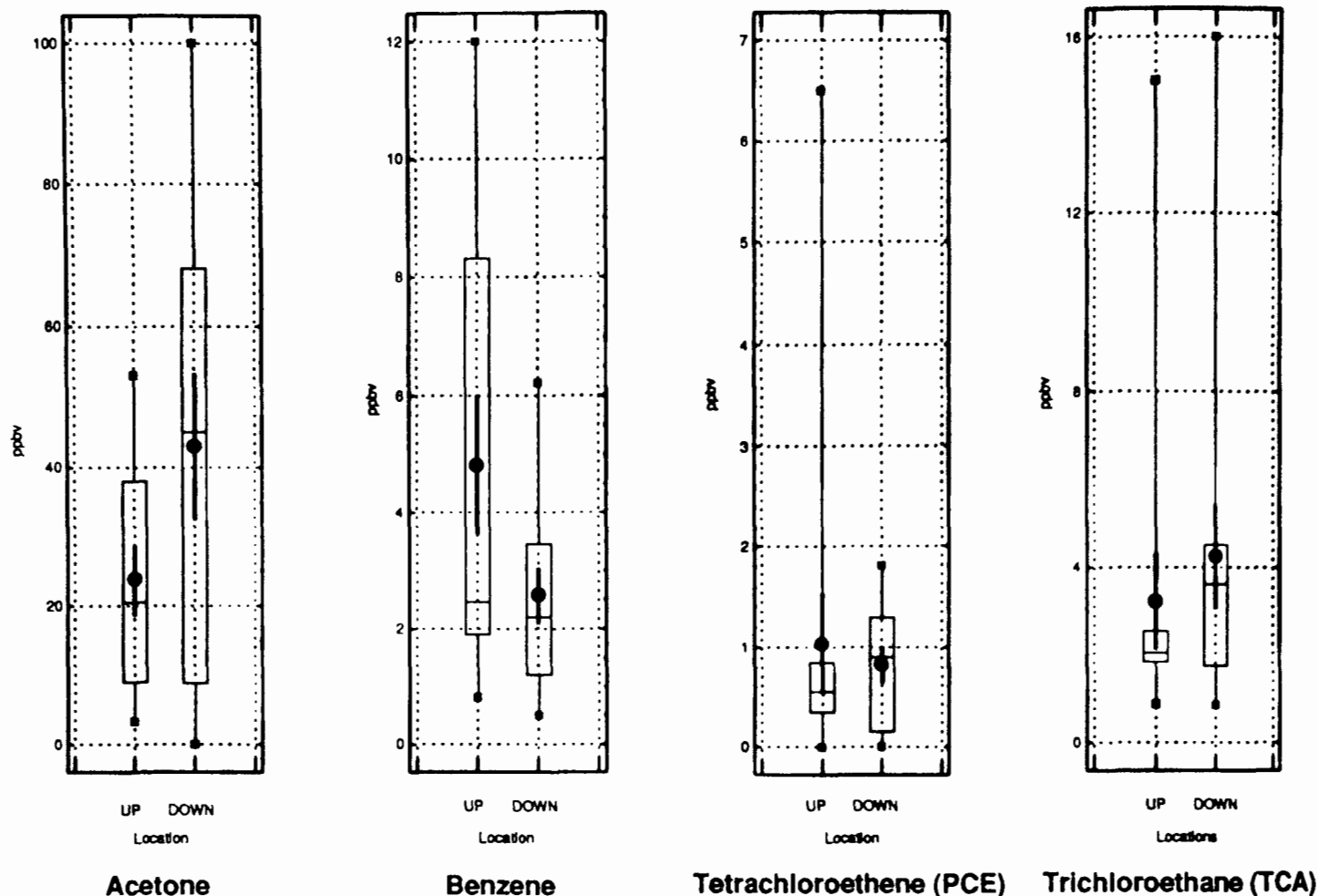


Figure 5
Box Plots for Activity Period: Acetone, Benzene, PCE and TCA

shown in Table 3. In Table 3 and in all subsequent tables including sample correlations, coefficients significant at the 10% level are flagged with a (<) symbol.

Table 2
Summary of Canonical Correlation Results
Downwind Solid Contaminants

Number	Canonical Correlation	Significance Level
1	0.9715	0.0069
2	0.9027	0.0951
3	0.7421	0.3274
4	0.4159	0.5145

Based on the significant correlations, the first pair of variates reflects low copper levels occurring with southerly winds. Considering all the correlations, the general relationship expressed by the first pair of scores is lower contaminant levels and more southerly winds, which is consistent with site geography. A stronger easterly wind component is necessary to carry contaminants towards the downwind site. Therefore, the southerly component would contribute to transport away from the site (dilution.) Therefore, the first set of canonical variates appears to represent the general reduction of contaminant levels at the downwind site by dilution.

The second pair of variates reflects higher lead levels and longer boring periods, based on the significant correlations. In general, the relationship is between higher contaminant levels and longer boring

Table 3
Downwind Correlations of Canonical Variates
With Component Variables

Contaminant Scores

	First Pair	Second Pair
Asbestos	-0.427	-0.048
TSP	-0.170	0.228
Copper	-0.511<	-0.190
Lead	-0.199	0.669<
Zinc	0.122	0.467

Wind/Activity Scores

	First Pair	Second Pair
North	0.704<	0.248
East	-0.061	-0.427
Boring	-0.209	0.939<
Drilling	0.383	-0.150

times. There is also a relatively high correlation in the activity/wind score with westerly winds. As previously discussed, westerly winds (high easterly components) are primarily responsible for contaminant transport to the downwind site. Therefore, the second pair of variates

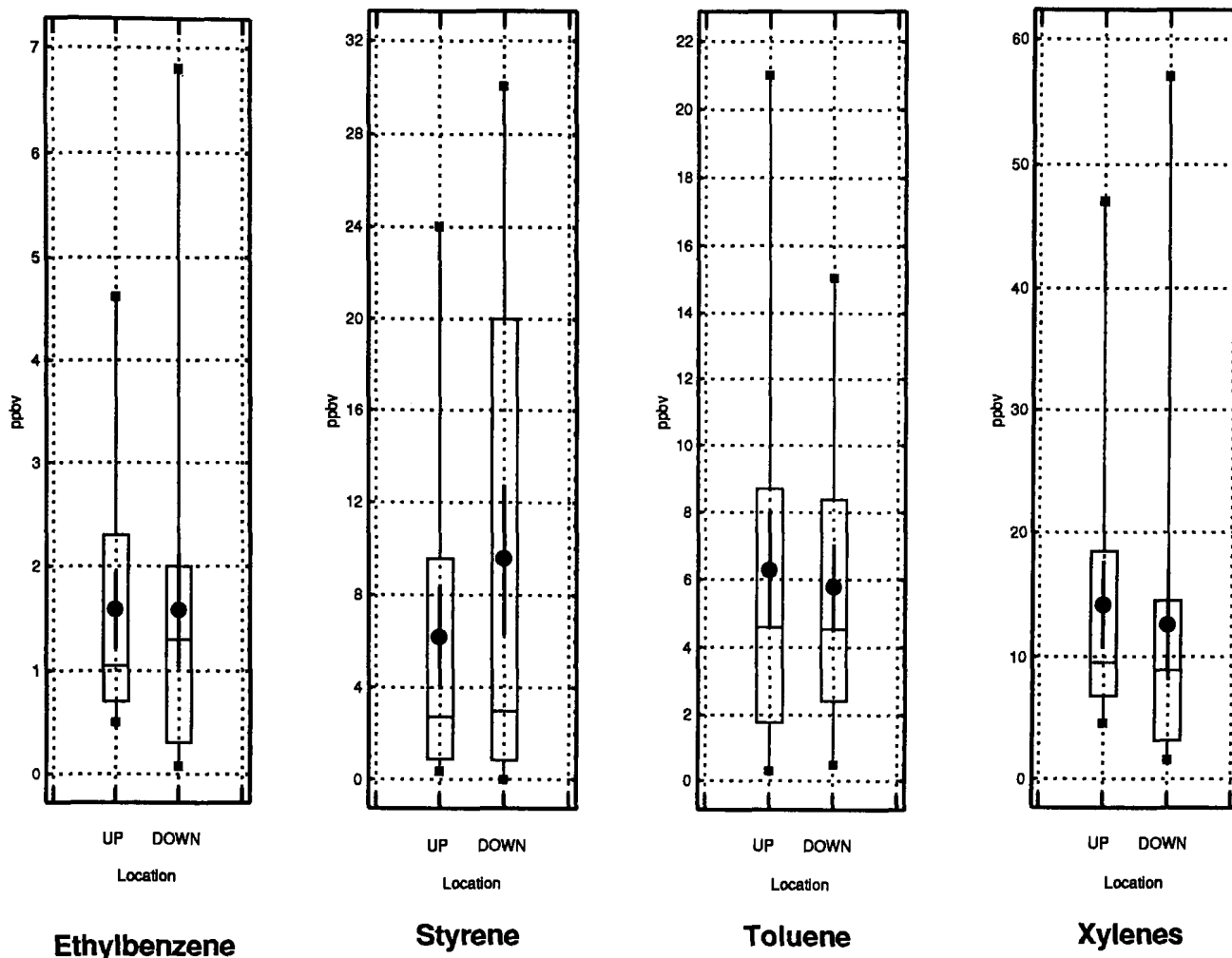


Figure 6
Box Plots for Activity Period: Ethylbenzene, Styrene,
Toluene and Xylenes

represents the general elevation of contaminant level at the downwind site during site activity with more westerly 'sea breeze' flow regimes.

The logical extension of this analysis would be to attempt to predict the quantitative effects of varying levels of site activity on contaminant levels. Constructing such a model would require establishing a solid relationship between the variables and the scores. Unfortunately, the correlations are too weak to be of predictive value. However, the canonical correlation analysis does indicate that elevated contaminant levels are qualitatively associated with increased boring activity.

Volatile Organic Contaminants

The canonical correlation analysis is summarized in Table 4, with one significant pair of variates indicated. The correlations in Table 5 show no contaminants significantly correlated to the contaminant score.

This type of ambiguity occurs in canonical correlation analyses whenever there are strong correlations between many variables in either group. Such a high degree of correlation does exist amongst many pairs

Table 4
Summary of Canonical Correlation Results Downwind Volatile
Organic Contaminants

Number	Canonical Correlation	Significance Level
1	1.0000	0.0000
2	0.9934	0.1675
3	0.7811	0.8137
4	0.7272	0.6406

Table 5
Downwind Correlations of Canonical Variates
With Component Variables

Contaminant Scores

	First Pair
Acetone	0.196
Benzene	-0.218
Ethylbenzene	0.013
Styrene	-0.023
PCE	0.018
Toluene	-0.082
TCA	-0.287
Xylenes	0.086

Wind/Activity Scores

	First Pair
North	0.716<
East	-0.640<
Boring	-0.329
Drilling	0.159

of VOCs, principally due to the influence of nearby traffic emissions. The use of highly correlated predictor variables in linear regression produces an analogous effect.

More definitive results might be possible if some of the highly correlated contaminant variables were eliminated. Such an elimination of variables would be arbitrary, based on available data and so was not attempted.

CONCLUSIONS

In the interpretation of ambient air sampling data collected during field investigations at a landfill, "traditional" statistical comparisons (e.g., comparison of means) may fail to reveal meaningful relationships between site activity and resulting air contaminant levels. This shortcoming is due to the inability of single-variable statistics to account for the more subtle interactions often present in air toxics sampling. The use of a multivariate technique such as canonical correlation allows a more detailed examination of the interrelationships among sampling variables.

When applied to a set of actual ambient air toxics data collected during activities at a landfill, comparisons of the upwind and downwind samples using box plots and Wilcoxon two-sample tests for equal medians did not reveal any significant increase in contaminant levels. This was due mainly to the wide variability inherent in the data.

Canonical correlation analysis of the solid contaminant levels and the activity/wind variables at the downwind site shows that:

- There is primarily dispersion of contaminants across the normal sea-breeze wind direction (southwest)
- Boring duration and elevated levels of metals are positively related

These canonical relationships are not strong enough for quantitative use.

Canonical correlation analysis of the VOC data at the downwind site are rendered indeterminant due to a high degree of inter-correlation among the volatile contaminants. These interrelationships are due mainly to traffic on the thoroughfares bordering the site, which likely obscures any relationships between VOC levels and site activity.

The overall conclusions of the canonical correlation analysis of ambient air toxics sampling during remedial investigations at this site may be summarized as follows:

- On-site activities resulted in slightly elevated concentrations of copper, lead and zinc in the ambient air downwind (northeast) of the site
- The increases in levels of these contaminants are not statistically significant
- No significant increases in toxic VOC levels were linked to site activity

The use of canonical correlation to analyze results from other air sampling efforts in support of RI/FS operations proved useful in this case and may prove to be of even greater use in the future.

RANDOM-WALK Modeling of Organic Contaminant Migration from the Theresienfeld Landfill Located in the Vienna Basin Aquifer of Austria

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ABSTRACT

The Theresienfeld landfill, located 30 km south of Vienna, Austria, contains several thousand drums of waste solvent material mixed with municipal garbage. The landfill operated from 1972 to 1985. Since the early operating periods at the facility, waste solvents have leaked and leached into a highly productive aquifer of the region. As part of a feasibility study/design process for remediation of this landfill, a limited groundwater modeling effort was undertaken to provide a general understanding of continual contaminant migration and a relative prediction of future solute transport under two scenarios: with remediation of the landfill materials and without remediation of these materials.

This waste facility is situated in the southern portion of the Vienna Basin, which is a large, elongated, trough-shaped depression created by classic horst and graben tectonics. Basin sediments consist of Tertiary-age clay deposits overlain by 100 to 150 m of Quaternary gravel intermixed with thin silt and clay lenses. The unconfined aquifer within the gravel deposit is a principal future groundwater resource for Vienna. General hydraulic conductivity values for this aquifer are in the range of 10^{-2} to 10^{-3} m/sec. Groundwater flow velocities within the aquifer range from 6 to 20 m/day along the longitudinal axis of the graben structure.

In the 1960s, gravel mining in this area was prominent. At this particular location, mining operations resulted in a large pit with dimensions of 100 m wide by 750 m long by 20 m deep. Early in the 1970s, mining was no longer profitable, and this site was sold to a local entrepreneur who began using the pit as a landfill, but without the use of contaminant prevention techniques such as liners and leachate control.

Leachate from the landfill has since seeped into the relatively fast-flowing Vienna Basin aquifer and resulted in organic contamination of several nearby downgradient monitoring, residential and industrial wells. Specific contaminants of the plume consist primarily of chlorinated hydrocarbons including trichloroethylene, tetrachloroethylene and 1,1-dichloroethane at total concentrations of approximately 500 to 1000 $\mu\text{g/L}$ immediately downgradient of the landfill.

In addition to this landfill, there are several other contaminant sources that likely are impacting aquifer ground water quality. Highly industrialized cities such as Wiener Neustadt and Ternitz are situated upgradient of the landfill. In particular, industrial facilities such as old steel mills in these two cities likely have contributed to groundwater contamination in the main recharge area of the aquifer.

Groundwater modeling consisted of evaluating average flow and solute transport conditions in the general basin area surrounding the landfill using the Analytical RANDOM-WALK Model. This model was used to assess two-dimensional flow conditions under a finite difference formulation, while integrating solute transport from particle-in-a-cell for convective effects and random-walk techniques for dispersion in a

porous medium as a random process. This particular code was selected for this study because of limited time constraints, limited data base and the model's ability to simulate two-dimensional mass transport problems in homogeneous/isotropic aquifers under steady-state water table conditions. Thus, although the results of this study are at best qualitative, they do provide a general and relative indication of long-term impacts on the aquifer.

In this modeling effort, flow parameters and contaminant loads were determined based on chronological assumptions and best available data in the general basin area with dimensions of 23 km by 46 km. Three general sources of contamination were incorporated in the model: the landfill as a point source, and two areas upgradient of the landfill as line sources to simulate existing and continual inflowing contaminated groundwater. These conditions were then calibrated to the most current data set to best simulate the actual contaminant plume extent in two dimensions as it currently exists.

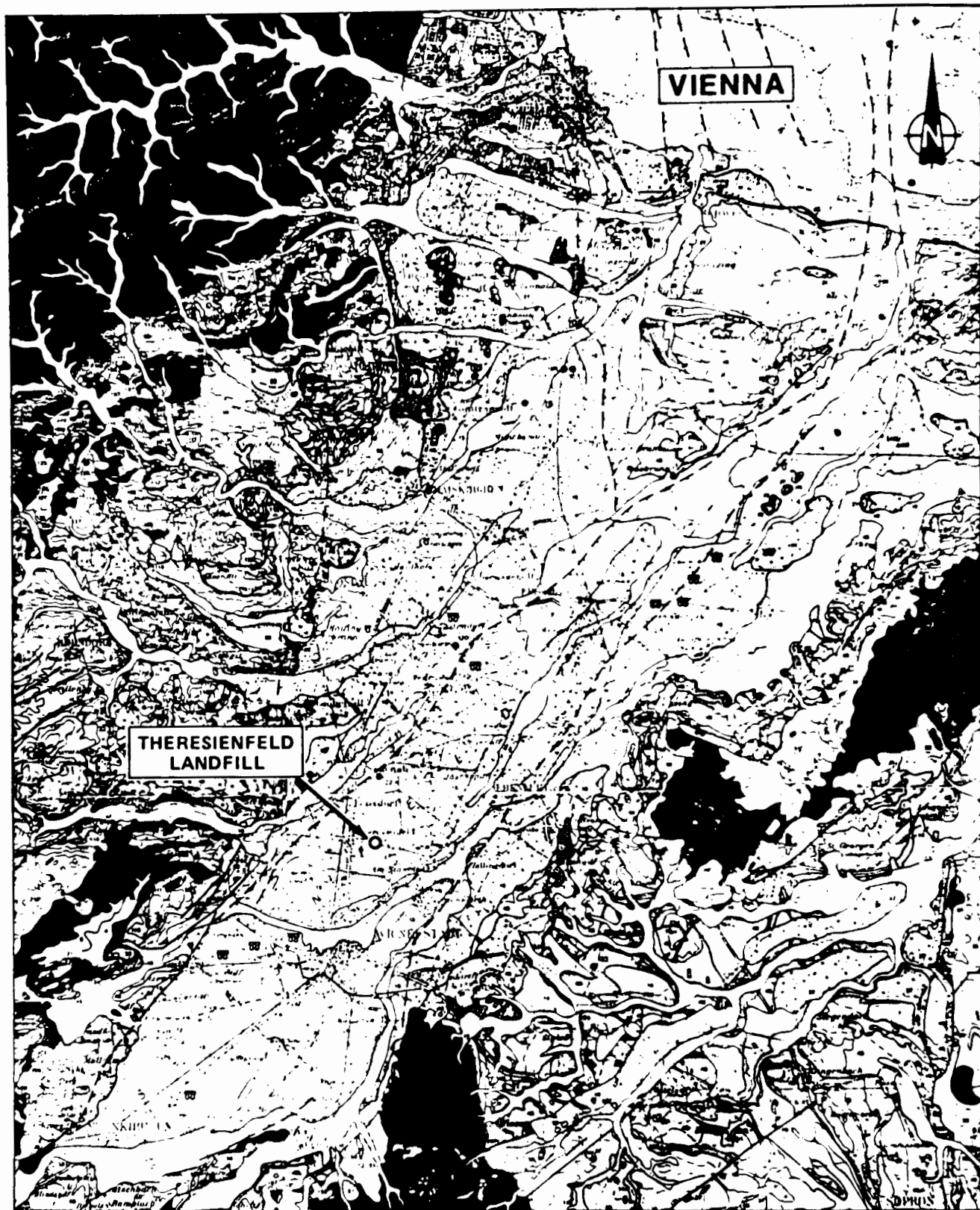
The calibrated modeling simulation showed clearly that remediation of the landfill source immensely improved groundwater quality of the aquifer. However, low level contamination slightly above Austrian drinking water standards would persist in much of the aquifer without remedial action on assumed upgradient sources in the cities of Wiener Neustadt and Ternitz. Without remediation of the landfill, the plume, as originally estimated, would become more concentrated with the various contaminants and would increase in extent to impact a much larger area of the groundwater resource.

INTRODUCTION

The Theresienfeld landfill is a large, uncontrolled hazardous waste facility located in a rural area about 30 km south of Vienna, Austria (Fig. 1). Environmental effects from this landfill resulted in national publicity and a government investigation of this and several other waste disposal facilities in the area.

The Theresienfeld site is situated in the Vienna Basin, one of the major present and potential future groundwater sources for Vienna. A few years ago, several communities installed drinking water production wells at a location downgradient of the landfill. To the dismay of these communities, the wells contained concentrations of chlorinated solvents ranging from 20 to 30 $\mu\text{g/L}$ throughout the central axis of the Vienna Basin.

As a result of detectable contamination in the water production wells, the Austrian government began monitoring the basin aquifer and detected a widespread problem. The Theresienfeld landfill, as well as other contaminant sources from Ternitz and Wiener Neustadt, industrial areas hydraulically upgradient of Theresienfeld, seemed to be contributing to the problem. Ternitz and Wiener Neustadt have been heavily industrialized since before World War II.



SOURCE: Geologische Bundesanstalt, Wien und Umgebung, 1:200,000

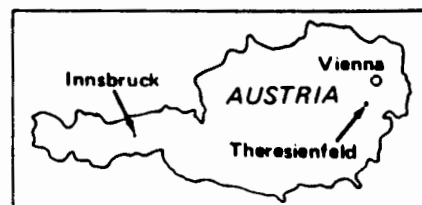
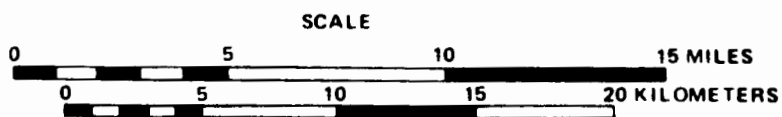
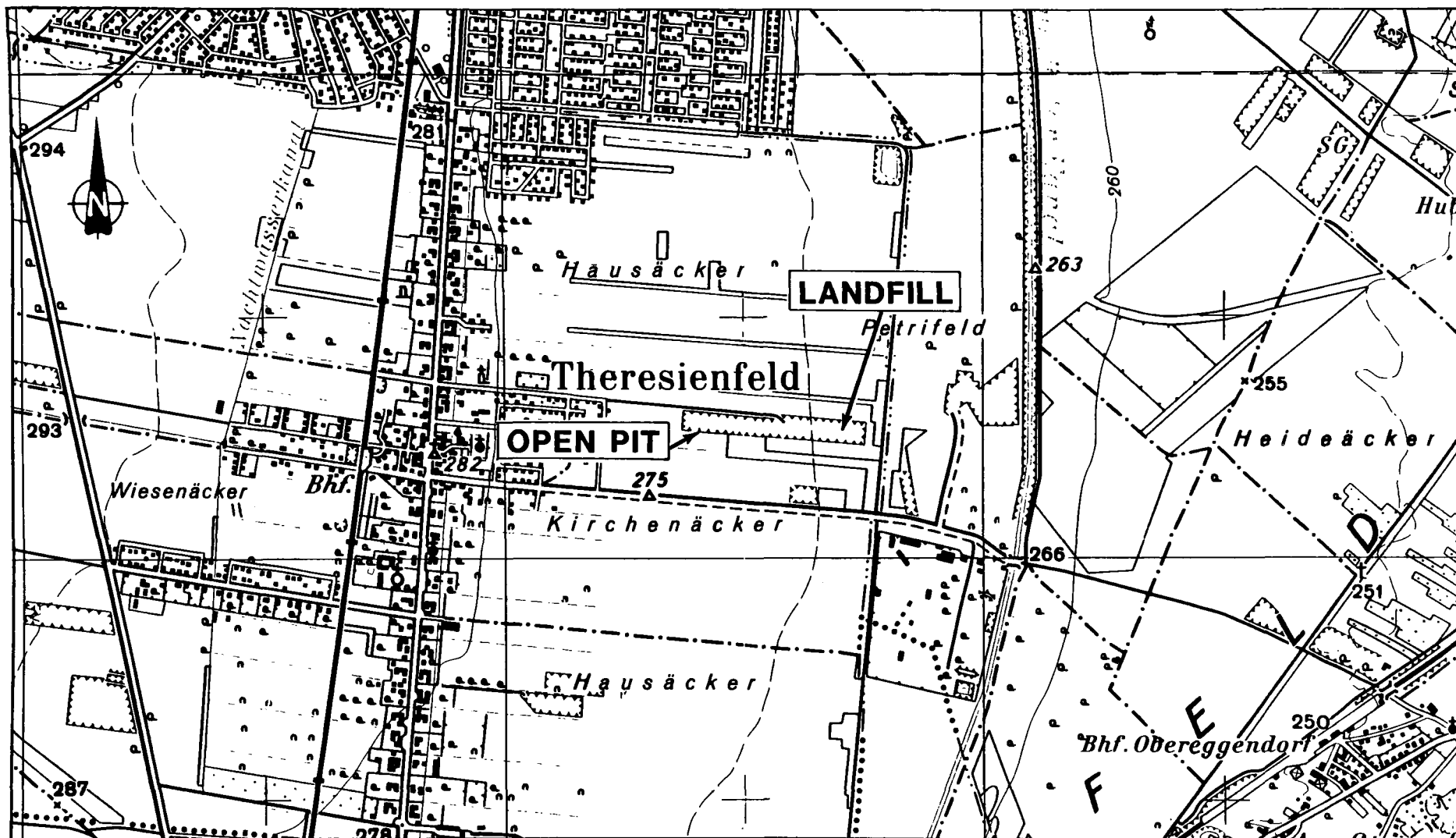


Figure 1
Location of the Theresienfeld Landfill in the Vienna Basin



SOURCE: Österreichische Karte; Wiener Neustadt (1:25,000)

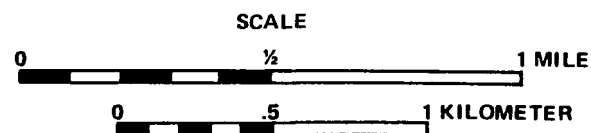


Figure 2
Local Theresienfeld Landfill Area



SOURCE: Geologische Bundesanstalt, Wien und Umgebung, 1:200,000

SCALE



KEY:

— 160 — Water Table Elevation (meters above sea level)

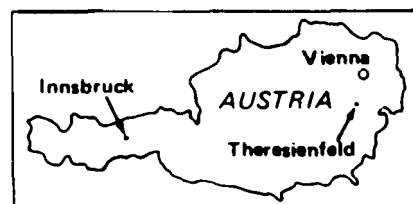


Figure 3
Generalized Vienna Basin Aquifer Water Table Isoline
(source: Berger 1983)

The purpose of this modeling effort was to illustrate a simplified relative impact on the aquifer of a total cleanup operation implemented at the landfill and to determine if the aquifer can recover to a useful condition if the contamination source is controlled. Generalized two-dimensional groundwater modeling results are presented under two scenarios that yield insight on potential future horizontal contaminant plume migration: (1) the landfill is left in its current condition, and (2) the existing contaminant source (landfill materials) is removed.

In order to simulate the contaminant plume, sources of contamination upgradient of Theresienfeld were simplified and taken into account. These sources generate the base load contamination of the upgradient groundwater, which is superimposed onto the load from the Theresienfeld landfill.

For this study, only the horizontal plume migration was evaluated. Furthermore, this evaluation was performed utilizing the best available data, which are limited in amount. However, the results demonstrate that the groundwater system will recover slowly if the source is controlled.

This two-dimensional model provided reliable results because the aquifer in this area is fairly homogeneous with increasing depth to the impermeable zone and vertical head differences likely are not significant. Because of limited data and funds, a vertical contaminant prediction was not performed.

BACKGROUND

Mined-out pits evidently end up being used for deposition of waste materials all over the world. This was the case at Theresienfeld. Beginning in 1966, an extensive gravel mining facility existed at this location. Sometime in the late 1960s, the gravel production business experienced dwindling prices, and by 1970 many gravel producers in the area shut down operations. The excavation at Theresienfeld was one such operation and resulted in an elongated pit about 100 m wide by 750 m long by 20 m deep.

In 1972, the owner leased the Theresienfeld gravel pit to a nearby paint and solvent manufacturing and recycling plant. The paint and solvent plant obtained a permit from local authorities to dispose of drummed waste materials in the pit. According to the permit, all drummed waste was to be deposited in layers, with 20 cm of fill material placed between each layer. However, the landfill operation was initiated without any contaminant migration prevention technology, such as impermeable liners, leachate collection or gas control systems, or even security. Later, the new operator also obtained permission to dispose of wastes from other industries in the pit. Within 1 yr after initiation of the landfill operation, inspection authorities observed pooled chemicals in various areas of the facility. The pools apparently were the result of haphazard drum disposal or the dumping of free liquid into the excavation. Improper disposal practices at the landfill continued, and numerous problems were documented. Over the remainder of the decade there were several chemical fires at the landfill. The operator began to accept waste materials such as paint and solvent residue sludges and shredded rubber, metal and manufactured items. Used oils were spread over the shredded materials, apparently under the assumption that they would serve as a sorbent.

By 1980, the landfill had begun to accept household wastes. By this time, nearly half of the pit was full. In addition, approximately 200 drums were illegally buried in trenches at the bottom of the unfilled half of the pit. Figure 2 is a map of the Theresienfeld area showing the filled and unfilled portions of the pit.

HYDROGEOLOGY

The Theresienfeld area is situated in the central portion of the trough-shaped depression known as the Vienna Basin (Fig. 3). In Austria, the basin is approximately 60 km long and in the Theresienfeld area approximately 10 km wide. The basin extends in a north-northeast direction from Neundirchen to the Danube River near Vienna. The basin was formed by classic horst and graben tectonics. The associated structural movement has resulted in down-thrown Tertiary- and Quaternary-aged rock materials which make up the graben and upthrown Jurassic- and Tertiary-aged units along the basin's flanks. Faulting has occurred deep

in the Tertiary sediments within the basin, perpendicular to the graben structure. In the area of Theresienfeld, the result of this faulting phenomenon is a sub-basin known as the Mittendorfer Senke, which is one of four major sub-basins within the larger Vienna Basin.

In general, the stratigraphy of the Vienna Basin consists of Quaternary gravel deposits which overlie Tertiary clays, clay marls and conglomerates. This gravel deposit was transported and deposited by the numerous rivers that drain into the basin from the surrounding upland terrain. The gravel formation is fairly homogeneous, with localized clay and sand lenses sporadically located throughout. In the Vienna Basin, the gravel varies in thickness from 3 m to 150 m. In the Mittendorfer Senke, the gravel is approximately 100 m thick.

A thick Tertiary clay deposit exists below the gravel and extends throughout the entire Vienna Basin. This formation consists of a blue-gray clay intermixed locally with limestone fragments and layers of sand. Most of this clay is impermeable. The average clay thickness in the basin is believed to be approximately 300 m. The interface between the gravel and clay is very distinct, and the depth of this boundary is highly variable within the Vienna Basin. In the Theresienfeld area, the clay surface is estimated to range in depth from 25 m in the area south of Theresienfeld, to 100 m in the immediate vicinity of Theresienfeld, to 25 m in the area north of Theresienfeld.

The unconfined, very permeable aquifer which resides in the gravel formation of the Vienna Basin is believed to be one of the best fresh water resources in Europe. The aquifer is recharged primarily by the Schmarzau and Piesting Rivers which flow out of the mountainous region located southeast and east of the Vienna Basin. These rivers, along with several others to the south, are also the main surface water features in the basin. All of the surface water eventually drains into the Danube River which transects the basin at the northwest end.

The depth to the water table in the Theresienfeld area is approximately 20 m below the surface. The regional groundwater flow direction of this aquifer is generally north-northeast, parallel to the longitudinal axis of the basin. In the Theresienfeld area, the local groundwater flow direction is also northeasterly. Dye tracer tests performed by local authorities have shown that flow rates in this aquifer in the Theresienfeld area are very rapid, ranging from 6 to 10 m/day near Theresienfeld, and increasing toward the recharge area at the southwest end of the basin to as much as 20 m/day.

This surficial aquifer supplies drinking water to most of the population of the Vienna Basin area, except for Vienna. The city of Vienna currently receives its water via aqueducts from the uplands to the southwest. However, the demand for water at Vienna is exceeding the capacity of current supply sources, and it is anticipated that the city will have to begin drawing on Vienna Basin groundwater sources in the near future.

In 1982, based on periodic sampling of several wells throughout the Vienna Basin area, local authorities directed the Theresienfeld landfill operator to sample and analyze groundwater from nearby existing wells for chlorinated hydrocarbons and metals. As a result of this sampling and regional ongoing investigations, the authorities concluded that the landfill was contributing substantial contamination to the groundwater with trichloroethylene, perchloroethane, toluene and 1,2-dichloroethane being the major chemicals of concern.

During the period from 1982 to 1985, the Austrian government installed a number of monitoring wells around the landfill perimeter and sampled these wells and nearby private wells on several occasions. The drilling installation methods and construction details of these wells are unknown.

Based on the available groundwater sampling data, a lateral contamination plume was defined (Fig. 4). In addition, in 1984, soil gas sampling was performed in the landfill area by a German firm. The soil gas results were quite similar to the groundwater sampling results. Thus, the data clearly indicate that significant contamination is leaching from the landfill to the groundwater aquifer and migrating downgradient.

MODEL DESCRIPTION

A semi-quantitative mass transport model known as Analytical RANDOM-WALK¹ was employed for this study. The flow portion of

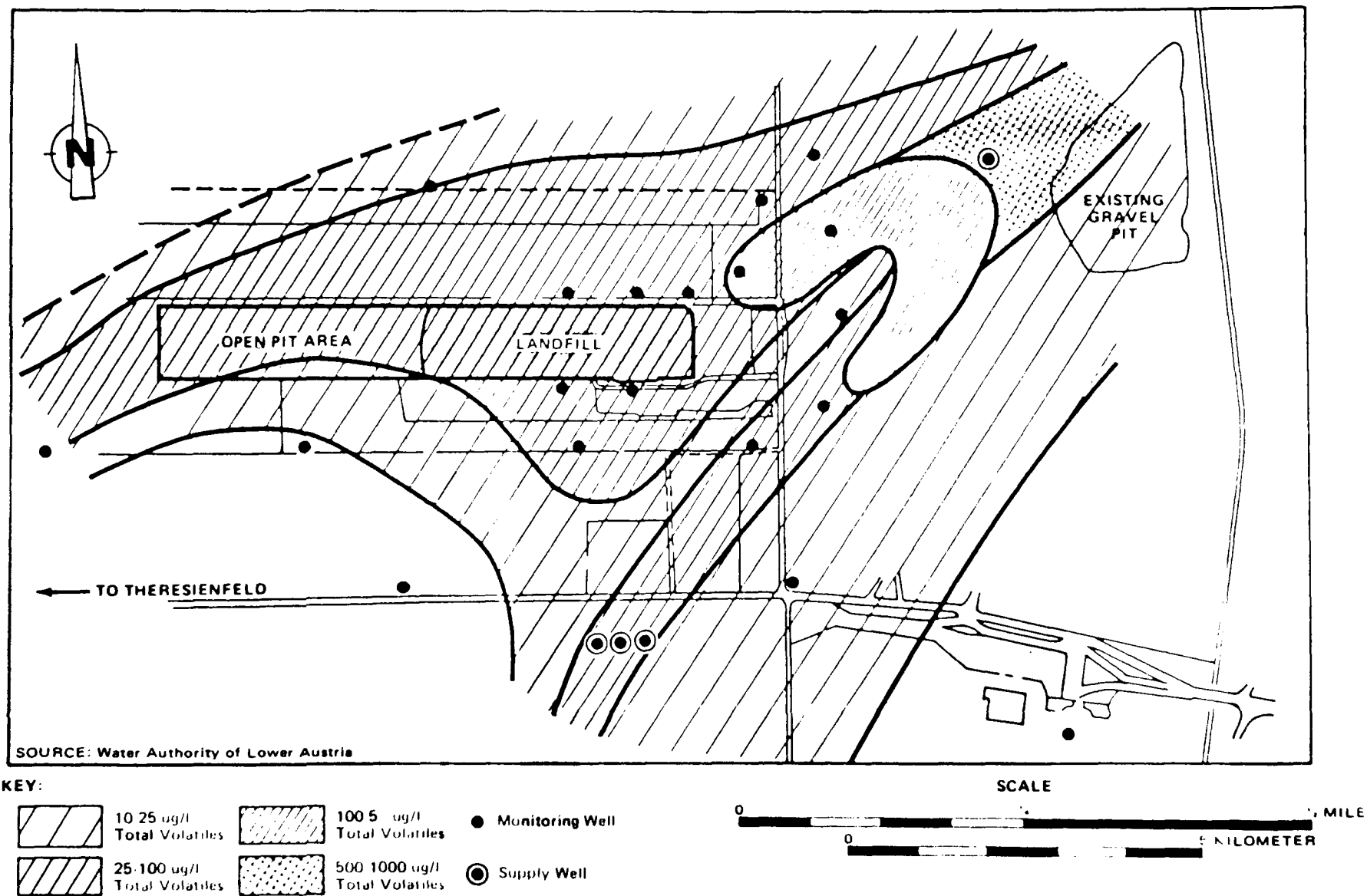


Figure 4
Contamination Extent (1982) at the Theresienfeld Landfill

this model is based on groundwater velocities actually measured in this basin aquifer.⁷ Expanded regional solutions for groundwater flow were obtained analytically in this model based on an average of these velocities.

Aquifer parameters were discretized by superimposing a finite difference grid over a map of the basin aquifer area. This grid covers a large area downgradient of the site with equidistant x and y axis lengths of 23 km by 46 km, respectively. This area was further divided into 100 distinct cells with dimensions of 2300 m by 4600 m (Fig. 4). Input parameters for this particular model include both flow and solute transport conditions. The final parameters used for this project are listed in Table 1. The following discussion explains how these final conditions were developed.

Table 1
Groundwater Model Input Parameters

	English	Metric
Aquifer thickness (saturated)	264 ft	80 m
Hydraulic conductivity	2,846 gpd/ft ²	1.34 x 10 ⁻³ m/sec
Porosity (dimensionless)	0.3	0.3
Regional flow velocity	19.7 ft/day	6 m/day
Transmissivity	747,000 gpd/ft	1.06 x 10 ⁻¹ m ² /sec
Storage coefficient (dimensionless)	0.2	0.2
Retardation (dimensionless)	10.0	10.0
Longitudinal dispersivity	60.0 ft	18.3 m
Transverse dispersivity	10.0 ft	3.05 m
Annual Mass Loading Rate	280,000 lb	27,170 kg

Flow Parameters

The parameters for the groundwater flow portion of the model consisted of transmissivity, hydraulic conductivity, storativity and flow velocity obtained from the available data base and personal interviews.

The flow field parameters were based on local research sources⁷ and showed that groundwater in this area commonly flows at 6 m/day in the general area of the basin. In this simplified modeling effort, only a single flow trend is used for mass transport conditions. Hydraulic conductivity (K) was obtained from average field measurements made during the November, 1985 geotechnical investigation of the empty west pit area. Transmissivity (T) was obtained by simply calculating the product of K and the estimated average saturated thickness of the aquifer (80 m). As expected, this groundwater system has a relatively large transmissivity. The storage coefficient was assumed at a value of 0.2, which is typical for an unconfined aquifer.⁴

Solute Transport Parameters

Parameters for the solute transport segment of the model were determined based on limited background information with regard to total chlorinated hydrocarbons as the primary leachate at the landfill. In the development of the solute transport parameters, a typical landfill leachate formation process has been assumed to occur. Under this assumption, once the leachate begins to form by precipitation recharge, it migrates slowly downward through the landfill where physical, chemical and biological forces act upon it. Eventually the leachate reaches saturated strata, where it moves as defined by the hydraulic flow velocities. From this point on, the leachate concentration will decrease due to several phenomena, including dilution, filtration, sorption, microbial degradation and dispersion. General input solute transport parameters to simulate the process described above in this modeling effort consist of contaminant mass flow rate, retardation and dispersion.

The leachate leakage rate was determined in a two-step process and based on the equation:

$$QC_o = \text{Leachate mass/year}$$

Where: Q = Source area X recharge rate

C_o = Initial concentration, (μg/l) of Leachate

In this equation, the source area and recharge rate were obtained from the available data as 35,000 m² and 716 mm/yr, respectively; thus, Q equals 68.7 m³/day. C_o has not been measured except for very high concentrations detected in samples collected from excavated drums. The drum concentrations, however, cannot be directly used because once the material leaks from the drums, mixing and dilution occur from recharge wastes. Therefore, the leachate concentration was first estimated based on the solubility of trichloroethylene and then adjusted to simulate concentrations that had been measured in the nearby wells. Hence, an annual input of 78,972 kg ⁷pounds⁸ was used as a mass contaminant loading rate into the model. This acontaminant loading, in turn, corresponds to an initial leachate concentration of approximately 3,146 mg/L in the landfill.

Retardation is used to represent the change in the solute concentrations of the groundwater caused by chemical reactions within the aquifer matrix. These reactions include absorption, organic fixation, chelation, etc. Chemical reactions between the dissolved components and the aquifer matrix have a tendency to retard contaminant movement relative to groundwater movement. The retardation value for this model was determined by using the following equation (Gabarini and Lion 1986):

$$R = \frac{V_o}{V_c} = 1 + \frac{P_b}{n_e} K_d \quad (2)$$

Where: R = Retardation (dimensionless)

V_o = Groundwater Velocity

V_c = Contaminant Velocity

P_b = Subsurface Bulk Density

n_e = Effective Porosity

K_d = % Organic Carbon (K_{oc})

K_{oc} = Soil/Substrate-Water Partition Coefficient for the Chemicals of Concern (chlorinated hydrocarbons) and Normalized to the Substrate's Organic Carbon Content

Dispersion of the leachate in the groundwater system essentially causes the contaminant concentrations to decrease with increasing distance of flow. It is caused by a combination of molecular diffusion and hydrodynamic mixing. Dispersion can be both longitudinal and transverse, the net result being a contaminant plume with a general conic configuration downgradient from the continuous pollution source. The contaminant concentrations are less at the margins of the cone and increase in the middle toward the source. For this modeling, dispersion is input as dispersivity, the difference being that the dispersion includes velocity.

The dispersivity parameters for this modeling evaluation were first obtained from literature values given for a groundwater system of a similar gravel aquifer in Loins, France¹ and then adjusted by model calibration using observed groundwater quality data from the landfill vicinity so that the modeled contaminant levels generally paralleled actual field measurements. As a result, the model output is most reliable near the source and progressively decreases in reliability with increasing distance away from the source.

Chronological Assumptions

The final step in setting up the model consisted of developing a reasonable chronological history of the site based on previous waste disposal practices at this location. Because of the large area covered in this modeling evaluation, contaminant loading was performed for both the continuous and discontinuous source simulations at a point where the landfill materials currently exist. In both cases, the modeling simulation began in 1972, which is the approximate date when disposal

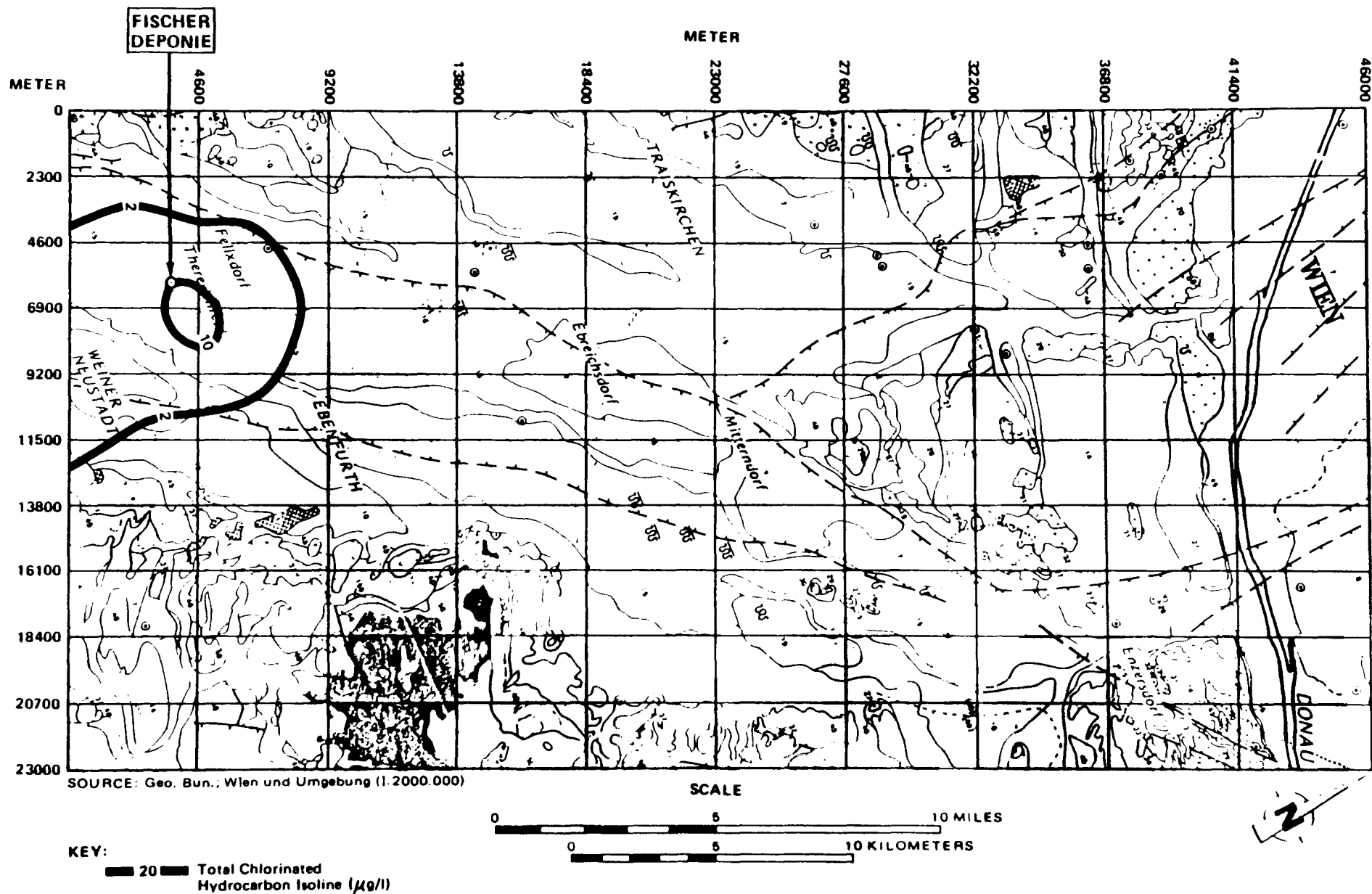


Figure 5
Modeled Contamination Plume — Year 1972
(Calibration Phase)

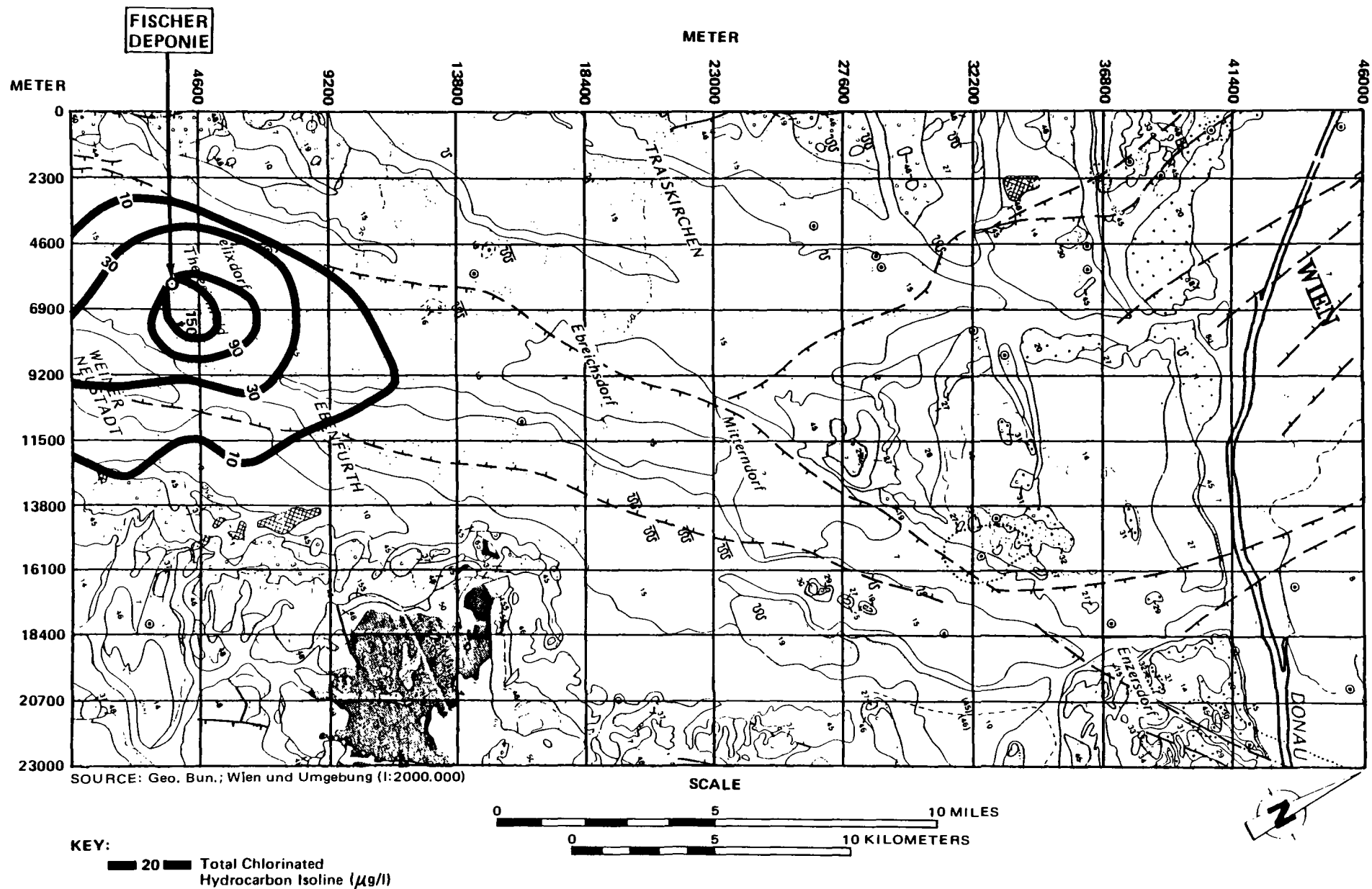


Figure 6
Modeled Contamination Plume — Year 1982 (Calibration Phase)

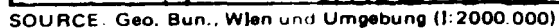


Figure 7
The Prediction Year 1990)

operations were initiated.

Sources of contamination were assumed as follows:

- Theresienfeld landfill as a "point source"
- Upstream sources as two "line sources"
 - One line source parallel to the groundwater flow to bring into the model in 1972 the already existing contamination.
 - One line source on the upstream boundary of the model, transverse to the groundwater flow, simulating the inflowing contaminated groundwater from upgradient sources.

It was assumed that the contamination from upgradient sources remain constant at an average of about 30 g/L which is the present situation. As previously discussed, in 1982 detailed groundwater quality measurements showed a contaminant plume extending beyond a nearby well (W-83) located hydraulically downgradient of the site. The horizontal longitudinal plume configuration is essentially parallel to the northwesterly groundwater flow direction, which is toward two recently installed Vienna production wells and the Danube River.

For the continuous source or no-action simulation, it was assumed that contaminant release would occur indefinitely and predicted to the year 2040, or 50 yr past 1990, which is the likely realistic point at which the source would be mitigated. In the second simulation, contaminant discharge was assumed to end in 1990 following implementation of source control measures and removal of waste materials.

SOLUTE TRANSPORT SIMULATION

The transport simulation was performed in two phases. First the simulation was calibrated to best parallel the limited data available. Next, following calibration of the model, two predictions were made to show what the horizontal plume extent effects are if: (1) the landfill situation is left in its present state and release of contaminants continues, or (2) the landfill materials are removed.

Calibration

Model calibration consisted of using the chronology and parameters previously discussed to best simulate the actual contaminant plume extent as it currently exists based on the known well data. As a result, several runs were performed starting with the initial 1972 period in order to achieve reasonable calibration. In each run of the model, input parameters consisting principally of contaminant particle mass, retardation and dispersion were altered in various combinations to a point at which the modeled contaminant plumes roughly resembled the current plume configuration. Figures 5 and 6 show the estimated total chlorinated hydrocarbon plume for 1972 and 1982, respectively. Figure 7 shows the predicted modeled plume for December, 1990, which has general dimensions of approximately 9.2 km long by 4.6 km wide, or a total approximate area of 42.3 km². These figures illustrate how the system was polluted over time and the associated contaminant spreading.

The variety of complex facts that control the movement of leachate and the overall behavior of the contaminant plume are difficult to assess accurately within the given data limitations in that the final effect represents several factors acting simultaneously. Therefore, the illustrations shown here, and the predictions of concentration and plume geometry that follow, are, at best, only to be used as relative estimates that provide an idea of potential aquifer restoration if the landfill source is removed.

Contaminant Movement Prediction: Landfill Source Continuous—(No Action)

The first prediction was based on the premise that the landfill would be left in its present state, i.e., no action and contaminant leaching continues. Figures 8 through 10 illustrate the modeled areal extent of the plume for the years 2000, 2020 and 2040, respectively. Essentially, these figures represent 10, 30 and 50 yr beyond the present time. Concentrations are shown in µg/L of total chlorinated organic contaminants.

As depicted in the figures, the model predicts that the plume evidently contaminates a wide and long strip of the aquifer. The predicted 50 yr contaminant plume extends approximately 19.5 km hydraulically downgradient of the landfill and attains a maximum width of approxi-

mately 10 km. Hence, a total approximate area of 195 km² of the aquifer will be contaminated at a concentration greater than 40 µg/L according to this simulation. Thus, from these results clearly show that as long as nothing is done to control the contaminant source, the resulting plume will grow larger and impact downgradient resources to a much greater extent. At the movement rate depicted by this simulation, the contaminant plume front theoretically could reach the Danube River area (about 40 km downgradient from the site) in 150 yr.

Contaminant Movement Prediction: Landfill Source Removed

A second prediction was made to show how the contamination will spread with time if the landfill materials are removed or contained so further leaching cannot occur. Figures 11 through 13 show the general modeled areal extent of the plume for the years 2000, 2020 and 2040, respectively. These figures represent time sequences 10, 30 and 50 yr following source control of the landfill. Concentrations are shown in mg/L of total chlorinated organic contaminants.

As shown in the illustrations, the model predicts that the plume will migrate as a large slug parallel to the predominant groundwater flow direction as expected. In addition, the 30- and 50-yr predictions show a slight transverse spreading due to advection and dispersion mechanisms as the plume migrates further. According to this prediction, the area immediately downgradient of the landfill will begin to be restored to natural conditions in 20 to 30 yr, provided that other upgradient sources, and any heavier-than-water contaminants that have possibly accumulated at the bottom of the aquifer below the landfill, do not exist.

It must be understood that this prediction does not account for what may occur vertically; the vertical plume spatial extent was not evaluated. Realistically, the effect of vertical relationships may be important because certain contaminants, such as trichloroethylene, may exist at high concentrations at low areas along the impermeable layer interface of the aquifer and thus act as additional sources. A verification of segregated concentration levels with depth is required to consider this condition further. The given prediction, however, provides a reasonable estimate for planning purposes. It also should be noted that the given predictions do not take into account additional increased pumpage effects associated with water demand from the City of Theresienfeld, the gravel pit operation or any other downgradient production wells as well as any impact from the nearby canal.

CONCLUSIONS

The Theresienfeld landfill represents Austria's first experience with hazardous waste site problems and the resulting effect on critical groundwater resources. In response to the growing concern of how this particular landfill has and will impact the Vienna Basin Aquifer of eastern Austria, a limited groundwater modeling study was implemented using the very flexible and dynamic Analytical RANDOM-WALK code⁶.

Although the area modeled was very large and the existing data base limited, through the use of this model, a qualitative prediction was performed to demonstrate on a general scale the overall impact to the aquifer under two separate scenarios: (1) with remediation of the contaminant source area and (2) without remediation of the source.

In essence, the two separately calculated scenarios show that by remediating the Theresienfeld landfill, i.e., total source removal, the groundwater quality of the Vienna Basin Aquifer will significantly improve. However, a contamination leachate slug that would still exist once the source is removed, together with other regional continuous contaminant sources upgradient of the landfill (located in Wiener Neustadt and Ternitz), would still adversely impact this aquifer, and contaminant levels will continue to exist in excess of Austrian drinking water standards unless these sources also are remediated. Hence, this limited RANDOM-WALK modeling study met an overall objective to provide the public with a general understanding of existing Theresienfeld landfill effects on the Vienna Basin Aquifer.

REFERENCES

1. Anderson, M.P., "Using Models to Simulate the Movement of Contaminants through Groundwater Flow Systems." *CRC Crit Rev. Environ. Cont.*, Vol. 9, 1979.

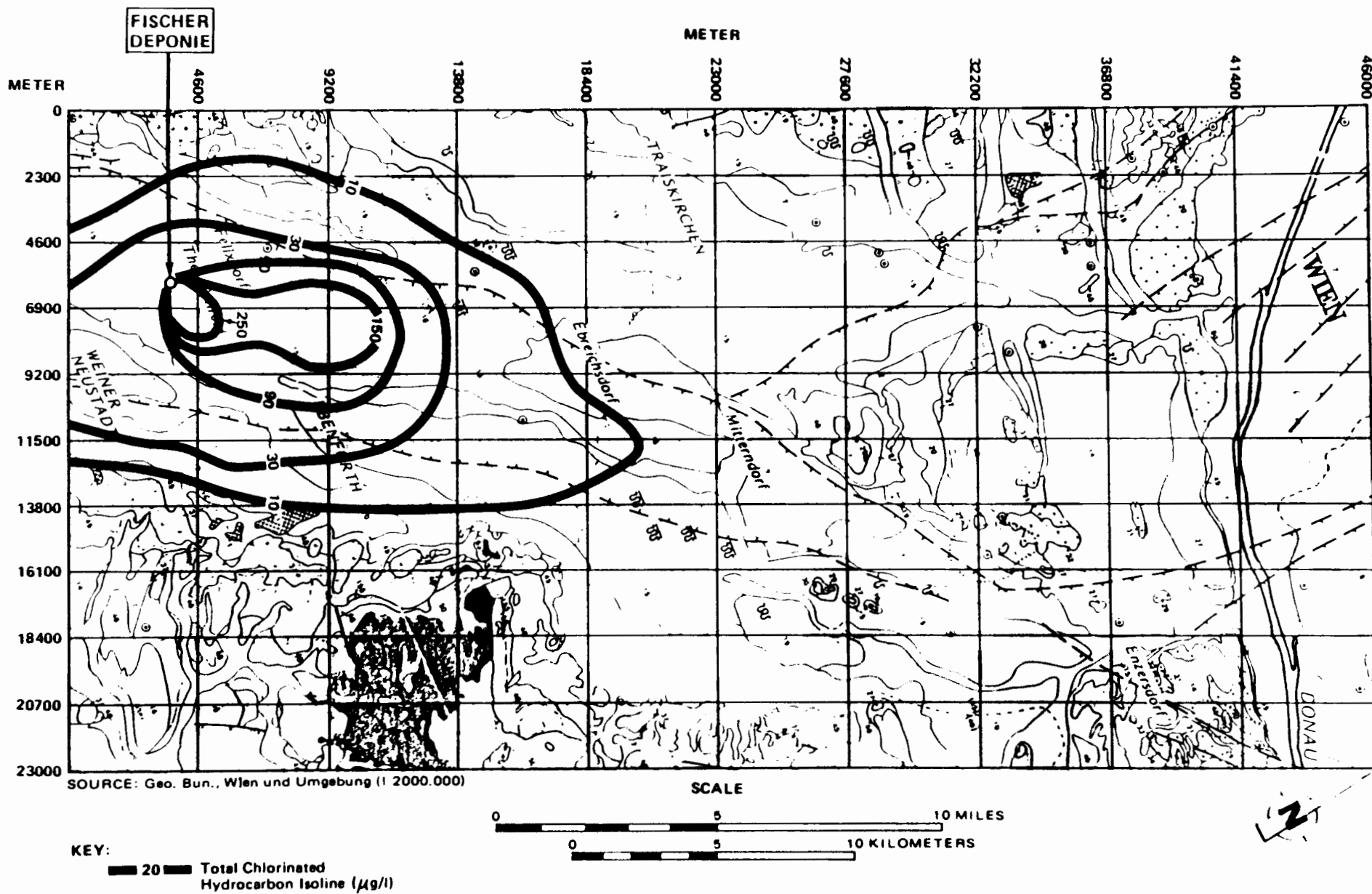


Figure 8
Contaminant Plume Prediction. Landfill Source Continuous
(No Action) -Year 2000

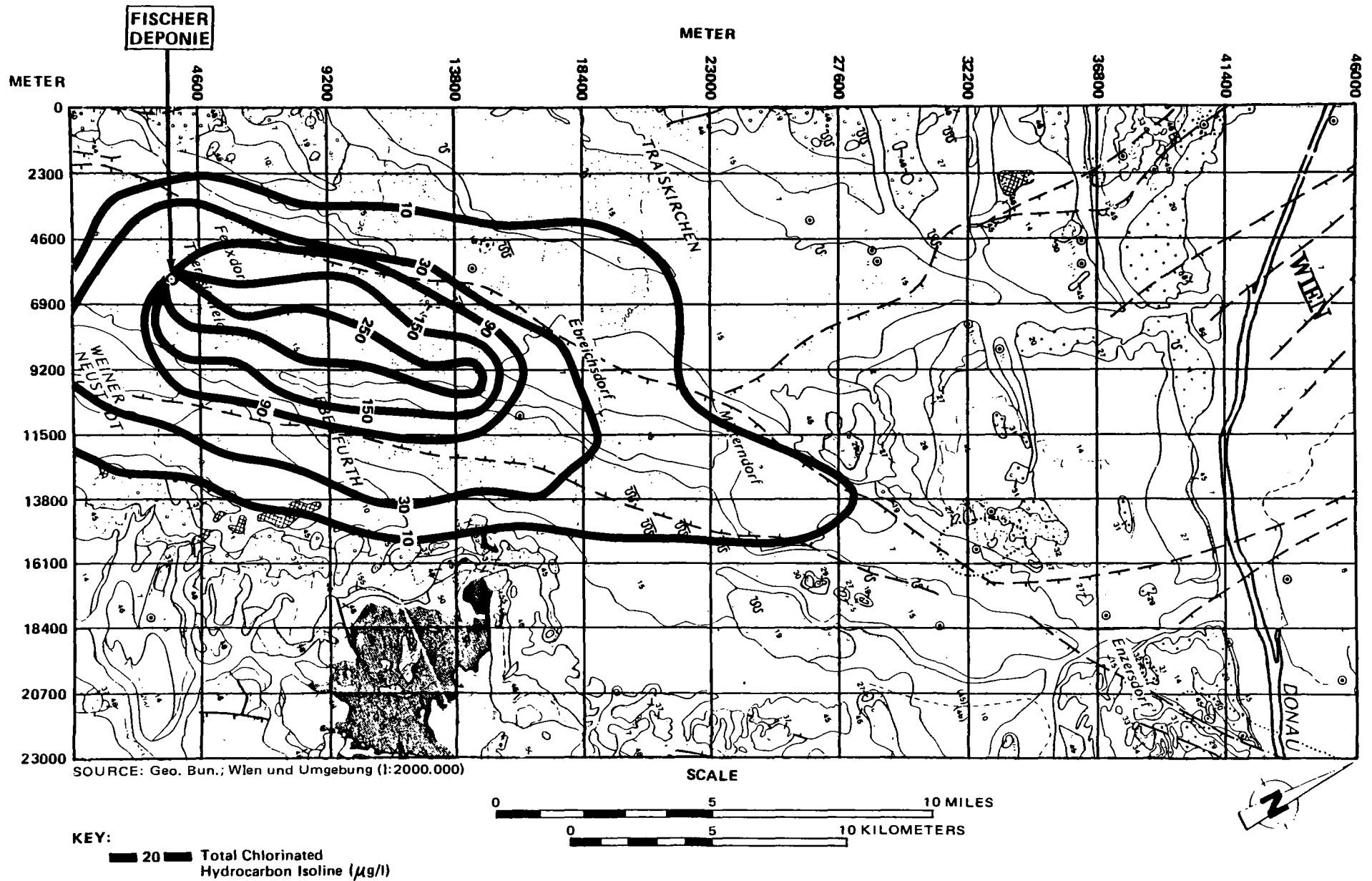


Figure 9
Contaminant Plume Prediction: Landfill Source Continuous—
No Action—Year 2020

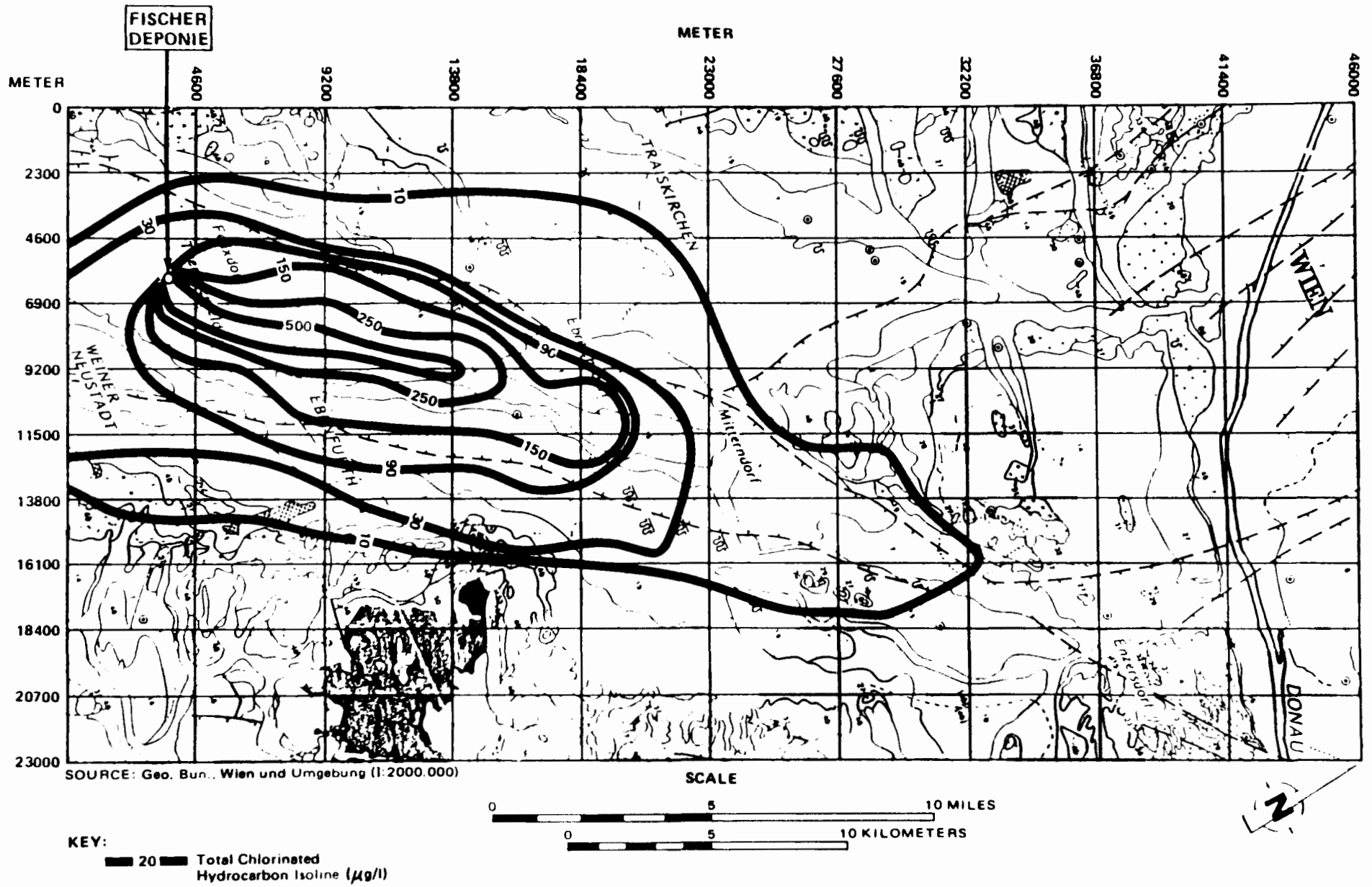
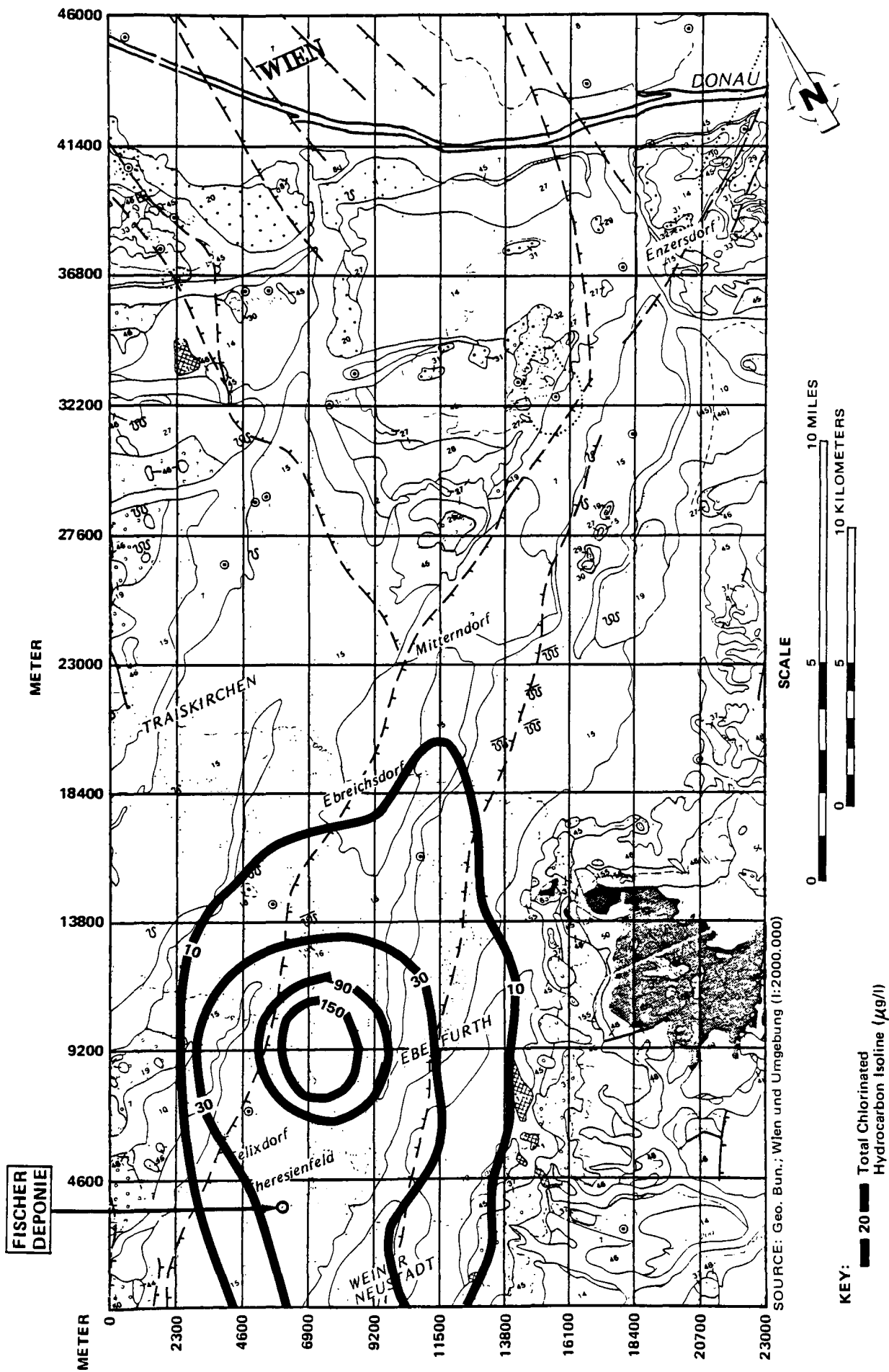


Figure 10
 Contaminant Plume Prediction Landfill Source Continuous—
 (No Action)—Year 2040



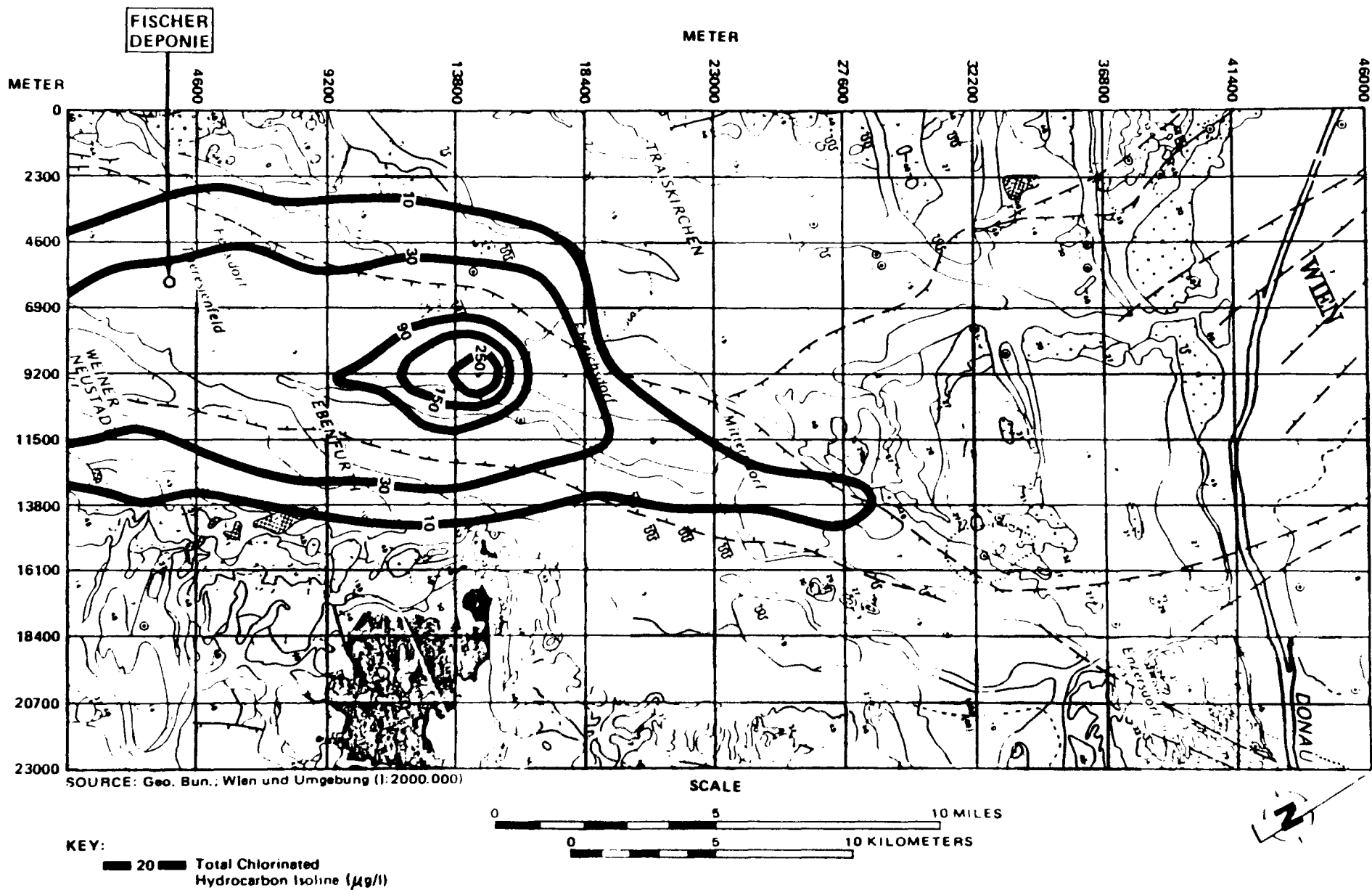


Figure 12
Contaminant Plume Prediction Landfill Source Removed Year 2020

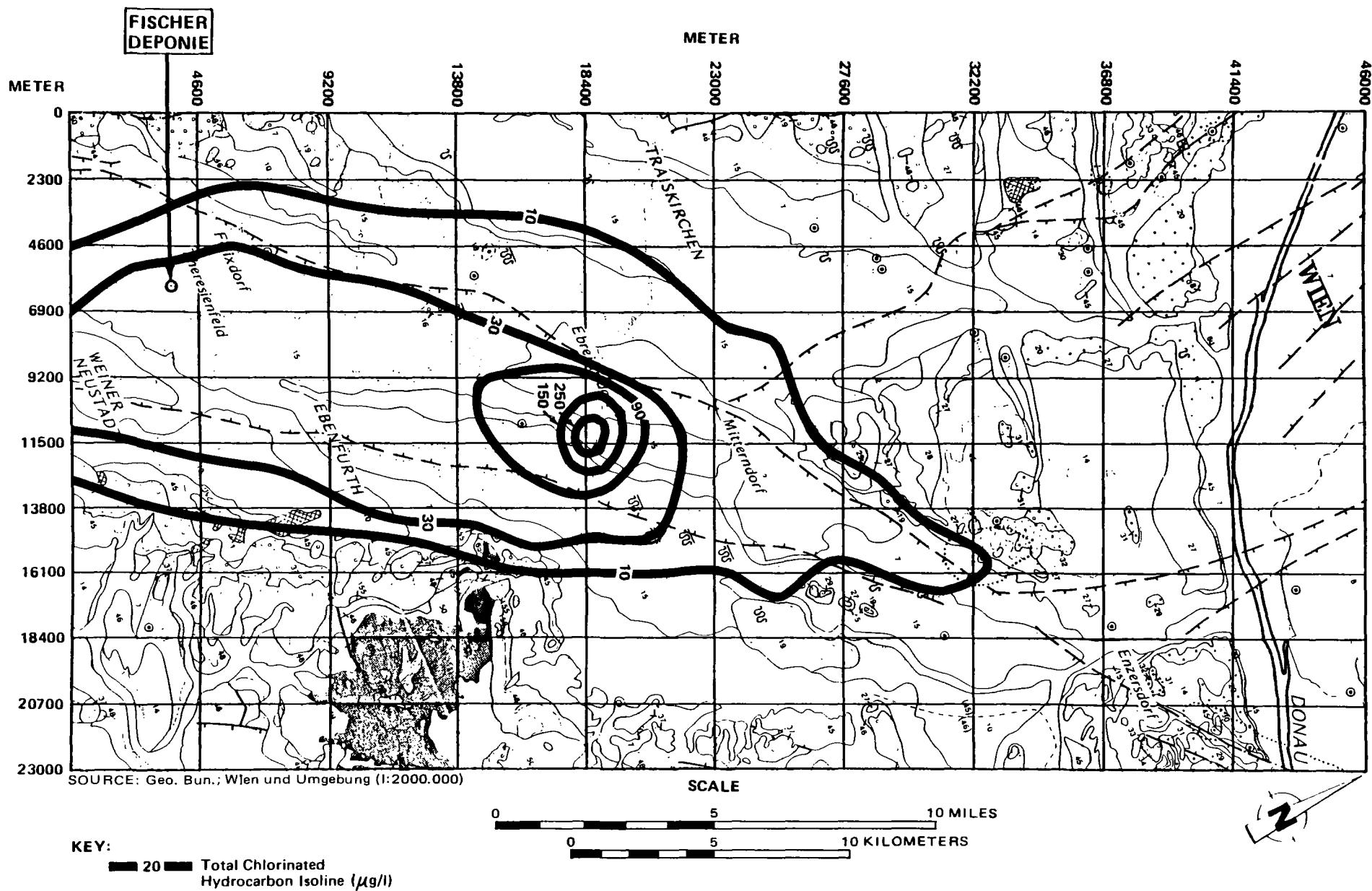


Figure 13
Contaminant Plume Prediction: Landfill Source Removed Year 2040

2. Berger, R., Unpublished Report of Groundwater Flow in the Vienna Basin, Vienna, Austria, 1983.
3. Brix, F. and Plocher, B., "Geologic Map of the Republic of Austria," 1:50,000; Plate 76 Wiener Neustadt, Geol. B. "A.", Vienna, 1982.
4. Freeze, R.A. and Cherry, J.A., *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979.
5. Gabarini, D.R. and Lion, L.W., "Influence of the Nature of Soil Organics on the Sorption of Toluene and Trichloroethylene." *Environ. Sci. Tech.*, 20, (12), 1986.
6. Prickett, T.A., Naymik, T.G. and Lanquist, C.G., A "RANDOM-WALK" Solute Transport Model for Selected Groundwater Quality Evaluations, Bulletin 654, Illinois State Water Survey, Champaign, IL, 1981.
7. Reitering, Personal Communication from Professor Reitering, University of Vienna, to Richard Rudy, Ecology and Environment, Inc, 1987.
8. Tollman, A., *Geology of Austria*, Volumes 1-3, Vienna, Austria, 1977, 1985, 1986.

Economic Analysis of Public and Private Management of Remedial Actions

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ABSTRACT

From 1983 to 1989, the two Superfund Projects analyzed in this paper proceeded from preliminary investigations to construction. One project was managed by a state agency (public), the other by PRPs (private). The U.S. EPA provided varying degrees of oversight for both projects. This paper discusses the magnitude and distribution of costs for the two projects and compares the project management performance.

Overall, private management controlled construction costs much better than public management, with bid prices for the Private Project being \$125,000/ac of clay cap, compared to \$512,000/ac of clay cap for the Public Project. However, the Private Project had significantly higher administrative and engineering costs due to the central role the U.S. EPA and its oversight contractors played in the remedial process. The redundant management style imposed on the private project added \$1,425,000 to the design phase and will add up to \$1,800,000 to the construction phase.

The U.S. EPA should reduce its oversight of privately funded remediation projects to a compliance review role. A reduced role would improve the design phase, the cost-effectiveness of projects and the rate at which remedial construction is completed.

INTRODUCTION

Private management, with the qualities necessary to succeed in the competitive marketplace, has the potential to outperform public management of remedial actions. Public agencies are organized and staffed to regulate, not construct, while private parties (industrial corporations) routinely design, bid and construct complex facilities. The most important quality necessary to manage projects is flexibility, the ability to develop an approach which continually adjusts to the specific needs of a project. When Public Agencies are placed in the unfamiliar role of project management, they are required to apply inflexible procedural requirements to all projects instead of developing an individual approach for each project.

This paper compares performance of public and private management by comparing two Superfund remediation project costs. Underlying reasons for differences in performance are examined for the two projects. The comparison is divided into three phases: (1) design, (2) bidding and (3) construction. The general characteristics of the projects are discussed first as background for the comparisons that follow.

GENERAL CHARACTERISTICS OF THE PROJECTS

Differences in the size, nature and location must be described before comparing the engineering and construction activities of different projects. For these projects there are a number of similar components in the remedial design which can be directly compared; however, the private site is remote and weather conditions frequently delay construction work.

Both projects proceeded in a similar path from preliminary investigations to construction over the time period 1983 to 1989. The Public Project has a clay/membrane cap which covers approximately 11 ac, while the Private Project's clay/membrane cap covers 41 ac. Both projects have slurry walls constructed using the excavated soil mixed with slurry for backfill. The maximum depths of both walls are 40 ft and the total square footage of the walls are similar: 100,000 ft² for the Public Project and 150,000 ft² for the Private Project (not all of the Private Project was contained by slurry walls).

The Public Project is in a major metropolitan area and is readily accessible to the labor, materials and utilities necessary for construction. The Private Project is remote, the daily commute to the site is approximately 40 mi and the site is not served by public telephone, water or sewer lines.

Annual rainfall at the Public Project site is 42 in compared to 62 in at the Private Project site. The Public Project is occasionally delayed by rainfall but site drainage is good. Construction schedules are strongly affected by weather at the Private Project site with flooding and rainfall frequently causing extended delays in the work. Contractors, in determining the cost of the work, considered weather an insignificant factor for the Public Project and a significant factor for the Private Project.

COMPARISON OF DESIGN PHASES

The design phase includes all of the work from preliminary site investigations to final agency approval of the construction documents. The RI/FS, consent decree, construction plans, specifications, worker health and safety plan, construction quality assurance plan, operation and maintenance plan, quality assurance project plan and all other reports, studies and contract documents necessary to proceed with bidding and contracting for the work are included in this phase. The magnitude and distribution of design phase costs for the Projects are compared in Table 1. It is evident that the Private Project has many more types of expenditures than the Public Project. These additional expenditures include negotiations with the agencies, monitoring U.S. EPA site activities, U.S. EPA oversight, legal and administrative costs.

Negotiations with the agencies include the engineering and legal work necessary to develop the comprehensive and detailed agreements between the U.S. EPA and the private parties for remediation. Negotiation of this agreement, the Consent Decree, added \$340,000 to the cost of the Private Project. There is not a directly comparable cost for the Public Project as potential responsible parties did not enter into a Consent Decree with the U.S. EPA.

Within the Private Project there is a broad area of duplicate effort which includes monitoring, oversight and preparation and review of duplicate reports. For example, both the U.S. EPA and the private parties produced RIs and FSs because U.S. EPA's early policies regarding Con-

sent Decree terms were not acceptable to the PRPs. Duplicate effort is an apparent significant burden on the Private Project, representing an additional cost of \$1,425,000. However, in the case of this site, it definitely reduced overall project costs because it prevented U.S. EPA from unilaterally selecting an overly conservative and more costly remedy. This duplicate effort is in part a result of the organizational set-up illustrated in Figure 1 in which the U.S. EPA and its Consultants play a poorly defined parallel management role from beginning to end of the project. The problems associated with this organizational setup are aggravated by the high turnover rate in the U.S. EPA and its oversight consultants. The U.S. EPA project manager and oversight contractor changed three times during the Design Phase of the Private Project.

Table 1
Design Phase Costs

	Public Site	Private Site
PRELIMINARY		
Remedial Investigation	\$670,000	\$270,000
Monitoring EPA	0	67,000
Feasibility Study	230,000	104,000
Past Agency Response Costs	0	800,000
EPA RI/FS Critique	0	43,000
Consent Decree Negotiations	0	340,000
	<u>\$900,000</u>	<u>\$1,624,000</u>
DESIGN		
Geotechnical Investigations	0	400,000
Remedial Design	250,000	380,000
Oversight Review Response	0	200,000
EPA's Oversight	0	70,000
EPA's Oversight Contractors	0	240,000
State's Oversight	0	5,000
	<u>\$250,000</u>	<u>\$1,295,000</u>
ADMINISTRATION		
Legal	0	400,000
Accounting	0	30,000
	<u>0</u>	<u>430,000</u>
TOTAL	\$1,150,000	\$3,349,000

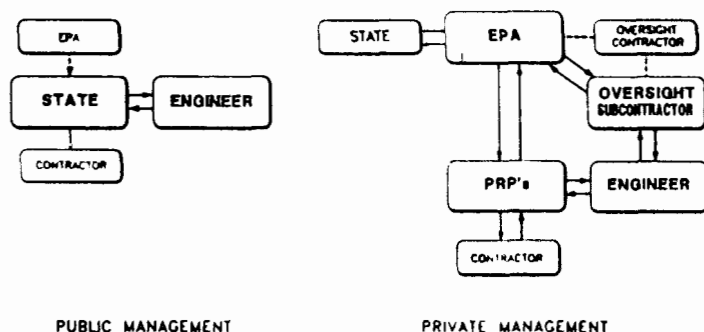


Figure 1

The parallel management role the U.S. EPA and their consultants played in the Private Project Design Phase can best be described by recounting the review and approval process for the plans and specifications. During this 12-mo process, there were a total of 251 review comments on the specifications and related documents and over 100 review comments on the plans. Responses to many of the comments required an extensive effort because of the broad nature of the questions and the many issues they raised.

The scope of the comments ranged from minute details to requests for far reaching revisions to the basic design which was carefully specified in the Consent Decree Statement of Work. A request to specify the tightening torque for certain fittings is an example of a minute detail request. A request to increase the thickness and slope of the clay cap

is an example of a comment which would have involved a major revision to the Consent Decree Design. The process was not a traditional regulatory review of compliance with defined design criteria. In effect, a parallel management team had been established by U.S. EPA which directed the design process away from the Consent Decree Design. It became private management's job to supply the parallel U.S. EPA management team with background and information necessary to bring the process back on the Consent Decree course after each review cycle. In this arrangement, private management had to devote its resources and talents to review response rather than design initiatives and refinement.

The central role assumed by the U.S. EPA and its oversight contractor during the design phase was not well defined or productive. Despite the hundreds of review comments submitted during the Private Site design phase, there were no significant changes in either the concept or details of the remedial design. Lengthy responses were drafted, discussed and submitted. For example, it took a considerable effort to convince the U.S. EPA and its consultants that SARA Title III did not apply, that federal, state and local permits were not necessary and that continuous temperature monitoring of the workers was unreasonable. There were extensive submittals accompanied by theoretical calculations concerning the mechanical stability of the geofabric, potential effects of lateral deformation of soft clays on the slurry wall and the moisture density ranges for the clay cap even though the geofabric, the slurry wall and the clay cap were routine applications, specified in a standard manner. Editorial comments and small changes which did not increase construction costs or unduly complicate the specifications were commonly adopted simply to advance the review process. In focusing the attention and resources of the private management team on the review process, opportunities in improving and refining the design concepts were certainly lost. These lost opportunities, the cost of the review and delays in the project were all the result of imposing a parallel management structure without clear objectives on the Private Project.

The Public Project design phase process took 6-mo as compared to 12-mo for the Private Project. The Engineer's efforts during the Public Project design were devoted to design instead of response to review comments. Review comments were limited and directed at correcting inconsistencies or omissions in the plans and specifications. The U.S. EPA played the traditional role of a regulatory agency: it reviewed the results of the design process rather than becoming part of it. The benefits of this brief review process are obvious in the schedule and costs of the Public Project design phase.

Legal and accounting costs for the Private Project were \$430,000. There is no comparable expenditure for the Public Project. These costs result from the continual threat of U.S. EPA taking control of the project and completing the project with Superfund monies and the need to develop written agreements among the many parties involved in the Private Project and to administer those agreements. The legal and accounting services include: researching the records; developing cost sharing agreements; pursuing non-responsive PRPs; and creating and supporting the steering committee in implementing the remedy.

Performance factors can be calculated and compared for the Public and Private RIs and FSs. The primary objective of the RI is to define the location and concentration of the hazardous wastes on the site through sampling and analysis activities. The costs of the sampling and analysis activities should be a high percentage of the total cost of the RI. The percentage of sampling and analysis costs to the total RI cost was 17% for the Public Project and 41% for the Private Project, indicating that the Private Project performed significantly better than the Public Project.

Accurate construction cost estimates for alternate remedies are an important part of the FS. The unit prices used in the Public Project FS were generally lower than the bid prices. The unit prices used in the Private Project FS were generally higher than the bid prices.

Neither FS accurately estimated the construction cost of the projects. FSs are an example of a rigid procedure developed by the U.S. EPA which does not serve a useful project management function, but is applied by regulation to all projects.

COMPARISON OF BIDDING PHASES

The Bidding Phase consists of preparing bid documents, bidding the project and awarding the construction contract(s). Table 2 compares the bid prices for the Public and Private Projects. The Public Project has very high mobilization costs compared to the Private Project. The high mobilization costs for the Public Project are the result of the Contractor's perception that initiating a job with a government agency is expensive and the specific mobilization requirements specified are more extensive than those for the Private Project. Table 2 indicates that the public management team selected off-site disposal as part of the remediation which represents a large portion of the construction bid. Excluding off-site disposal, the Public Project construction bid prices were \$512,000/ac of clay cap compared to \$125,000/ac of clay cap for the Private Project. Table 3 compares the unit costs for construction common to both projects. With the exception of sand, the unit costs are much higher for the Public Project than for the Private Project. The higher sand costs for the Private Project are associated with the remoteness of the site.

Table 2
Bidding Phase Results

	<u>Bid Amounts</u>	
	<u>Public Site</u>	<u>Private Site</u>
<u>Construction Costs</u>	\$4,590,000	\$5,140,000
<u>Non-Construction Costs</u>		
Bonds	117,000	0
Mobilization/Demobilization	730,000	145,000
Sampling/Analysis	210,000	0
Administrative Delay	27,000/day	0
<u>Transportation/Disposal</u>	<u>10,500,000</u>	<u>0</u>
TOTAL	\$16,130,000	\$5,285,000
<u>Estimated Construction Phase Engineering Costs</u>		
Oversight	500,000	800,000
Sampling/Analysis	0	200,000
EPA Oversight	<u>Unknown</u>	<u>1,800,000</u>
TOTAL	\$500,000+	\$2,800,000
GRAND TOTAL	\$16,630,000+	\$8,085,000

Table 3
Unit Cost Comparison

	<u>Public Site</u>	<u>Private Site</u>
Clay (\$/cu.yd.)	8.00	5.00
60 mil HDPE (\$/sq.ft.)	0.50	0.35
Sand (\$/cu.yd.)	15.00	16.85
Topsoil (\$/cu.yd.)	18.00	2.50
Slurry wall (\$/sq.ft.)	3.70	1.50
Seeding (\$/sq.yd.)	0.65	0.25
Clearing (\$/acre)	4,500.00	1,300.00

Bid prices depend on the Contractor's perception of the project and the prices suppliers quote for the materials of construction. The Contractor's perception includes how he perceives his competition, clarity of the contract documents, the unit pricing structure, contract imposed project overhead costs, contingencies and the working relationship with the Owner. Material prices depend on how well the specifications foster competition between suppliers.

Successful bidding requires the management team to do much more

than prepare plans and specifications and put them out to bid. They must develop a bidding strategy and actively address concerns and options raised by contractors and suppliers during the bidding process. The bidding strategy must develop a unit pricing structure which isolates contingencies but comes as close as possible to a single lump sum, hard money contract. Where unit prices are used, there must be an accurate method of selecting the quantity to bid and measuring quantities constructed. This may require a predesign site investigation more detailed and directed toward the selected remedy than that accomplished during the RI. An investment in such a predesign data gathering step usually will return its cost several times over in lower construction costs. The Bidders should believe that a good working relationship will be established with the Owner. The management team must develop this belief through the manner in which the pre-bid conference and other communications with the bidders are conducted.

The cost differences summarized in Tables 2 and 3 are the result of specific differences in the bid documents and different bidding strategies.

The Public Project required performance and payment bonds in the amount of the contract price. These bonds added \$117,000 to the cost of the Public Project. The purpose of the bonds is to provide security that, in the event the contractor fails, the work will be completed by the bonding company at the prices bid and subcontractors will be paid so that liens are not placed on the property.

Public agencies typically require bonds on construction projects, but the costs often exceed the benefits. If there are many competitive bids for a project, it is easy to find a replacement for a failed contractor and the procedure for replacing a contractor is simpler if a bonding company is not involved. With proper construction management, the contractor always has completed more work than he has been paid for at any given time in the contract, and it is not difficult to verify that subcontractors are being paid. Bonds are expensive insurance for problems that can be handled effectively through the contractor selection process and construction management.

The bid strategy for the Public Project resulted in 40, mainly unit quantity, bid items. The bid strategy for the Private Project resulted in 12 bid items, half of which were unit quantities. The success of the Public Project bid strategy depended on accurately estimating bid quantities and completely defining the work with a large number of specific bid items. The difficulty in accurately estimating quantities, especially for hazardous waste work and without detailed site investigations directed specifically toward the selected remedy unit quantities, leaves the Public Project open to change orders and scope of work disputes.

The Private Project combined 85% of the work into two lump sums. Unit pricing was used to isolate contingencies and allow adjustment of certain field controlled activities where there was a potential for considerable savings if properly managed and small downside risks. The structure of the Public Project's unit pricing allowed payment of \$700,000 for quality control, health and safety and mobilization before the start of construction. Comparable costs for the Private Project were \$120,000, and this amount was paid after the start of construction.

The Public Project left contingencies in some bid items. For example, there was only one unit price used to bid the slurry wall, but the specifications defined several actions the contractor would have to take if affected materials were encountered. The contractor had no choice but to assume the worst and include the contingency costs in the one bid item. This contingency is one explanation for the higher slurry wall unit cost for the Public Project as shown in Table 3.

The Public Project placed the primary responsibility for QA/QC on the Contractor. This requirement distorts the engineering costs for the Public Project by making the QA/QC costs part of the construction costs and, more importantly, this does not provide independent construction quality assurance as required by U.S. EPA guidance documents. The construction quality assurance personnel and organization were independent of the Contractor in the Private Project, providing clear definition of engineering and construction costs and the separation necessary between the Contractor and QA/QC work.

The Public Project bid documents have many standard requirements absent in the Private Project. These additional requirements include pollution liability insurance, a procedure to obtain indemnification which

includes lengthy documentation, MBE/WBE requirements, Davis-Bacon labor and wage requirements, federal audit, procurement and record-keeping procedures and the requirement for preparation and submission by the contractor of several technical plans for quality control, health and safety and spill control. Private management can be flexible in developing contract documents including only the requirements necessary for particular projects and insurance and indemnification necessary for potential risks. Private management also has the ability to pre-qualify contractors and sub-contractors which can be used to improve the bidding and contractor selection process.

Public management's rigid procedures and standard requirements discourage all but a limited group of large national contractors who specialize in bidding U.S. EPA-funded remedial work. This limits competition and will drive bid prices up rapidly if the U.S. EPA increases the rate at which projects are put out to bid. Private management has the flexibility to limit bidding requirements and the ability to solicit bids from local contractors. This flexibility creates a competitive bidding environment, results in low unit prices for the work and the selection of a prequalified contractor familiar with local working conditions.

COMPARISON OF CONSTRUCTION PHASES

The construction phase starts with the contractor mobilizing onto the site and ends with completion of the work. It includes all of the construction work necessary to complete the remedial action and the engineering oversight required to assure compliance with the plans and specifications. One means of measuring performance during the construction phase is the comparison of estimated quantities, bid prices and projected oversight costs to the actual quantities, prices and costs. The number and extent of change orders are also an indicator of performance. Numerous or extensive change orders which increase the contract time or price indicate problems in the bid documents and/or project management.

As of June, 1989, the Public Project had been under construction for 14 mo and the Private Project for 7 mo. While the projects are not complete, there is sufficient information to measure the Public and Private management performance through June, 1989 and discuss the trends established.

Mobilization and site clearing were the only work items completed during the first 14 mo of construction for the Public Project. Even with the small amount of construction work completed, the effect of delays, inaccurate quantity estimates and change orders on the project costs have been established. Oversight, stormwater disposal and administrative costs have continued to increase during the delays. Engineering oversight and stormwater disposal costs have increased \$1,000,000 from the bid amounts. Administrative delays claimed by the contractor during the first 14 mo will add \$1,500,000 to the Public Project. The site clearing quantity, the only construction item completed during the first 14 mo, was three times the bid quantity, increasing the cost for this item from \$50,000 to \$150,000. Twelve change orders were issued for the Public Project in the first 14 mo of construction, increasing the Contract Price by approximately \$200,000.

All of the site clearing work, drainage facilities and slurry walls construction, and 60% of the geofabric, porewater drain system and cap fill were completed during the first 7 mo of construction at the Private Project. There have been no increases in the contract price due to delays, quantity estimates or change orders. The project should be completed substantially ahead of schedule and engineering oversight costs should be at least \$300,000 less than the originally estimated amount.

Construction phase results are shown in Figure 2 for the Public Project. The shaded area illustrates the effect of having several contract cost items adjusted by delays; the construction costs continue to increase while the percentage of construction completed remains unchanged. Figure 2 presents the same information for the Private Project, illustrating that the project is on schedule and should be completed for the bid price. Tables 4 and 5 compare the costs as they are projected in the construction phase to the bid amounts for two projects.

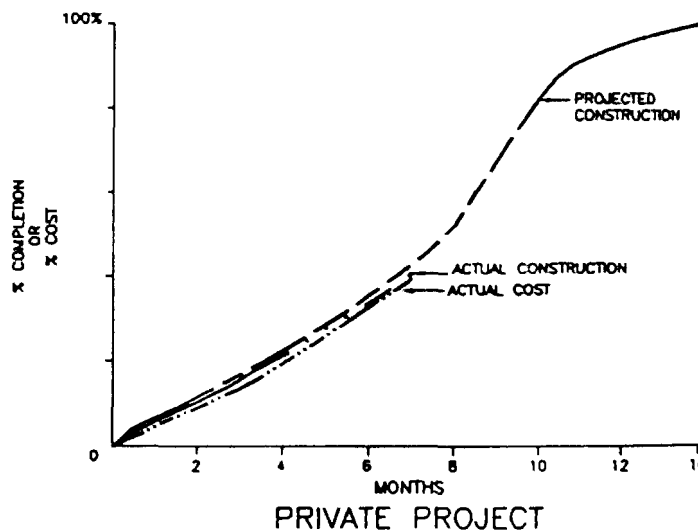
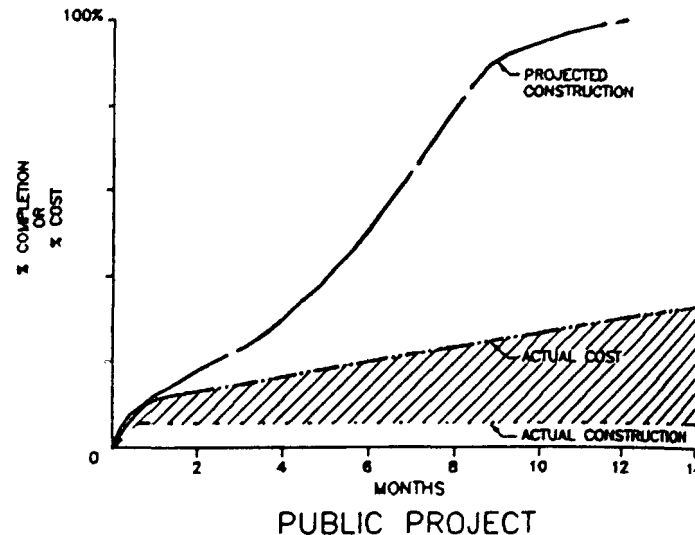


Figure 2
Construction Phase Results

CONCLUSION

The results of the Contracting and Construction phases demonstrate the ability of Private Management to outperform Public Management in Superfund remediation projects. The Private Project is on schedule and there have been no increases in the contract price during construction. The Public Project has experienced extensive delays, the contract price has, in the initial phase of construction, already increased by 15% and the per-acre bid prices were four times greater than those for the Private Project.

The design phase demonstrates a problem with the U.S. EPA's approach to oversight of private projects. The Private Project's construction costs only account for 50% of the total project cost. Construction costs, especially for projects of this size, should account for at least 75% of the total project cost. The redundant management style imposed on the Private Project by the U.S. EPA's oversight role and standard procedures are the primary reason for the imbalance between

construction and non-construction costs. The U.S. EPA does not take an active central role in publicly funded remedial actions and should not in privately funded actions. They are not staffed to do it and it does not improve the site remediation process.

The U.S. EPA should regulate privately funded remediation in the

same manner they regulate industrial wastewater discharges. They should issue clear standards and actively enforce those standards. If this were done, the abilities of private management would be free to achieve the U.S. EPA's goal of remediating Superfund Sites in a fast, cost-effective manner.

Table 4
Public Project Construction Phase Results

	<u>Bid</u>	<u>Projected Total After 14 Mo. of Construction</u>
<u>Construction Costs</u>	\$4,590,000	\$ 5,590,000
<u>Non-Construction Costs</u>		
Bonds	117,000	117,000
Mobilization/Demobilization	730,000	730,000
Quality Assurance	210,000	210,000
Administrative Delay	27,000/day	1,500,000
<u>Transportation/Disposal</u>	<u>10,500,000</u>	<u>10,500,000</u>
TOTAL	\$16,147,000	\$18,647,000
<u>Estimated Construction Phase Engineering Costs</u>		
oversight	500,000	800,000
Sampling and Analysis	0	0
EPA Oversight	<u>Unknown</u>	<u>0</u>
TOTAL	\$500,000	\$ 800,000
GRAND TOTAL	\$16,647,000	\$19,447,000

Table 5
Private Project Construction Phase Results

	<u>Bid</u>	<u>After 7 Mo. of Construction</u>
<u>Construction Costs</u>	\$5,140,000	\$ 5,140,000
<u>Non-Construction Costs</u>		
Bonds	0	0
Mobilization/Demobilization	145,000	145,000
Quality Assurance	0	0
Administrative Delay	0	0
<u>Transportation/Disposal</u>	<u>0</u>	<u>0</u>
TOTAL	\$5,285,000	\$5,285,000
<u>Estimated Construction Phase Engineering Costs</u>		
Oversight	800,000	600,000
Sampling and Analysis	200,000	100,000
EPA Oversight	<u>1,800,000</u>	<u>500,000</u>
TOTAL	\$2,800,000	\$ 1,200,000
GRAND TOTAL	\$8,085,000	\$ 6,485,000

Use of the New OWPE CERCLA Cleanup Cost Data Base System For Calculating Settlement Premium Payments, Evaluating Cleanup Costs and Reviewing Remedial Technologies

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ABSTRACT

The U.S. EPA Office of Waste Programs Enforcement (OWPE) has developed a data base to provide a basis for estimating response action costs at CERCLA sites for settlement purposes. OWPE may use these estimates in the CERCLA settlement process to add a "premium" to response action cost estimates. The premium payment is an additional amount included in the settlement to account for the possibility of cost overruns or additional, unforeseen response actions. This data base is important to OWPE, the U.S. EPA Region, and the states because it represents the first empirically based source of data and methodology to calculate premium payments.

The estimates the data base provides are unique because they are derived from information on both the estimated cost that usually is developed at the ROD stage and the actual remedial cost that has accrued over time. The difference between the ROD estimate and the actual costs for a given technology can serve as a basis for the premium payment.

The data base currently contains more than 350 records. Each record represents an NPL site for which a ROD has been signed. Records contain general background information on the site, the type of remedy being implemented, the type of contaminants at the site and the contaminated media, the cost estimate for the remedy as set forth in the ROD and the actual costs that have accrued over time. The actual costs were generated from CERCLIS reports that show the outlays and obligations for each NPL site.

The data base has additional uses besides calculating premium payments and cost estimates. It can be used to quickly gather figures on the number of sites using a particular remedy or the number of sites with a particular type of contamination.

THE CERCLA CLEANUP COST DATA BASE SYSTEM (CCCDS)

The CCCDS combines cost, location and technical information from the U.S. EPA RODs and the Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS) to assist the U.S. EPA in the Superfund settlement process and other Superfund activities. To date, the U.S. EPA has entered data from more than 350 RODs and corresponding CERCLIS data fields into CCCDS.

The data from the RODs include both general identification and location information (such as the ROD identification number, site name, ROD publication date, state and region) and more detailed technology, contaminant and cost information. The data from CERCLIS provides location and identification information (such as operable unit number, U.S. EPA identification number, address, remedial project manager name and telephone number) as well as cost information on remedial design and remedial action obligations and outlays for each operable unit.

CCCDS combines the ROD and CERCLIS information to produce 35 different data elements (listed and described in Table 1) for each record in the data base. Each record represents an individual Superfund site operable unit that has a signed ROD. CCCDS has been designed to generate reports or provide various analyses.

After the ROD information was included in the CCCDS, the remaining data fields were completed with CERCLIS information. The CERCLIS information was generated by two ad-hoc CERCLIS reports that showed the site location information and the obligation and outlay data for each site that had a signed ROD.

As the data base currently exists, the CERCLIS cost information is a one-time, "snapshot" view of the actual costs. The cost information is updated quarterly in CERCLIS as it accrues for each site, but was entered only once into CCCDS. Updates of CCCDS will link the quarterly CERCLIS updates directly into CCCDS.

USING CCCDS TO CALCULATE SUPERFUND SETTLEMENT PREMIUM PAYMENTS

A primary purpose of CCCDS is to provide an empirical basis for calculating settlement premium payments using historical Superfund site data. The U.S. EPA's Superfund settlement policy¹ allows the Agency under certain circumstances to offer responsible parties at Superfund sites a limited release from liability in exchange for reimbursement of response costs that may include a "premium" payment to cover the risk of cost overruns or the need for additional response actions. Additionally, as the Superfund program evolves, the use of historical data becomes more and more viable as an analytical aid.

Background

Section 107 of CERCLA, as amended by SARA, holds responsible parties liable for cleaning up a hazardous waste site — whether as current or past owners, or as operators, transporters or generators of hazardous substances. Through CERCLA, the Congress demanded that those responsible for the presence of hazardous substances at Superfund sites either carry out the site cleanup themselves or pay for the response actions the U.S. EPA conducts.

The liability standard for cleanup under CERCLA is "strict, joint and several,"² so that the U.S. EPA may recover the entire cost of cleanup from any contributor without obligation to identify or seek out all liable parties. In practice, however, the U.S. EPA has attempted to negotiate with responsible parties, though there may be hundreds at a site, in an effort to persuade them to allocate costs among themselves. The agency increasingly has encouraged out-of-court settlements, that do not compromise protection of public health and the environment, to procure PRP cleanup of the site or recover cleanup funding. The U.S. EPA prefers to have the PRPs conduct the remedial actions rather

Table 1
CCCDs Data Elements for Each Site Record

CCCDs DATA ELEMENT	DESCRIPTION
SITENAME	Preferred name of the site
RODID	Record of Decision identification number (EPA assigned number to a particular ROD)
EPAID	A unique identifier (either in Dun and Bradstreet or GSA format used to indicate a hazardous waste site or an unanticipated removal (incident) occurring at a location not previously identified as a site in the CERCLIS inventory (e.g. oil spill)
OPUNITNUM	A designation for the operable unit at which events are occurring. Legitimate entries are '00' to '99'
REGION	EPA Region in which the site is located
ADDRESS	Street address, route number, or other specific identifier of the physical location of the site or incident
CITY	Name of the city, town, village or other municipality in which the site is located or incident occurs. If the site is not located or if the incident did not occur within such a jurisdiction, the nearest geographical place name
STATE	Code that identifies the state or territory in which the site is located or incident occurs
ZIP	Code that identifies the U.S. Postal Service delivery area in which the site is located or incident occurs
RCNAME	Regional contact name
RCPHONE	Regional contact phone number
RODDATE	Date when the Record of Decision was signed
REMTECHTYPE	Code(s) of the type(s) of remedial technology selected by EPA and described in the ROD
REMTECHSP	Code(s) of remedial technology specifications (design/engineering specifications)
ESTDESCOST	Estimated design cost (cost to complete the remedial design)
ESTCONCOST	Estimated construction cost (cost to construct or implement the remedial technology after a final design has been completed)
DESCONCOSTS	Total costs of design and construction (only if total is provided in the ROD)
ESTOMCOST	Estimated operations and maintenance O&M cost (cost to operate and maintain the remedial technology after construction)
NUMOMYEAR	Number of years of operations and maintenance
ESTPRWORTH	Estimated total present worth of the remedial technology (sum of estimated design, construction and O&M costs only as listed in the ROD)
RDCOMPDT	The actual completion date of the remedial design
RDPRIOROBL	The dollar amount that was obligated (set aside) for the remedial design for the prior fiscal year
RDCURROBL	The dollar amount that was obligated (set aside) for the remedial design for the current fiscal year
RDOUTLAYS	The dollar amount outlaid (paid) for the remedial design to date
RACOMPDT	The actual completion date of the remedial action
RAPRIOROBL	The dollar amount that was obligated (set aside) for the remedial action for the prior fiscal year
RACURROBL	The dollar amount that was obligated (set aside) for the remedial action for the prior fiscal year
RAOUTLAYS	The dollar amount outlaid (paid) for the remedial action to date
KEYCONTAMN	Code(s) of the key contaminant(s) at the site
DRUMS	Drums as a contaminated medium or source of contaminated medium at the site
BKLIQUID	Bulk liquid as a contaminated medium or source of contaminated medium at the site
SOIL	Soil as a contaminated medium at the site
GROUNDWATR	Ground water as a contaminated medium at the site
SURWATER	Surface water as a contaminated medium at the site
AIR	Air as a contaminated medium at the site

than simply provide cleanup funds.

Congress in SARA Section 122(f) authorized the U.S. EPA to enter into covenants not to sue, empowering the agency to provide limited releases from liability to PRPs in settlements. The covenants not to sue usually include "reopeners" that allow the U.S. EPA to revisit the settlement to recover additional costs incurred due to unknown conditions or new information that arises after remedial actions begin — but that

may be waived when, for instance, the U.S. EPA has determined that "extraordinary circumstances" exist. The extraordinary circumstances waiver may be applied based on the effectiveness and reliability, or permanence, of the remedy, the nature of remaining risks at the facility, the demonstrated effectiveness of the technology, the involvement of PRPs, litigative risks or "whether the Fund or other sources of funding would be available for any additional remedial actions that might eventually be necessary at the facility."³ Under certain circumstances, the U.S. EPA may thus waive the usual reopeners when PRPs have submitted a premium payment above baseline remedial costs.

METHODOLOGY FOR DEVELOPING CCCDS

The CCCDS data base was designed for easy use by the U.S. EPA regional and headquarters staff involved in CERCLA settlements and other activities. Because the CCCDS is menu-driven, little or no training is necessary to begin using the data base. The CCCDS software has been compiled for speedy operation using the royalty-free Foxbase runtime PC software. Foxbase, however, is not required to run the software. The U.S. EPA also is developing a users manual for routine procedures such as data input, report generation, data querying, coding form generation, data backup, data displaying and printer selection.

The U.S. EPA conducted a detailed review of each of the 350 RODs in CCCDS and recorded data on coding sheets. The data on the coding sheets were then entered into the system. Professional judgment was sometimes required to match site-specific technologies with a master list of control, removal and treatment technologies. Additionally, extended review and professional judgment were required to identify technical specifications associated with each technology.

The Premium Payment Concept

The premium payment concept is documented in the U.S. EPA policy and guidance.⁴ The premium payment levies a surcharge above cleanup costs. Similar to an insurance premium, the payment offsets the risk the U.S. EPA assumes in providing PRPs with a limited release from liability with a payment that exceeds the cost contemplated to complete remediation. That premium should be enough to compensate for both potential cost overruns and unexpected additional costs,⁵ yet may provide an incentive to settlement by supplying a release from future liability. When using a premium payment, releases from liability are of two general types: (1) a release from responsibility for cost overruns in implementing the remedy contemplated in the settlement agreement, or (2) a release from additional site remediation if the selected remedy is not protective of human health and the environment. Either type commonly carries reopeners that allow the U.S. EPA to recover additional costs from PRPs if conditions arise that were unknown when U.S. EPA determined that remediation was complete.

The U.S. EPA guidance states that the premium should be set at a level that shields the government from having to bear potential cost overruns and that provides funds "to protect public health and the environment in the event that additional response work will be needed at the site." The premium should be adequate to protect against future liability that may arise due to remedy failure or mistaken assumptions about the effectiveness of the remedy. In addition, new information discovered about a site, perhaps during the U.S. EPA's 5-yr review required under CERCLA section 121(c), may demand further remedial work. In such cases, the guidance says, both the likelihood and the cost of future remediation should be considered, and the premium should be allocated in terms of each PRP's percentage of the total estimated remediation cost.

Still, the method of calculating the premium remains unresolved. The current U.S. EPA OECM guidance provides only general guidelines. A recent publication has suggested a framework of procedures that can be used to derive a premium payment on a case-by-case basis.⁶ The methodology relies on premium ratio multipliers that were derived from statistical distribution functions that represent the consequence of the risk the U.S. EPA retains balanced against the probability that the premium will be sufficient to cover any additional costs. CCCDS provides an empirical foundation for the premium payment previously

discussed. The system provides, for the first time, an historical picture of cost overruns and unexpected additional expenses in the Superfund remedial program.

Calculating Premium Payments Using CCCDS Historical Data From Other Superfund Sites

Ideally, two types of cost information are needed to calculate a premium payment: (1) the estimated cost of cleanup at the time of settlement, and (2) the actual cost of cleanup at the completion of cleanup. The difference between these two costs represents the premium payment that should be assessed during a cash-out settlement.

At the time of a cash-out settlement, however, both parties (the U.S. EPA and the PRPs) have only the estimated cost for each site specific remedial technology that will be used in the cleanup. Because of the nature of premium payment (included as part of an up-front, cash-out settlement), actual costs are not available. Although actual costs are not available for the specific site being settled, they may be available for other sites that have implemented the same or similar technologies.

If, therefore, historical data are reviewed for other sites that have implemented the same or similar technologies, then a premium payment may be based on the statistical mean (or other measure of central tendency) of the difference between the estimated costs and the actual costs for each site. An alternative approach would be to calculate the statistical mean of the difference between the site-specific estimated cost and the actual costs at each of the other sites.

Sources of Estimated Costs

Estimated costs of cleanup are refined throughout the RI/FS process. Generally the closest estimate at the time of settlement are the figures that appear in the Superfund ROD. These estimates generally are based on the results of the feasibility study and are calculated using a U.S. EPA costing model. This model is a software-based system that incorporates the recommended remedial technology specifications and site considerations into a site-specific cost estimate.

The ROD usually includes cost estimates, technology specifications and other site characteristic data. Through a review of sites with similar technology specifications and site characteristics, the estimated costs from RODs at other sites can be used to help calculate a premium payment for settlement purposes.

Sources of Actual Costs

Actual costs are available only when the cleanup has been completely designed and constructed and all operations and maintenance completed. While this figure rarely is available, since most Superfund sites have not reached this phase, different types of actual costs may be obtained. One type of actual cost is the cost of implementing the remedial technology as indicated by the final remedial design. For premium payment purposes, the actual cost would be the sum of: (1) the cost of the remedial design, and (2) the projected cost of implementing the final design.

Another type of actual cost is the cost at the completion of the remedial action (construction), but before long-term operation and maintenance begins. For premium payment purposes, this would be: (1) the cost of the remedial design, and construction, and (2) the projected cost of the operating and maintaining the technology until the site is properly cleaned.

These actual costs are shown in CERCLIS as either obligations or outlays. Obligations are dollar set-asides that the Agency has committed to spend. For example, an obligation for remedial action is based on its projected cost as documented in the final remedial design. CERCLIS shows both current year and prior year obligations. Outlays are dollar amounts that the Agency has already spent. For example, an outlay for remedial design or remedial action represents an invoiced amount that the Agency has paid.

CCCDS Capacity To Calculate CERCLA Premium Payments

CCCDS is designed to help the U.S. EPA calculate premium payments using many different combinations of data. As discussed above,

Table 2
List of Technologies Coded and Entered into CCCDS

ENGINEERING CONTROL TECHNOLOGIES	TREATMENT TECHNOLOGIES
Technologies	Direct Waste Treatment
Air Emissions Control	Biological Methods
<ul style="list-style-type: none"> • pipe vents • trench vents • gas barriers • gas collection • overpacking 	<ul style="list-style-type: none"> • modified conventional wastewater treatment techniques • anaerobic, aerated, and facultative lagoons • supported growth biological
Surface Water Control	Chemical Methods
<ul style="list-style-type: none"> • surface seals (caps) • surface water diversion and collection systems • dikes and berms • ditches, diversions, waterways • chutes and downpipes • levees • seepage basins and ditches • terraces and benches • gradings • revegetation • surface water pumping 	<ul style="list-style-type: none"> • chlorination • precipitation, flocculation, sedimentation • neutralization • equalization • chemical oxidation • dechlorination
Groundwater Control	Physical Methods
<ul style="list-style-type: none"> • impermeable barrier <ul style="list-style-type: none"> • slurry walls • grout curtains • sheet piling • permeable treatment beds • groundwater pumping wells, galleries <ul style="list-style-type: none"> • water table adjustment • plume containment • leachate control <ul style="list-style-type: none"> • subsurface drains • drainage ditches • liners 	<ul style="list-style-type: none"> • air stripping • carbon absorption • ion exchange • reverse osmosis • permeable bed treatment • wet air oxidation • incineration • vapor phase absorption • activated sludge
Asphalt Dryer	Treatment of Solids and Sediments
On-site RCRA Landfill	Incineration
Temporary On-site Storage	Wet Air Oxidation
On-site Disposal	Solidification
Aeration	<ul style="list-style-type: none"> • solidification w/separation
OFF-SITE TRANSPORT, STORAGE, TREATMENT OR DISPOSAL	Encapsulation
Off-site Transportation to RCRA Landfill	In situ Treatment
Off-site Transportation to RCRA Incinerator	<ul style="list-style-type: none"> • solution mining, (soil washing or flushing) • neutralization/detoxification • microbiological degradation
Off-site Transportation to other Treatment	Relocation of Residents
REMOVAL TECHNOLOGIES	Building Removal
Excavation	Tank Removal
Hydraulic Dredging	Bulk Liquid Removal
Mechanical Dredging	Debris Removal
Provision of Alternative Water Supplies	Soil Replacement
<ul style="list-style-type: none"> • individual treatment units • water distribution systems • new wells in a new location or deeper wells • cisterns • upgraded treatment for existing distribution systems 	SAMPLING/MONITORING TECHNOLOGIES
Drum Removal	Install Monitoring Wells
	Sampling and Analysis (of wells, soil, leachate, surface water, air etc.)
	SITE PREPARATION TECHNOLOGIES
	Access Road
	Grading
	Revegetation
	Clearing and Grubbing
	Fencing
	Decontamination
	<ul style="list-style-type: none"> • Building Decontamination

these premium payment calculations are based on the actual costs associated with sites that already have implemented similar technologies.

CCCDS is best suited to calculate the cost overrun component of the premium payment. The cost overruns can be calculated using either obligations or outlays. Because outlays more realistically represent actual costs, the calculations using outlays are also more realistic.

To calculate overruns using outlays, CCCDS would first be queried to list all sites where: (1) the total of remedial design and remedial action outlays is greater than the ROD's estimated costs (total estimated cost

of design and construction), and (2) the ROD's estimated costs are greater than zero. For each of these sites, CCCDS can calculate the absolute value of the overrun (difference between total outlays and the estimated cost) as well as the percentage of overrun. CCCDS can then calculate a mean, median, variance, standard deviation or standard error, among other measures, for the resulting sample of cost overruns.

CCCDS can perform a similar calculation using only the obligation fields for remedial design/remedial action (RD/RA). Use of the obligation fields would provide a greater sample size because many more sites have funds obligated for RD/RA but have not yet had actual outlays. The obligations, however, would not provide premium payment calculations that are as accurate as the outlays, for two reasons. First, funds may be obligated for RD/RA and then deobligated. Second, the obligation may be greater or less than the subsequent outlay. The calculation of the premium payment would in any case proceed the same as in the calculation for the outlays. CCCDS would first be queried to list all sites where: (1) the total remedial design and remedial action obligations are greater than the ROD estimated costs, and (2) the ROD estimated costs are greater than zero. CCCDS would then calculate statistical summaries of the cost overrun.

CCCDS also can calculate the cost overruns using a combination of outlays and obligations. For example, it can list cost overruns for all sites where the RD outlays plus the RA obligations were greater than the ROD estimates. CCCDS also can display the results in different subgroups. Determining the cost overruns by different technologies probably would be the most useful for premium payment calculations, but the system can further show cost overruns by the U.S. EPA region, type of contaminant or contaminated medium, ROD date and other aggregations.

CCCDS also is capable of providing historical data on the need for additional, unplanned response actions, although this calculation is more involved and less empirically based. Determining the need for additional, unplanned response actions would first involve a search of CCCDS to determine which sites contain more than one operable unit. A further review would be needed to determine if the additional operable unit was described in the original site plan. If it was not, then the total outlays for that operable unit would represent an additional component

of a premium payment. These calculations could be grouped easily by technology, region or other components.

OTHER USES OF CCCDS

CCCDS can be used for purposes other than calculating settlement premium payments. Because the system contains detailed information on remedial technology types, remedial technology specifications and contaminants and contaminated media, the system can be used to help plan site-specific response actions at other sites. For example, this might include reviewing other sites that already have implemented a particular technology, addressed certain contaminant types or any combination thereof. Table 2 shows a list of the technologies that have been coded into the system.

CONCLUSION

CCCDS can help provide an empirical basis for calculating settlement premiums at Superfund sites. The system can provide estimated costs from Superfund RODs and actual costs from CERCLIS for each site that has a signed ROD. CCCDS can perform various calculations with the ROD and CERCLIS data to develop premium payments based on: (1) cost overruns and (2) the need for additional response. CCCDS also can be used to review technology types, specifications and site-specific data for remedial planning.

REFERENCES

1. 50 *Fed. Reg.* 5034, Feb. 5, 1985.
2. The standard of "strict" liability in CERCLA Section 101 (32) is incorporated from the Clean Water Act. Courts ruling in CERCLA cases have further held that the standard is joint and several.
3. Public Law 96-510, Superfund Amendments and Reauthorization Act, Section 122(f)(4)(F).
4. *U.S. EPA Guidance on Premium Payments in CERCLA Settlements*, the U.S. EPA Office of Enforcement and Compliance Monitoring and Office of Solid Waste and Emergency Response, signed Sept. 15, 1988.
5. *Guidance on Premium Payments in CERCLA Settlements*, p.2.
6. Johnson, Gillis and Fries, "Using the Premium Payment Concept to Promote Superfund Settlements," presented at the HMCRI Superfund Conference, Nov., 1988.

De Minimis Settlement — A Success Story

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ABSTRACT

Under Section 122(g)(1) of SARA, the U.S. EPA is provided the explicit authority to enter into so-called "de minimis" settlement, involving only a minor portion of the response costs, with certain classes of responsible parties. De minimis parties would include, for example, a landowner who did not contribute to a hazardous waste release and did not conduct, have knowledge of or permit hazardous waste activities at the site. During the past few months, a significant de minimis settlement was reached involving a Superfund site in the midwest. The settlement was reached based on a unique quantitative approach utilized during the negotiation phase of site remediation. All site records were organized, screened and analyzed for information regarding waste shipments to the site. Quantitative information was entered into a computerized data base. The data base was then manipulated to identify hundreds of de minimis parties. These parties were approached by the U.S. EPA for their portion of the cleanup. During negotiations, the data base was modified using suggestions from the U.S. EPA staff to "fine tune" the levels of responsibility for each de minimis party. The end result was one of the largest de minimis settlement to date - over 11 million dollars for site remediation.

INTRODUCTION

Section 122(g)(1) of SARA provides the U.S. EPA with explicit authority to enter into so-called de minimis settlements with certain classes of PRPs whose involvement at the site mandates responsibility for only a minor portion of response costs. Although individually these de minimis settlements usually include small sums of money, a de minimis settlement with several hundred PRPs can yield quite a substantial amount. The case study described below is just such an example— A "de minimis" settlement for over 11 million dollars.

SITE DESCRIPTION AND HISTORY

Located on less than 100 ac in the Midwest, the landfill site ("the site") accepted industrial wastes for nearly 10 yr prior to the 1980 implementation of hazardous waste disposal regulations mandated by the passage of RCRA. Close to 20,000,000 gal of wastes were indiscriminately disposed of at the site, including hundreds of toxic chemical compounds. Hazardous substances and wastes were dumped into unlined ponds and barrels were deposited in an unlined pit and subsequently buried. Wastes from the ponds and drums polluted hundreds of thousands of cubic yards of soils, producing toxic sludges and contaminating local groundwater.

The U.S. EPA closed the site in the late 1970s after years of chronic violations of its state permit and of industrial disposal laws. A high hazardous ranking system (HRS) package score resulted in the site's placement on the NPL in 1983. Cleanup of the site will involve resto-

ration of groundwater quality and require some form of removal and destruction of contaminated soils and sludges. Site investigation and remediation costs will probably stretch well into the nine figure range.

To date, several hundred PRPs have been identified. These PRPs include generators and transporters of hazardous substances and wastes disposed of at the site. Approximately one-third of these parties formed a steering committee to participate in investigation and cleanup activities at the site.

In the mid-1980s, the United States filed suit under CERCLA against more than 30 responsible parties at the site, many of whom were steering committee members, for implementation of the U.S. EPA's selected remedy and for payment of response costs. Later, the steering committee filed a third-party action against more than one hundred other PRPs not named in the U.S. EPA's earlier suit. The action sought to show that these third-party defendants were also liable in connection with activities at the site and asked the court to order these parties to pay their share of cleanup costs.

Many of the defendants identified in the third-party actions were "de minimis" parties, as determined by the U.S. EPA pursuant to Section 122 of SARA. This section of SARA provides for settlement with parties whose waste contributions have been minimal in comparison with the total volume of hazardous substances at a site. The U.S. EPA negotiated with a group of the "de minimis" parties and the parties agreed upon a consent decree for "de minimis" settlement and release from liability in connection with the site.

The proposed Consent Decree: provides for final settlement of alleged liabilities for site cleanup and response costs; raises revenues to be applied to cleanup activities; and will greatly reduce the expense and complexity of pending litigation with defendants and non-settlers. Effectively, "de minimis" parties will be released from future liability with regard to the site as long as no new information on their waste contribution to the site is uncovered. By entering into the settlement and resolving the liability issue, a "de minimis" party also will be protected from the third-party action filed by the defendants.

Eligibility for participation in the settlement was based on a party's waste contribution to the site. Volumetric waste allocations were determined using a transactional data base developed by the authors under a litigation support contract to the U.S. EPA. An alphabetic listing of participating parties and their respective volumes and cash payments was developed from the data base and appears as an attachment to the proposed Consent Decree. Cash payments were calculated by multiplying a party's percentage of total waste volume at the site by the U.S. EPA's estimate of total past and future response costs plus premiums. To date, the settlement includes over 170 "de minimis" parties and is valued well in excess of 11 million dollars.

The authors were first hired to provide litigation support and evidence audit services on the case in the mid-1980s. These services included sample chain-of-custody audits, case file inventories, the development of a transactional data base, and the ongoing compilation of a record documenting the findings made by the U.S. EPA in entering into the "de minimis" settlement. Through this 5-yr process, the authors became thoroughly familiar with the elements of the case and the case documentation. This familiarity enhanced the authors' ability to develop a transactional data base made up of more accurate volumetric waste transactions.

Documentation for developing the data base was acquired by the U.S. EPA at first by using its authority under RCRA Section 3007 and CERCLA Section 104(e) to request information. Additional evidence was gathered during the discovery phase of litigation and during settlement negotiations with parties interested in participating in a "de minimis" settlement.

Reports were obtained from state agencies detailing monthly transactions by transporters. These reports specified the source of wastes, the volume and waste type hauled and the destination for disposal. While transporters from out-of-state who used the site were not required to file monthly reports with state agencies, most kept in-house records providing similar information.

Shipping tickets and receipts provided additional information on site transactions. Manifests and logs often cited receipts and tickets, providing additional evidence that a transaction had actually occurred. A transaction poorly supported by other documentation was often confirmed by a receipt or ticket bearing the site owner's signature.

Documents from the above sources were sorted, numbered and then organized in transaction packets. Each packet contained documentation supporting a specific disposal event at the site. Packets were then filed in chronological order in a folder assigned to individual PRPs.

A written record was created for each PRP that contained its name, an assigned code, addresses, the name and address of its contact and the names of any other companies with which the PRP was associated. Lists also were created for all the unique waste types and unit types that were found in the transaction documents. Each unique waste or unit was assigned a code number. This information was thus prepared for entry into computerized data bases.

The computer system used to store extracted information was a

Extraction Date

GENERATOR:

Initials

[illegible]

Four main data file structures were developed to accommodate the four major sources of information that the U.S. EPA provided. The first three structures respectively held data from transporter reports filed with state agencies, the site's monthly log and transporter in-house records. The fourth data file contained data from the site's daily log, as well as supporting evidence from waste manifests, CERCLA Section 104(e) responses, shipping tickets and receipts.

Programs were developed for the production of summaries listing particular information in the various data files. For instance, one program converted all unit types into gallons, from which summaries were generated that could rank generators or transporters by the amount of waste contributed to the site and identify waste types associated with each volume. These summaries, an example of which is shown in Table 2, assisted the U.S. EPA attorneys in identifying the relative status of PRPs.

<u>RANK</u>	<u>GENERATOR</u>	<u>WASTE TYPE</u>	<u>GALLONS</u>	<u>% OF TOTAL</u>
72	COMPANY A	ASBESTOS	3150.00	0.061
		ASBESTOS INSULATION	<u>3600.00</u>	<u>0.070</u>
			6750.00	0.131
73	COMPANY B	CYANIDES	990.00	0.019
		ETCHING-SOLUTION	3250.00	0.063
		NITRIC ACID	1430.00	0.028
		OIL	935.00	0.018
		PAINT SLUDGE & WATER	<u>110.00</u>	<u>0.002</u>
			6715.00	0.130
74	COMPANY C	ALCOHOL	200.00	0.004
		CHLOROTHENE	825.00	0.016
		ISOCYANATES	440.00	0.009
		OIL	1485.00	0.029
		PAINT SLUDGE	1485.00	0.029
		PHENOLIC SAND RESIN	<u>1650.00</u>	<u>0.032</u>
			6085.00	0.119

Ultimately the four main data files were combined into a comprehensive data file which contained all the information extracted from the site documentation. Software was developed to produce a transactional summary printout of this data file. The transactional summary report was organized alphabetically by facility/party. Transactional information specific to a facility/party was listed chronologically by month (Table 3). Monthly volumes were presented from up to four of the data files containing the four categories of transactional data mentioned earlier. Of the volumes present for a specific month, the largest quantity was reported in the last column. Totals for each data category and the "largest quantities" column appeared at the bottom of each party/facility report.

Table 3
Transactional Summary Report
Note: All amounts given in gallons

GENERATOR: COMPANY D						
ADDRESS: 123 HELP STREET						
	STATE REPORT	MONTHLY LOG	TRANS. LOG	DAILY LOG	LARGEST QUANTITY	WASTE CODES
DEC 1975	400.00				400.00	33
SEP 1976	360.00	300.00		300.00	360.00	11,12
NOV 1977	300.00	300.00	280.00	300.00	300.00	33,57
NOV 1978	300.00	200.00		300.00	300.00	77
NOV 1979		300.00		300.00	300.00	33,77
TOTALS	1360.00	1100.00	280.00	1200.00	1660.00	

Using this transactional summary report, the U.S. EPA was able to identify parties it considered "de minimis." This process facilitated the formation of a coalition of "de minimis" parties interested in settlement negotiations with the U.S. EPA.

PROBLEMS

Early drafts of the transactional summary report were somewhat inaccurate for a variety of reasons. "De minimis" parties were quick to point out perceived discrepancies in their individual volumes. The U.S. EPA attorneys were soon cognizant of the need for adjustments to some reported volumes.

Volume discrepancies were attributable to a variety of factors. Opinions on the proper conversion factors to be used in the data base to convert some unit types to gallons were diverse. For example, the U.S. EPA assumed that the amount of waste in a drum was 55 gal unless irrefutable evidence to the contrary could be presented. PRPs often claimed that the drums that they disposed of at the site were smaller or contained a lesser amount of waste.

A recurring problem arose in reconciling different types of documentation pertaining to a specific transaction. Discrepancies in reported information between documents often led to the entry of a transaction into the data base twice (i.e., double counting a single transaction). For example, a daily site log might record receipt of a shipment a month later than the pick-up date recorded by the transporter in his report to a state agency. Similarly, two pieces of documentation on one transaction might report two seemingly different waste types, e.g., spent hydrochloric acid in the generators 104(e) response and tank bottoms on the site log, or incompatible units, e.g. cubic yards on an invoice, pounds on a receipt. Once again, the potential for double counting existed.

Another type of problem arose from the general task of party/facility identification. The PRP files were originally compiled at the direction of U.S. EPA attorneys and contained aliases, name changes and affiliation information for parties identifying subsidiaries, parents, etc. During the course of litigation and negotiations, some of these relationships changed either because of acquisitions, mergers or other reasons. The result was that some parties had transactions listed under multiple names or had the same transaction attributed to two different entities not known

to be the same or related. In both situations, there was potential for reporting the correct amount of waste for the PRP.

Finally, some transactions were simply not well documented. Only by developing transactional packets and comparing supporting documentation could they be substantiated. Certain generic assumptions had to be made.

SOLUTIONS

Discrepancies were resolved by a variety of means. As negotiations began to produce potentially realizable settlement terms, the authors re-audited transactional packets and eliminated the cited sources of errors in quantities. A hierarchy was established for ranking the quality of data presented by the many document types, and standards for evaluating the quality of documentation as evidence of a transaction at the site were re-examined. Additional information obtained from depositions and new or supplementary responses to information request letters clarified many of the quantity, conversion factor and party/facility identity problems. Negotiations and communications with some "de minimis" parties on their volumes also resulted in the submission of additional or clarifying information. Volumes were literally negotiated in a few cases where irrefutable evidence of a transaction existed but the volume or some other factor was unclear.

Changes were made to the data files, reflecting the resolution of discrepancies, and reports similar to Table 4 were generated for use in the "de minimis" settlement process. One of these reports ultimately became part of the volumetric allocation attached to the proposed Consent Decree.

Table 4
Transactional Summary Report
Note: All amounts given in gallons

GENERATOR: COMPANY E						
ADDRESS: 123 YOUR LANE						
	STATE REPORT	MONTHLY LOG	TRANSP. LOG	DAILY LOG	REVISED QUANTITY	WASTE CODES
SEP 1979				3600.00	3600.00	81
NOV 1979				4200.00	3600.00	81
DEC 1979				4000.00	3600.00	84
FEB 1980	3200.00			3200.00	3600.00	81
APR 1980		4200.00	4200.00	4200.00	4200.00	65
JUN 1980		4200.00		3600.00	3600.00	81
TOTALS	3200.00	8400.00	4200.00	22800.00	22200.00	

TOTAL: 22200.00

RESULTS—PROPOSED CONSENT DECREE FOR "DE MINIMIS" SETTLEMENT

The re-audit of the transactional files and the data base was completed last fall. The process was documented in a series of audit reports submitted to the U.S. EPA, reporting on discrepancies identified and their resolution at the direction of the U.S. EPA attorneys. Subsequent to the generation of a list of "de minimis" parties, the negotiated Consent Decree was distributed to parties for consideration. By early spring of this year, over 150 parties, representing nearly half of those eligible, had submitted executed Consent Decrees.

The U.S. EPA's decision making process in entering into the settlement has been carefully documented in a "De Minimis" Settlement Record. At this writing, the proposed Consent Decree still has not been formally entered by the court. Discrepancies with all participating parties have been resolved, and comments received during a public comment period were addressed with the assistance of the authors.

CONCLUSIONS AND RECOMMENDATIONS

The de minimis settlement process described was a definite success story, but the authors learned several lessons during the project. These lessons are summarized in the recommendations listed below:

- Start the process early - identify as many de minimis settlers as possible so the response costs can be spread and thus reduced for any given party.
- Identify and collect all relevant waste transaction documentation—new waste information will change totals.
- Organize—a complete document organization and control system will facilitate location and retrieval of important waste contribution data.
- Automate—modifying waste contributions is much easier using the

computer.

- Communicate—all parties on both sides of negotiations must be aware of all waste transaction assumptions used in building the data base.
- Check for accuracy—constant quality assurance will increase the level of comfort for all involved in the process.

DISCLAIMER

This paper was prepared with the knowledge of the U.S. EPA's National Enforcement Investigations Center (NEIC) and has been reviewed by representatives of this agency office. Statements and opinions expressed are those of the authors. No official support or endorsement by the U.S. EPA or any other agency of the federal government is intended nor should be inferred.

CERCLA Natural Resource Damage Release Request Delaware's Approach

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ABSTRACT

It is important that both Federal and State natural resource trustees become involved early in the remedial process at superfund sites. By doing so, their concerns regarding the identification of any natural resource damages may be heard and incorporated into the RI/FS and the ROD. When a PRP is financing the remediation at a site, trustee involvement is essential as the PRP may request a release from future liability for natural resource damages after the ROD is signed. The Delaware Department of Natural Resources and Environmental Control has found the end result of this process to be successful compensation for natural resource damages. This was demonstrated in negotiations for a remedial action by a PRP at the Wildcat Landfill Superfund Site.

INTRODUCTION

A great deal of emphasis traditionally has been placed on the threat Superfund sites pose to public health. Though this is of primary importance, CERCLA as amended by SARA of 1986, also requires the assessment of any adverse impacts to the environment. In recent years, this need to address the environment has begun to be recognized. As a result, there has been a rising emphasis on performing environmental assessments as part of Superfund investigations. This assessment process has resulted in a heightened awareness of natural resource trustee concerns at Superfund sites. It has forced us to recognize the need to address natural resource damage issues early in the remedial process, with coordination between Federal and State natural resource trustees and PRPs.

The assessment of natural resource damages resulting from a release of oil or hazardous substances has been ignored, particularly in the Superfund program. Although the requirement has always been mandated under CERCLA, Section 107 and by the Clean Water Act (CWA), Section 311, the issue was forced into the limelight by promulgation of regulations by the Department of the Interior (DOI) in 1986 and 1987¹ on how such assessments might be conducted. Unfortunately, the DOI regulations have been contested by regulatory agencies and environmental groups alike, due to a lack of agreement on the proposed economic valuing of damages². Incorporation of the natural resource damage assessment requirement into the already existing Superfund program further complicates the issue.

In the event natural resource damages are identified at a site, CERCLA, as amended by SARA, allows PRPs to request a release from future liability for any additional natural resource damages upon agreement on a remedial action. Such a release request was received by the State of Delaware from a group of PRPs for the Wildcat Landfill Site. This prompted us to address the natural resource damage assessment and release requirements. This evaluation also resulted in the development of a mechanism to address future release requests.

REGULATORY FRAMEWORK

CERCLA, as amended by SARA, Section 107 and CWA, Section 311 required the Governor of each State to appoint a natural resource trustee for State natural resources. The Governor of Delaware appointed the State's Secretary of the Department of Natural Resources and Environmental Control (DNREC) as the State's trustee in February, 1987.

CERCLA, Section 101 (16) defines natural resources as "...land, fish, wildlife, biota, air, water, groundwater, drinking water supplies..." The State natural resource trustee, similar to its Federal counterparts, is responsible for carrying out the assessment of damages to, or potential for damages to, natural resources resulting from a release of hazardous substances or oil. Furthermore, the trustee is responsible for ensuring that any natural resources damages are rehabilitated, restored, replaced or that equivalent resources are acquired³.

For Superfund sites, it is important that both the Federal and State natural resource trustees become involved early in the remedial process. By doing so, their concerns regarding the identification and appropriate remediation of any damages to natural resources can be heard and incorporated into the RI/FS and ROD. (Fig. 1). Such early involvement will hopefully preclude any unnecessary delays at the end of the process.

When a PRP is financing remediation at a site, trustee involvement is essential as the PRP may request a release from future liability for natural resource damages after the ROD is signed. In accordance with CERCLA, Section 122(j)(2), a covenant not to sue may be granted by natural resource trustees "...if the potentially responsible party agrees to undertake actions to protect or restore the natural resources damaged by such a release or threatened release of hazardous substances."

Though a natural resource trustee is responsible for assessing damages resulting from any release of hazardous substances or oil, the scope of this paper is limited to the discussion of natural resource damage assessments for Superfund sites on the NPL. In the case of a catastrophic release, there are usually obvious damages to natural resources and a clear need to assess the damages and acquire compensation for restoration of the resources. For NPL sites, where the release often is ongoing, the damage assessment process will be more subtle and can be incorporated into the already existing remedial process for Superfund sites. This can prevent any overlap in the performance of environmental assessments, limit the role of the trustee to one of oversight and enhance the overall scope of the remedy selected.

DELAWARE'S APPROACH

The State of Delaware was prompted to take action towards the development of its own natural resource damage assessment policy upon receipt of the request for a release from future liability for damages to natural resources associated with a Superfund site. The State natural

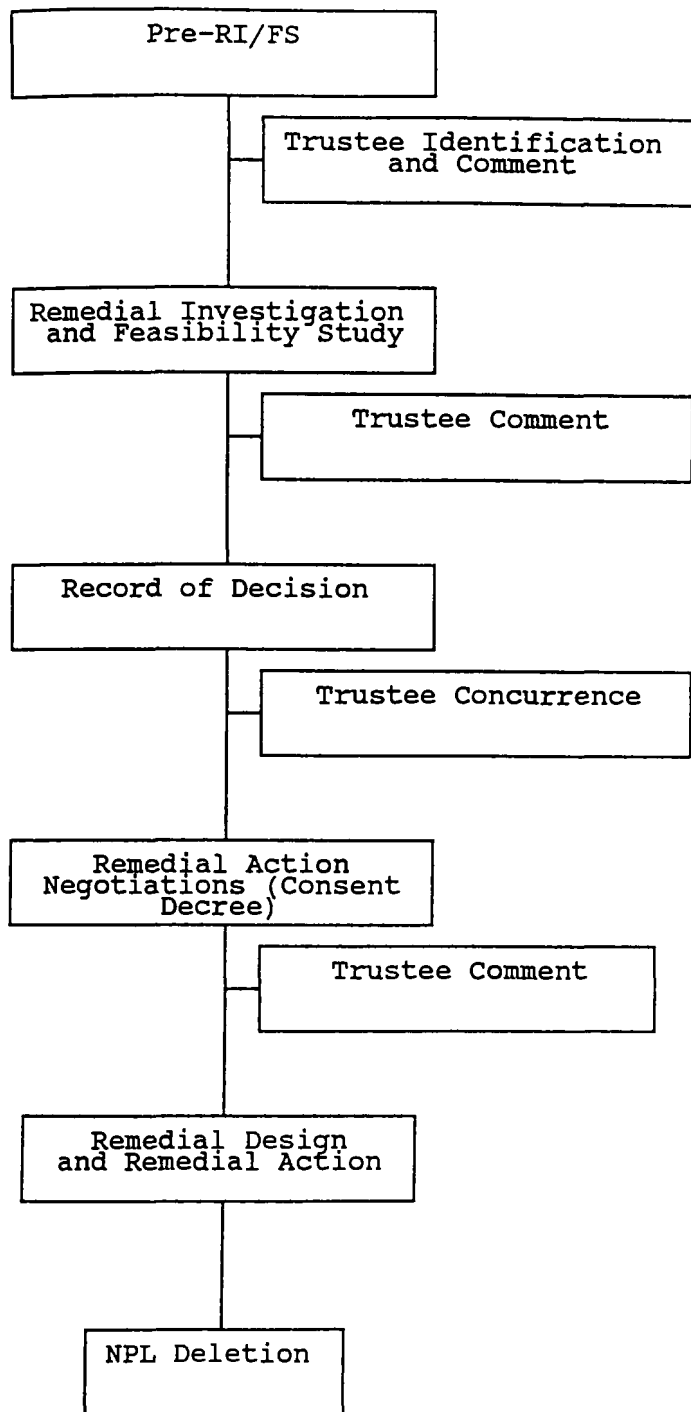


Fig. 1

Natural Resource Trustee Involvement in the Superfund Process.

resource trustee (the Secretary of the DNREC) oversees the management of the State's environmental concerns in the Department's five divisions. These divisions of the agency include the Division of Air and Waste Management, the Division of Water Resources, the Division of Fish and Wildlife, the Division of Parks and Recreation and the Division of Soil and Water Conservation (Fig. 2). Those divisions with affected resources were formally contacted to comment on the RI/FS and ROD and to "sign off" on the release for the specific resources in question. The following pathway led to their eventual concurrence on the damage release requested:

- Various division representatives were involved throughout the remedial process for technical support.

- The investigation of any damages to natural resources was incorporated into the RI.
- The development of restoration/replacement activities was performed during the FS.
- The selection of an appropriate remedial action to compensate for any natural resource damages identified was made along with other remedial decisions during the development of the ROD.
- The design of the appropriate remedial action was incorporated into the remedial design document.

The agreement by the PRP to perform a remedial action was prompted because of the authority the State and Federal trustees held with the covenant not to sue. The end result was adequate compensation for any natural resource damages.

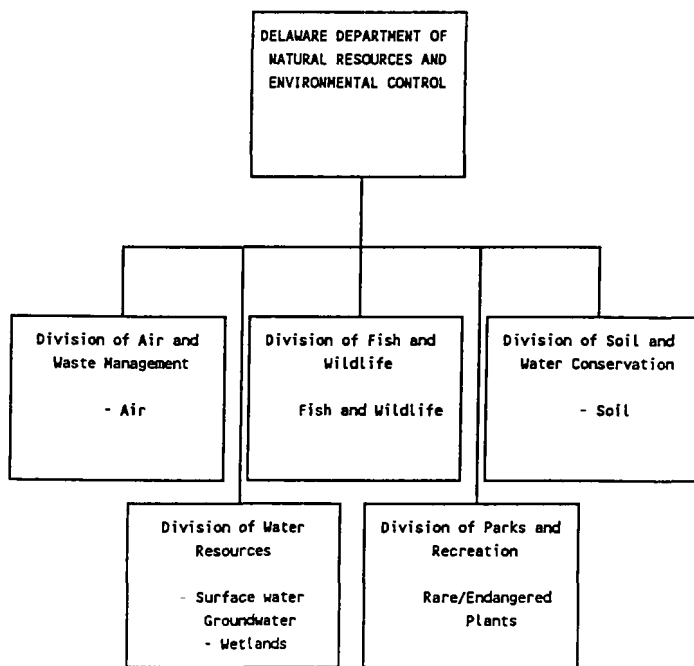


Fig. 2

Structure of the Delaware Department of Natural Resources and Environmental Control (DNREC).

MAKING THE PROCESS WORK: A CASE STUDY

The Wildcat Landfill is a 45-ac site located along the St. Jones River in Kent County, Delaware, approximately 2.5 mi southeast of Dover (Fig. 3). The landfill was privately operated, accepting both municipal and industrial wastes from 1962 until it was ordered closed by DNREC in 1973 due to numerous permit violations. The landfill was later investigated by the U.S. EPA and DNREC and placed on the NPL in 1982. From late 1985 to 1988, an RI/FS⁴ was conducted by DNREC under a cooperative agreement with the U.S. EPA.

The major findings of the RI were:

- Groundwater beneath the landfill and to the southeast of the landfill was contaminated with low levels of trace metals and organic constituents.
- Landfill contents, including drummed wastes, were exposed within and at the boundary of the landfill.
- Leachate seeps with inorganic and organic constituents were found along the periphery of the landfill in the area of an adjacent pond.
- Surface water and sediments in the adjacent pond were contaminated by inorganics.
- Aquatic fauna in the adjacent pond exhibited elevated levels of inorganics.

Two RODs were developed to address the activities required to remediate the site and the adjacent pond. The problems on and within

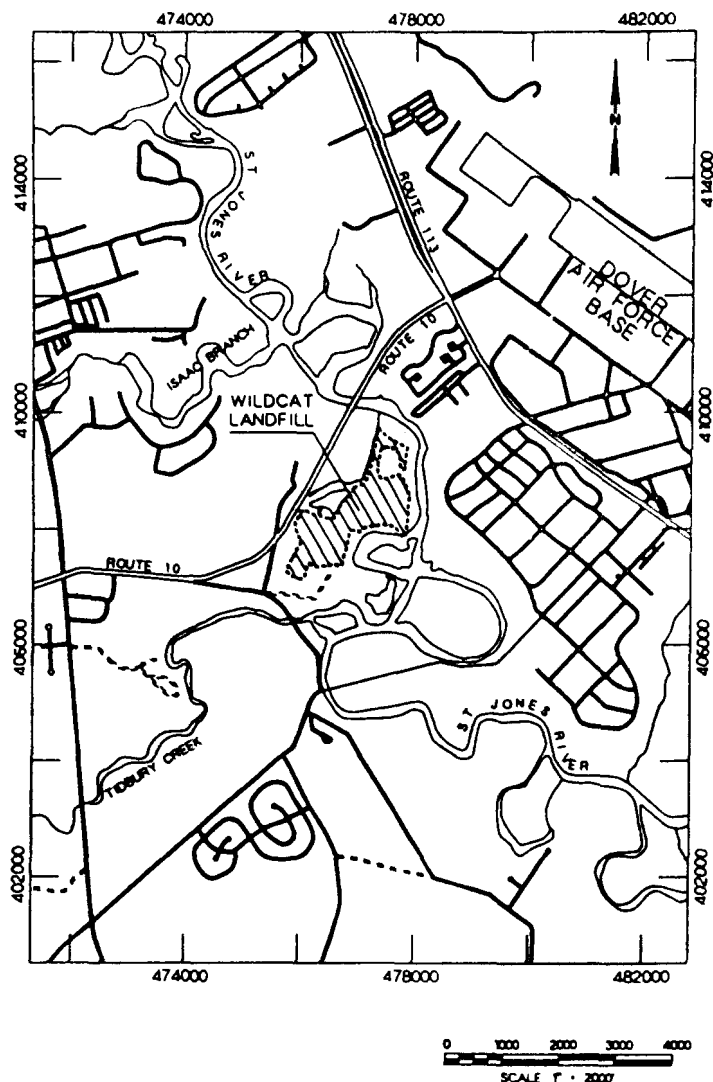


Fig. 3

Location of the Wildcat Landfill Site in Kent County, Delaware.

the landfill were addressed in the first ROD in June, 1988⁵. The pond adjacent to the site was addressed in a second ROD in November, 1988⁶.

The first ROD required a partial landfill cover, replacement of certain private wells in close proximity to the landfill, removal and disposal of drummed wastes, placement of institutional controls on-site and to the southeast of the site, and groundwater monitoring. The second ROD required that the pond adjacent to the site be filled to eliminate possible future impacts to indigenous and migratory fauna. Additionally, a replacement pond was to be created elsewhere on the owner's property in an area unaffected by the landfill.

Both the U.S. EPA and DNREC agreed that the first ROD should be finalized in the interest of keeping the remedial process moving. Because the environmental assessment of the pond was ongoing at that time, it was decided a second ROD would be developed pending the outcome of the assessment.

Negotiations with the Wildcat PRPs began almost immediately following finalization of the first ROD and prior to the second ROD (negotiations with the PRPs prior to initiation of the RI/FS were unsuccessful). During these negotiations (for implementation of the selected remedy), the PRPs requested that the second ROD be completed prior to entry into a consent decree and that a release from future liability for natural resource damages, from both Federal and State trustees, be granted. The Federal trustees for this site included the Department of Interior (represented by the U.S. Fish and Wildlife Service) and the Depart-

ment of Commerce (represented by the National Oceanic and Atmospheric Administration). The State of Delaware's trustee was DNREC.

The second ROD was finalized and required filling the adjacent pond and creating a replacement pond on an unaffected portion of the property. The alternative selected for the pond represented a worst case scenario and was selected partly because of the request for release from liability for future natural resource damages from the PRPs. Both the U.S. EPA and DNREC regarded the biological evidence for the pond as somewhat inconclusive and placed language in the second ROD such that the selected remedy would be re-evaluated if it was not implemented by the PRP group.

The language granting the natural resource damage release was incorporated into a consent decree negotiated between the PRPs, the U.S. EPA and DNREC, with considerable comment by the Federal and State trustees. The wording of the release is as follows: "The United States and the [State of Delaware] hereby waive and release with respect to the Settlers any claim that they may have for damages to natural resources at or arising from the Wildcat Site resulting from releases or threats of releases at or from the site for which the Settlers are alleged to be liable pursuant to Section 107 (a) of CERCLA or from the implementation of the Remedial Action pursuant to the Decree." Note that the natural resource damages, as defined in the release language, can be either from releases from the landfill or from implementation of the selected remedy.

The damages associated with releases from the landfill include contamination of groundwater, contamination of surface water and sediments, and bioaccumulation of inorganics in mummichogs (*Fundulus heteroclitus*) and painted turtles (*Chrysemys picta*) in the pond. The damages associated with implementation of the remedy include the loss of wetlands around the periphery of the pond and potential effects on rare plants on the site. It should be noted that 29 acs of wetlands were originally lost at the time the landfill was operated due to the direct placement of landfill wastes upon prior existing tidal wetlands. This loss of wetlands occurred prior to the existence of Federal or State statutes protecting wetlands. Further, this loss is not the result of release of any hazardous substances from the site nor from the remedial action. Consequently, the Federal and State agencies did not pursue recovery of these resources.

The Secretary of DNREC, as the State's designated trustee, required the concurrence of numerous agencies within the Department, including the Division of Water Resources (for groundwater, surface water and wetlands), the Division of Parks and Recreation (for plants) and the Division of Fish and Wildlife (for fauna). As discussed earlier, an efficient internal mechanism was required to ensure the timely input by these divisions prior to agreement by DNREC to grant the release. The Division of Air and Waste Management, responsible for the Superfund program, coordinated involvement of the other divisions in the remedial process (RI/FS and ROD stages) and also in the subsequent development of the remedial action work plan attached to the consent decree. This assured that the State's natural resource concerns were adequately addressed during all stages of the process. Concurrently, the U.S. EPA coordinated involvement of the Federal trustees, assuring that their natural resource concerns were adequately addressed.

Both the Federal and State trustees were signatures to the consent decree. These agencies will also be involved in review of the remedial design prior to initiation of remedial action at the site.

Though the Federal and State natural resource trustees took a risk in granting the release request, they were comfortable in doing so because of their participation throughout the process. The consent decree contains a reopener clause should the remedial actions not be completed by the PRPs or not meet the requirements defined by the two RODs. Nonetheless, the PRPs felt that the remedies would be successful and agreed to enter into the consent decree in spite of the inclusion of the reopener language.

CONCLUSION

The State of Delaware's experience on the Wildcat Site has led us to move forward on the development of a policy to address natural

resource damages resulting from any releases of hazardous substances or oil. It has taught us the importance of early notification and coordination of natural resource trustee agencies to effect a favorable resolution to environmental issues surrounding Superfund settlements.

The proposed policy calls for DNREC to identify damages to natural resources resulting from any release of hazardous substances or oil. Upon discovery of the release, a central coordinator within DNREC is notified. This individual then works with the appropriate DNREC division responsible for managing the investigation and cleanup of the release. Together, along with the Federal agencies in cases of joint trusteeship, the assessment of any damages to natural resources is completed and, if necessary, the appropriate compensation is pursued. In this way, the necessary natural resource damage assessments of incidents ranging from slow releases at NPL sites to major spill events can be addressed in a consistent and organized fashion.

The implementation of the remedies selected for the Wildcat Landfill represents a landmark for interagency, intra-agency and PRP cooperation at a Superfund site. The development of an efficient mechanism for the identification of natural resource damages and the subsequent damage claim release procedures by the State allowed for

successful and timely completion of negotiations by Federal and State government and private parties in rectifying environmental problems at Superfund sites within the State of Delaware.

FOOTNOTES

1. Two sets of Natural Resource Damage Assessment rules were published by DOI. The Type A rule, finalized on Mar. 20, 1987 in 52 FR 9042, addresses assessments for spills of hazardous substances or oil in coastal and marine environments. The rule uses a computer model to perform simplified assessments. The Type B rule, finalized on Aug. 1, 1986 in 51 FR 21674, addresses more complex assessments of damages in other environments.
2. A federal ruling made on July 14, 1989 requires DOI to revise both the Type A and Type B natural resource damage assessment procedures.
3. See CERCLA/SARA Section 107 (f) (2).
4. CH2M Hill Southeast, Inc. *Wildcat Landfill Remedial Investigation Report*, Volume 1, May, 1988.
5. Record of Decision. ROD Decision Summary: Wildcat Landfill Site, Kent County, Delaware., June, 1988.
6. Record of Decision. ROD Decision Summary: Wildcat Landfill Pond, Kent County, Delaware., Nov., 1988.

Characterization and Washing Studies on Radionuclide Contaminated Soils

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ABSTRACT

Soils from sites in Montclair and Glen Ridge, New Jersey, are contaminated with radium-226 and thorium-230. Barium-radium sulfate, partially extracted ores and other radiominerals, allegedly an artifact from a radium extraction mill, are found mixed to varying degrees with the native soil and constitute a radiological hazard characterized by elevated levels of radon and gamma radiation.

Soil samples from the site were characterized with respect to radionuclide distribution and particle size by wet screening and radiochemical analysis. In both soil samples, a significant amount of radium-226 and thorium-230 activity is found in the smaller-sized soil fractions. Based on the results, a washing process that includes vigorous mixing of the soil with water and physical separation of particles by size was developed.

INTRODUCTION

Soils from residential and business communities in Montclair stopped and Glen Ridge, New Jersey, are contaminated with radium-226 and thorium-230. The contamination allegedly was produced by a radium extraction mill that operated nearby in the early part of the century. As a result of the subsequent use of this radium residue as landfill during construction, approximately 300,000 yd³ of soil on more than 95 ac are contaminated; almost 1,700 people in more than 500 homes are affected to some degree by elevated levels of gamma radiation and radon-222 gas. The radon, produced by the radioactive decay of radium-226, is of particular concern since it may enter homes constructed on areas containing contaminated fill material. The most significant contaminants producing the gamma radiation are radon and radium-226, ranging from approximately 40 to 1,000 pCi/g of soil, and thorium-230, ranging from approximately 20 to almost 900 pCi/g^{1,2}.

The contamination is the result of the presence of process residue containing barium-radium sulfate precipitates, partially extracted ores and other radiominerals that are mixed to varying degrees with the native soils¹. Earlier studies on uranium mill tailings indicated that volume reduction by physical separation and chemical extraction might be a feasible means of remediation of the Montclair and Glen Ridge sites⁴.

PROCEDURES

Determination of Particle Size and Size Distribution

Wet sieving was performed on two soil samples from the Montclair site and on one soil sample from Glen Ridge. One Montclair sample was labeled "Montclair," while the other was labeled "Representative" since, as reported in CDM Reports^{1,2}, the specific activity of radium-226 contamination in the latter represents an average value for the overall sites. The soils were dried at 60°C and wet-sieved using a Brinkman, model VS, vibrating sieve.

Radiochemical Analysis

All soil samples and soil fractions were dried at 60°C and prepared for analysis of radium-226 by gamma-ray spectroscopy using high purity germanium detectors³. Radium-226 was identified and measured using the 186 KeV photopeak. Since only very small quantities of uranium-235 were found in the samples (less than 0.1%), interference by the uranium-235 185 KeV photopeak was not a significant consideration. Selected samples with low specific activity were counted after being sealed in air-tight containers for 30 days to allow for equilibrium of radon-222 and its daughters.

Soils and selected wet sieved fractions and samples were also analyzed for thorium-230³. Aliquots were completely solubilized in acid mixtures, and the thorium was separated by ion-exchange chromatography and counted by alpha spectroscopy using thorium-234 as a tracer to determine the chemical yield of the procedure.

Wash Studies

Four soil fractions were identified for wash studies: (+4 designates material retained by a number 4 sieve), -4/+16 (-4/+16 designates material that passes through a number 4 sieve but is retained by a number 16 sieve), -16/+30 and -30/+50. Based on the literature survey⁴, water and several salt or salt/acid solutions were selected as initial wash reagents (Table 6).

Samples of the selected soil fraction, prepared by dry screening on a Gilson TM-4 screener, were analyzed for radium-226. The samples were then mixed with water or the selected wash solution (5 mL/g) in a 1-gal container and shaken between 100 and 350 rpm on a Lab-Line Orbit Shaker, model 3590, at room temperature for 1 hr. At the end of that time, they were rinsed with water, and the solid residue (RI) was collected over the appropriate sieve (i.e., number 4 for a +4 soil fraction or number 16 for a -4/+16 fraction). The residue was dried at 60°C, weighed and analyzed. The filtrate was subsequently filtered through a Whatman No. 1 filter paper and then a 0.4m polycarbonate filter. These residues were dried and weighed. The volume of the filtrate was measured and, along with the residues, analyzed for radium-226.

Two-cycle wash studies were performed as described above for a one-step study, but water was used exclusively as the washing agent during the first cycle. The initial wash mixture was shaken for a period of only 5 min. The residue from the first cycle was washed again for 1 hr with water or one of the wash reagents selected for the study.

Three-step wash studies were performed as described for a two-step study except that the residue from the second step was washed again with water for 1 hr.

To determine the recycle capability of the wash water, samples of soil fractions were washed using the procedure described for one-step wash studies; the micropore filtrate was collected for the second step

of the study. In the second step, a new soil fraction was washed with the filtrate from the first step. The filtrate from the second step was, in turn, used to wash a third new soil fraction.

Combined Washing and Wet Sieving of Total Soils

Soil samples were weighed and analyzed for radium-226. After analysis, the samples were mixed with tap water (5 mL/g) in a 1-gal container and shaken at 350 rpm at room temperature for 30 min. The soil mixtures then were sieved under vacuum on a Gilson Wet-Vac Sieve Tester using the selected sieve sizes.

RESULTS AND DISCUSSION

Particle Size and Radiochemical Distribution

Table 1 gives the average specific activity of radium-226 and thorium-230 in the Montclair, Glen Ridge and Representative soil samples based on their dry weights. The specific activity of radium-226 is approximately six times higher in the Glen Ridge soil than in the Montclair soil, while the Representative soil contains less than one half that of the Montclair soil. Thorium-230 specific activity in the Montclair and Glen Ridge soils is equivalent to that of radium-226. The thorium isotope specific activity in the Representative soil is considerably less than that of the Montclair soil.

Table 1
Total Soil Radiochemical Analysis

Soil	Ra-226 (pCi/gr)	Th-230 (pCi/gr)
Montclair	132 ± 18	123 ± 12
Glen Ridge	828 ± 51	826 ± 28
Representative	54 ± 10	18 ± 2

Error for specific activity represents ± 1 sigma.

The distributions of radium-226 and thorium-230 by particle size are indicated in Tables 2, 3 and 4 for the Montclair, Glen Ridge and Representative soil fractions, respectively. Note in Table 2 that the radium-226 specific activity is moderate, less than 100 pCi/gr, in the Montclair fractions larger than 600 micron (30 mesh size), but it generally increases as the particle size decreases. There is a noticeable increase between the -10/+16 and the -16/+30 fractions and between the -200/+400 and the -400 fractions and an unexpectedly high value for the -16/+30 fraction—more than twice the value of the preceding fraction. The thorium-230 values are, with the exception of one fraction (-16/+30), less than that of radium-226.

Table 3 shows that radium-226 is distributed in a similar manner in the Glen Ridge soil, but the increase in specific activity is not as uniform with decreasing particle size. There is, again, a noticeable increase from the number 16 to 30 mesh size and from 400 to -400 mesh; a doubling in activity, with a very high activity in the -400 fraction. Thorium-230 activity specific activity is also inversely related to the particle size with the activity, doubling between the 16 and 30 mesh size and between the 400 and -400 fractions. In each fraction, however, the thorium-230 is less than that of radium-226.

Table 4 indicates that the radium-226 is more evenly distributed in the Representative soil, but an increase in specific activity is observed with relatively significant increases from the -30/+50 fraction to the -50/+100 fraction and from the -100/+140 to the -140/+200 fraction. Each fraction contains less thorium-230 than radium-226.

The elevated specific activity in the fine soil material is clearly demonstrated by these data. Thus, partial remediation of the soils by wet sieving techniques appears to be feasible.

Table 2
Montclair Soil Wet Sieving

Size	Weight Percent*	Ra-226 (pCi/gr)	Th-230 (pCi/gr)
+4	18.25	44 ± 20%	7 ± 6%
-4/+10	7.94	26 ± 24%	12 ± 9%
-10/+16	3.23	39 ± 31%	15 ± 8%
-16/+30	4.54	84 ± 15%	175 ± 4%
-30/+50	7.46	117 ± 12%	71 ± 5%
-50/+100	14.16	113 ± 12%	62 ± 5%
-100/+140	6.74	138 ± 11%	68 ± 5%
-140/+200	5.55	170 ± 8%	115 ± 4%
-200/+400	10.85	194 ± 11%	132 ± 4%
-400	<u>21.28</u>	382 ± 8%	283 ± 5%
	100.00		

*Percentage of sieved material; 3.34% of soil is large rocks and 1.46% is trash.

Percentage error for specific activity represents ± 2 sigma error.

Table 3
Glen Ridge Soil Wet Sieving

Size	Weight Percent*	Ra-226 (pCi/gr)	Th-230 (pCi/gr)
+4	31.78	346 ± 9%	76 ± 6%
-4/+10	9.74	307 ± 7%	154 ± 4%
-10/+16	3.61	268 ± 10%	108 ± 5%
-16/+30	4.93	535 ± 8%	211 ± 4%
-30/+50	5.85	492 ± 5%	289 ± 4%
-50/+100	11.09	472 ± 5%	302 ± 4%
-100/+140	5.64	498 ± 5%	365 ± 3%
-140/+200	4.02	677 ± 5%	500 ± 3%
-200/+400	7.62	1,006 ± 4%	987 ± 4%
-400	<u>15.70</u>	2,855 ± 3%	2801 ± 5%
	99.98		

*Percentage of material sieved; 0.65% of soil is large rocks and 0.30% is trash.

Percentage error for specific activity represents ± 2 sigma error.

Tables 2 through 4 also summarize the particle size distributions of the material sieved. In the Montclair soil, Table 2, approximately 30% of the soil is retained by the number 16 sieve; 34% is retained up to the number 30 sieve (600 micron). Table 3 indicates a similar trend for the Glen Ridge soil. At least 45% of the sample is retained up to the number 16 sieve during wet sieving; 50% is retained up to the number 30 sieve.

Table 4 indicates that the Representative soil is similar to the Montclair in distribution of particles by weight. However, it contains approximately 10% more fine material (-400 mesh); unlike the Montclair soil, no large rocks (> 2 in.) are present in the soil.

Soil Wash Studies

Examination of the distributions of radium-226 concentrations in the Montclair and Glen Ridge soils along with data from the geological characterization³ indicated that preliminary wash studies should be performed on +30 soil fractions. These fractions had been separated,

Table 4
Representative Soil Wet Sieving

Size	Weight Percent*	Ra-226 (pCi/gr)	Th-230 (pCi/gr)
+4	15.79	14 ± 9%	5 ± 9%
-4/+10	6.70	22 ± 9%	8 ± 6%
-10/+16	2.65	27 ± 10%	8 ± 6%
-16/+30	4.74	25 ± 9%	9 ± 5%
-30/+50	7.73	25 ± 7%	16 ± 5%
-50/+100	12.29	33 ± 5%	23 ± 5%
-100/+140	5.55	33 ± 25%	23 ± 5%
-140/+200	4.56	52 ± 16%	39 ± 5%
-200/+400	10.48	58 ± 10%	55 ± 4%
-400	29.51	105*	**
	100.00		

*Calculated from total activity of the sample sieved and percentage of the fraction.

**Not measured.

Percentage error for specific activity represents ± 2 sigma error.

by the methods described above, from Montclair and Glen Ridge soils obtained from the New Jersey site in October, 1987.

Table 5 is a summary of the initial results of single-step wash studies with water and gentle shaking. With one wash, water removes approximately 50% of the radium-226 activity from the +4 fraction and approximately 85% of that in the -4/+16 fraction. The data indicate that these results were primarily accomplished by removing fine soil particles and suspending them in the wash water — note the weight percentage of sample recovered during washing, especially the percentage of the -4/+16 and -16/+30 fractions recovered. It is not surprising that less sample is recovered (more is lost) from the smaller-sized fractions during washing, since more surface area is available for adherence of fine material on these fractions, and this fine material should be removed during the wash process. In addition, these smaller fractions would be expected to contain a larger percentage of loose fine material from dry screening than the larger-sized fractions. In each case, the filtrate contains little to no activity (data not shown in Table 5). The final average specific activity of the Montclair samples ranges from 10 to 71 pCi/g. Although the Glen Ridge samples follow the same trend, the final activity is well above 71 pCi/g (121 to 330 pCi/g), since the activity of the samples initially is high.

Table 5
Summary of Results from One-Step Wash Study with Water

Soil	Size	Initial Sp. Act. Ra-226 (pCi/gr)	Final Sp. Act. Ra-226 (pCi/gr)	Percent of Total Activity Removed	Weight Percent of Sample Recovered	Int./Final Sp. Act. Th-230 (pCi/gr)
M	+4(a)	19 ± 7.0	10 ± 3.7	52 ± 7.0	84 ± 9.6	37/3
	-4/+16(b)	104 ± 14	33 ± 8.3	68 ± 3.4	45 ± 2.0	104/19
	-16/+30(c)	168 ± 15	71 ± 9.7	58 ± 3.9	34 ± 1.9	158/55
G	+4(a)	193 ± 87	121 ± 28	40 ± 14	93 ± 4.3	1,087/48
	-4/+16(b)	850 ± 84	238 ± 93	82 ± 3.5	46 ± 2.5	611/108
	-16/+30(c)	1,082 ± 67	330 ± 44	87 ± 2.2	44 ± 1.3	794/147

(a) Represents the average and standard deviation of seven runs.

(b) Represents the average and standard deviation of eight runs.

(c) Represents the average and standard deviation of four runs.

Shaking velocity was 100 rpm.

The final specific activity of the Montclair +4 and -4/+16 fractions indicates a promising trend for remediation by washing and screening, since their average values after washing are 10 pCi/g and 33 pCi/g, respectively. Thorium-230 values are lower than those of radium-226, indicating that ingrowth of radium-226 would not be a long-term problem.

In most instances, the salt solutions produce similar, and in several cases slightly better, results (Table 6). The data generally indicate, however, that, relative to water, salt solutions increase the activity of radium-226 in the filtrate, apparently by solubilizing more of the radionuclides.

Table 6
Summary of Results from One-Step Wash Study with Salts

Soil	Size	Reagent	Initial Sp. Act. Ra-226 (pCi/gr)	Final Sp. Act. Ra-226 (pCi/gr)	Filtrate Sp. Act. (pCi/L)	Percent of Total Activity Removed	Weight Percent of Sample Recovered
M	+4	NaCl	35	28	104	46	68
		NaCl	38	10	72	70	84
		CaCl ₂ /NaCl	28	14	538	54	84
		EDTA	26	11	0	64	95
M	-4/+16	NaCl	83	41	106	76	49
		NaCl	92	19	287	91	44
		CaCl ₂ /NaCl	101	26	1,890	89	42
		EDTA	147	32	0	90	64
G	+4	NaCl	331	184	352	51	88
		NaCl	276	142	745	59	88
		CaCl ₂ /NaCl	202	122	4,588	44	92
		EDTA	174	100	0	40	97
G	-4/+16	NaCl	945	520	0	62	70
		NaCl	822	194	1,492	84	65
		CaCl ₂ /NaCl	898	125	5,120	91	62
		EDTA	813	244	0	81	64

* Not measured.

Shaking velocity was 100 rpm.

An important consideration in a large-scale remediation process using water is the amount of water required. If the wash water can be recycled, an appreciable amount of water will be conserved during volume reduction. Further, recycling will avoid the necessity of disposal or treatment of large volumes of radioactive liquids. In a study designed to examine the feasibility of water recycling, a -4/+16 soil fraction was washed first with deionized water; the filtrate was collected after filtering through a micropore filter and used to wash a new -4/+16 fraction. The filtrate from the second wash was used, in turn, to wash another new fraction. In each step of the wash process, the same percentage of activity is removed leaving samples with comparable specific activities. The activity of the filtrate in each case is less than 5 pCi/L. Thus, the study indicates that wash water filtered through a micropore filter to remove suspended particles may be recycled at least twice with no significant decrease in removal efficiency.

The effect of two- and three-step washing also was examined. With each fraction, the study indicates that the two-step process, compared to the one-step process, removes a greater percentage of radium-226 activity. Like the single-step procedure, each step of the process removes some mass from the sample. The first step removes the majority of the associated fines, but visual examination of the sample after two wash steps indicates that the material has less fine particles associated with it than does a comparable sample washed only once. The loss of material during the second wash step is approximately 5% of the initial sample weight. In every experiment, the specific activity of the filtrate is less than 5 pCi/L. The results of the three-step wash study with water indicate that only a very small amount of additional sample is removed by the third wash step. Examinations of the residues from the two- and three-step studies support this observation since there is no visual physical difference in comparable residues. There is no significant increase in the loss of total activity of the samples after the third wash, and the specific activity is essentially the same.

A preliminary study of washing rocks with water was initiated. Similar to the +4 soil fractions, the geometry of the rock sample presents more of a problem for radium-226 analysis by gamma-ray spectroscopy than those of smaller fractions. The Montclair rocks, however, indicated a specific activity of less than 15 pCi/gr and were not washed. On the other hand, the Glen Ridge rocks with more coal-like and coaly-slag

character have a specific activity of 260 ± 217 pCi/g, but the wash study is not conclusive.

Combined Washing and Wet Sieving Studies of Total Soils

The results of the wet sieving and water-wash studies indicated that the examination of a combination of the two processes applied to a total soil sample would be appropriate. The results presented in Table 7 demonstrate that by combining vigorous shaking (350 rpm) with vacuum sieving, up to 35% of the Montclair soil can be separated with an average radium-226 specific activity of 15 pCi/g, a specific activity very similar to that obtained in the preliminary studies. With the inclusion of the -50/+100 fraction, however, almost 43% of the Representative soil can be recovered with a radium-226 specific activity of 15 pCi/g. It is important to note that 56% of this soil sample can be recovered with a specific activity of 16 pCi/g and 67% can be recovered at 19 pCi/g.

Table 7
Final Studies of Vigorous Shaking and Subsequent Sieving of
Soils on the Wet-Vac Siever

Size	R		M		G	
	Weight Percent	Ra-226 (pCi/gr)	Weight Percent	Ra-226 (pCi/gr)	Weight Percent	Ra-226 (pCi/gr)
+4	11.06	12	21.94	15	18.68	102
-4/+16	5.59	21	5.69	15	11.73	151
-16/+30	4.10	14	2.67	16	2.91	175
-30/+50	7.99	14	4.49 34.79*	18 15**	5.52 38.84*	182 134**
-50/+100	13.82 42.63*	15 15**	10.46	42	11.63	174
-100/+200	13.46	22	13.61	59	11.41	246
-200/+400	11.40 67.49	24 19**	13.12	92	8.23	484
-400	22.51 100.00	180	28.02 100.00	427	29.82 100.00	1,581

Th-230 specific activity for each fraction was less than the specific activity of Ra-226.

*Cumulative weight percent.

**Weighted average of specific activities of above fractions.

Although vigorous shaking and wet sieving with vacuum do not produce a sufficiently remediated Glen Ridge soil, the process does separate approximately 55% of the soil (+30) with less than half the specific activity of a sample that has been shaken gently (125 rpm), 120 pCi/g compared to 290 pCi/g.

CONCLUSIONS

Considering the need to develop a simple, safe, economical, on-site treatment process that would produce a significant volume of remediated soil to remain on-site, the results of these studies indicate that water washing is a prime candidate for a process that meets these criteria. Using water exclusively would eliminate the necessity for removal of salt and/or acids by processes that would require one or more steps, possibly including, among others, ion-exchange, neutralization, or precipitation. Since the data indicate that little radium-226 is present in the filtrate after washing the soil fraction up to three times with water, it is likely that the water could be disposed directly or, more importantly, be recycled several times during the washing process. Thus, a wash process that would include wet screening of the Montclair soils to separate the +50 or +100 fraction would be followed by filtration of the -50 or -100 fraction to remove wash water that in turn would be recycled in the process. The -50 or -100 fraction could then be collected for disposal or additional treatment.

REFERENCES

1. *Remedial Investigation Study for the Montclair/West Orange and Glen Ridge, New Jersey Radium Sites*, Vol. I, Camp Dresser and McKee, Inc., Roy F. Weston, Inc., Clement Associates, Inc., ICF, Inc., U.S. EPA Contract No. 68-01-6939, New York, Sept. 13, 1985.
2. *Appendices for Remedial Investigation Study for the Montclair/West Orange and Glen Ridge, New Jersey Radium Sites*, Vol. II, Camp Dresser and McKee, Inc., Roy F. Weston, Inc., Clement Associates, Inc., ICF, Inc., U.S. EPA Contract No. 68-01-6939, New York, Sept. 13, 1985.
3. Nieheisel, J., *Characterization of Contaminated Soil from the Montclair/Glen Ridge, New Jersey Superfund Sites*, Inhouse Report, U.S. EPA, Office of Radiation Programs, Washington, DC, 1988.
4. Richardson, III., R.S., Snodgrass, G.B. and Nieheisel, J., *Review of Chemical Extraction and Volume Reduction Methods for Removing Radionuclides from Contaminated Tailings and Soils for Remedial Action*, U.S. EPA, Office of Radiation Programs, Analysis and Support Division, Washington, DC and Eastern Environmental Radiation Facility, Montgomery, AL, U.S. EPA, July 24, 1987.
5. Lieberman, R., ed., *Eastern Environmental Radiation Facility Radiochemistry Procedures Manual*, U.S. EPA, Report No. 520/5-84-006, Montgomery, AL, June, 1984.

Evaluation of U.S. EPA Soil Washing Technology for Remediation at UST Sites

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ABSTRACT

It has been estimated that approximately three to five million underground storage tanks in the United States are used to store liquid petroleum and chemical substances. Further estimates indicate that 100,000 to 400,000 of these tanks and their associated piping systems may be—or have been—leaking. The resulting soil and groundwater contamination, especially to primary drinking water aquifers, have left the United States with a massive cleanup problem, and in some cases, with the necessity of abandoning water supply wells for indefinite periods of time.

The U.S. EPA through its Risk Reduction Engineering Laboratory's Release Control Branch has undertaken research and development efforts to address the problem of remediating contaminated soils resulting from leaking underground storage tanks. Under this initiative, the Releases Technology Staff is currently evaluating soil washing technology as an economically viable and technically feasible cleanup remedial alternative to the current practice of hazardous landfill disposal.

Soil washing is a high energy, dynamic physical volumetric reduction and feedstock preparation process in which soluble contaminants are extracted from the solid fraction into liquid medium, usually water. In addition, the separation of the highly contaminated fine soil particles (silts, clays and colloids) from the bulk of the soil matrix is accomplished through the mechanism of volume reduction. As a result, significant fractions of the contaminated soil can be "cleaned" and returned into the original excavation or used as cleaned "secondary" fill (i.e., road beds, bridge foundations) or aggregate material for concrete and asphalt production. Since the contaminants of interest are typically concentrated in the fine soil fractions, their separation and segregation from the bulk soil increases the overall effectiveness of the process. Treatment of the spent wash solution prior to recycling is required. The "enriched" contaminated "fines" fraction has now been readied for an appropriate ultimate treatment technology such as solidification/stabilization, biological treatment, solvent extraction, low temperature desorption, incineration, etc.

The soil washing program is evaluating the effectiveness of soil washing technology in removing petroleum products (unleaded gasoline, diesel/home heating fuel and waste crankcase oil) from soils and treating the generated residuals. The program consists of testing of soil washing technology at the bench scale, pilot scale, and through field demonstrations in order to develop the applicability and design criteria for full scale implementation as a long-term corrective action at leaking underground storage tank sites.

INTRODUCTION

Based on the Hazardous and Solid Waste Amendments of 1984 and its Land Ban Regulations, the U.S. EPA has discouraged the excavation and landfill disposal practices of the past for contaminated soils resulting from leaking underground storage tanks (USTs). The U.S. EPA has encouraged the use of on-site treatment technologies, however, problems have plagued the development of on-site treatment technologies for the treatment of petroleum contaminated soils. Technical support is needed to develop effective long-term corrective actions at leaking underground storage tank sites, design cleanup program guidance, and help implement state programs.

The remedial options available for the treatment of contaminated soils from UST sites are broadly segregated into two main categories, namely those which remove the contaminants without excavation (in-situ techniques) and those which require excavation of the soil and subsequent cleaning on-site. The former group of remedial options have not yet been demonstrated for high efficiency removal of contaminants from the subsurface. These techniques are plagued by the uncertainty of soil contamination levels in the subsurface after treatment. Soil excavation followed by extensive cleaning of the soil will ensure a more complete and expedient removal of contaminants over in-situ techniques which require long periods of time.

On-site soil washing of excavated soils is a viable alternative to in-situ techniques and has been shown to be effective for the cleanup of applicable Superfund and leaking underground tank sites. The goal of this effort is to demonstrate the feasibility of soil washing for cleaning up petroleum contaminated soils.

The U.S. EPA developed soil washing technology is a physical process in which excavated soils are contacted with an aqueous based wash solution with selective additives predicated upon the soil characteristics and specific contaminants of interest. The highly water soluble contaminants in the soil matrix are extracted from the solid fraction into the liquid medium. The two principle cleaning mechanisms include the dissolution of the contaminants into the extractive agent and/or the dispersion of the contaminants into the extraction phase in the form of particles (suspended or colloidal).

In addition, the separation of the highly contaminated fine (>74 micron) soil particles (silts, clay and colloidal) from the bulk of the soil matrix is accomplished through the mechanism of volume reduction. As a result, a significant fraction of the contaminated soil is cleaned and can be put back into the original excavation following testing and

approval by the appropriate lead agency. Since the contaminants are more concentrated in the fine soil fractions due to their typically higher cation exchange capacity and "relatively" high surface areas, their removal from the bulk soil increases the overall effectiveness. Subsequent treatment is typically required for the spent wash waters and the fine soil fractions. The information developed from this project is assisting the U.S. EPA in defining the criteria for developing soil washing as a long-term corrective action at leaking underground storage tanks.

PROGRAM STRATEGIES

Under Phase I of the U.S. EPA's research program, a surrogate soil matrix containing a range of petroleum products at varying concentration levels was prepared and subjected to bench-scale performance evaluations of soil washing technology. This paper covers the formulation and characterization of the U.S. EPA's surrogate soil matrix described as the Synthetic Soil Matrix (SSM).

Prior to spiking the full scale quantities of SSM, several bench scale experiments were performed to develop a dose/response relationship between the quantity of petroleum product added to the soil matrix and the analysis quantification. The petroleum products evaluated during this study include unleaded gasoline, diesel oil and waste crankcase oil. The full scale SSM was then blended with a specific quantity of petroleum product to obtain a predetermined concentration level. TPH analysis was performed to verify the concentration levels for diesel and waste oil and BTEX analysis was performed to verify the concentration levels for gasoline.

The bench-scale washing experiments were designed to simulate the U.S. EPA-developed pilot-scale Mobile Soils Washing System (MSWS) or also known as the "mini-washer." Bench-scale experiments simulate the pilot- and full-scale drum-screen washer which separates the >2-mm soil fraction (coarse material) from the <2-mm soil fraction (fines) by use of a rotary drum screen. In the pilot and full scale system, high pressure water knives operate at the head of the system to break up soil lumps and strip the water soluble contaminants of the soil particles and separate the highly contaminated fines from the cleanable coarse fractions.

SYNTHETIC SOIL MATRIX CHARACTERIZATION

The basic formula for the SSM was determined by the U.S. EPA under the Best Demonstrated Available Technology Program from an extensive review of contaminant groups and soils types found at Superfund sites throughout the United States. The SSM was blended from a predetermined mixture of clay, silt, sand, top soil and gravel in two 15,000 pound batches.

A review of the existing soil characteristics were made and additional tests were conducted to further delineate the physical and chemical properties of the SSM. The tests included particle size distribution, moisture retention curve, Atterberg limits, cation exchange capacity, base saturation, organic matter, chemical constituents and mineralogy. Quantification and assessment of these specific properties will assist the technical community to understand the differences that may be observed between the performance of soil washing technology on the SSM and on actual site specific UST site soils.

The SSM is composed of 60 percent sand, 19 percent silt and 21 percent clay as determined by particle size distribution analysis (Table 1 and Figure 1). Based on this composition the SSM would be classified (USDA) as having a sandy clay loam texture. Particle size distribution data may be used to estimate hydraulic properties (Mishra et al., 1989), residual saturation (Hoag and Marley, 1986), capillary movement, bulk density, and surface area of the soil prior to more extensive analyses.

The moisture content of the SSM ranged from 33.1 percent at saturation (0 bar) to 8.7 percent at the permanent wilting point (15 bars). The moisture content at field capacity (0.1 bar) was 21.0 percent. The moisture-retention curve (Fig. 2) developed from the moisture content data was indicative of a finer textured soil. The moisture content data can be used to evaluate moisture and chemical characteristics of the SSM. For example, the amount of soil water that can be extracted from the SSM under typical environmental conditions (0 to 15 bars) will be

Table 1
U.S. EPA Synthetic Soil Matrix Particle Size Distribution (USDA)

		USDA(%)	USCS (%)
GRAVEL			
SAND	TOTAL	60.0	58
	V. COARSE	16.0	
	COARSE	8.8	
	MEDIUM	11.7	
	FINE	23.5	
SILT		19.0	15.2
CLAY		21.0	26.8

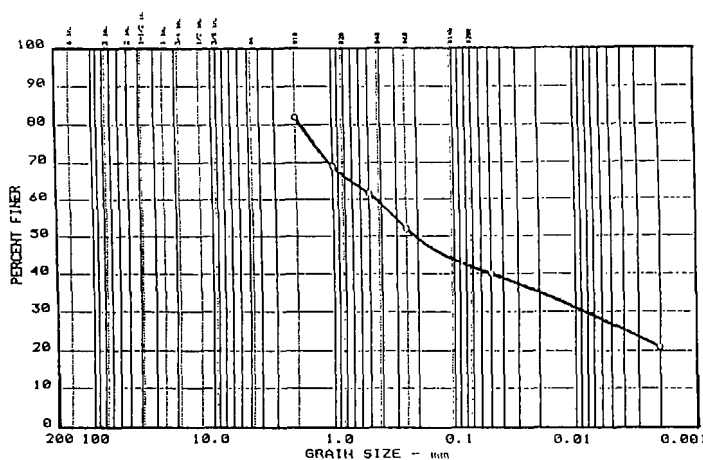


Figure 1
U.S. EPA Synthetic Soil Matrix Particle Size Distribution Curve

24.4 percent. The remaining soil water is considered as "unavailable" which can be removed by artificially induced vacuums or pressures. Some similarities exist between the moisture content and residual saturation of petroleum hydrocarbons in the soil. Generally, stronger competitive adsorption of water for soil occurs and displaces non-ionic organic chemicals that are present in petroleum hydrocarbons (Chiou

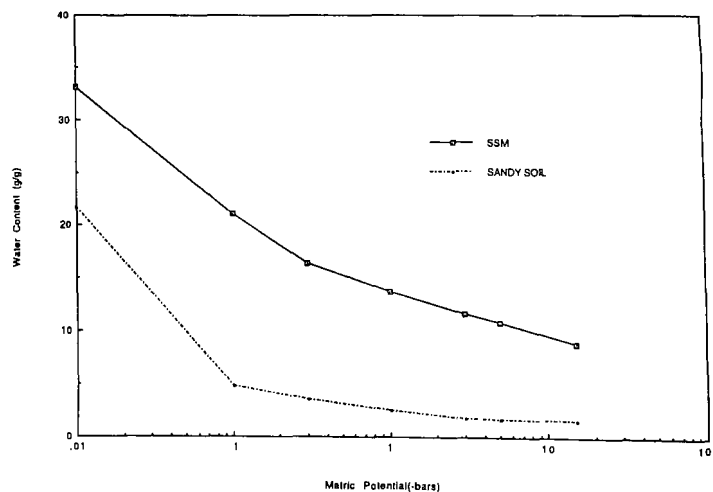


Figure 2
U.S. EPA Synthetic Soil Matrix Moisture-Retention Curves

et al, 1989). Residual saturation will be dependent on moisture content and decrease with increasing moisture.

Analysis of the SSM for concentrations of various exchangeable ions indicated that phosphorous was moderate, potassium was low, and both magnesium and calcium were very high (Table 2).

Table 2
Chemical Characteristics of SSM

PARAMETER	UNITS		TYPICAL RANGE
ORGANIC MATTER	%	1.3	0.4 - 10.0
pH		8	4
CATION EXCHANGE CAPACITY (CEC)	meq/100g	21.7	4 - 34
BASE SATURATION	%	99%	
Ca		86.2	
Mg		12.4	
K		1.3	
H		0	
AVAILABLE PHOSPHORUS	ppm		
WEAK BRAY		20	
NaHCO ₃		31	
POTASSIUM	ppm	112	
MAGNESIUM	ppm	324	
CALCIUM	ppm	3740	

The pH of the SSM was 8.0. This pH value is generally the result of the presence of bases such as Ca²⁺ and Mg²⁺ ions. Such bases may be readily removed with addition of water and/or other ions which may displace the Ca²⁺ and Mg²⁺ ions and thus lower the pH. The pH of the SSM will in part effect the CEC of the pH dependent fraction of the soil (primarily organic matter), and the adsorption of metals. Mobility of most metals such as lead (Pb) will be minimal as long as the SSM pH exceeds a value of 6.5.

Cations exchange capacity of the SSM was 21.7 meq/100g. This CEC value is somewhat typical of soil with a texture finer than a sandy loam or with elevated organic carbon content. Determination of CEC is essential in the evaluation of the fate and transport of charged ionic species, but will have little influence on the non-ionic organic compounds present in petroleum hydrocarbons.

The base saturation of the SSM was 99.9 percent, and was dominated by the Ca²⁺ ion (86.2 percent). Addition of water or any leaching solution should considerably reduce the base saturation of the SSM as the Ca²⁺ is replaced by H⁺ and Al³⁺ ions.

The results of the dose/response tests are shown in Table 3. The lab tests indicate that the soils reach a level of liquid saturation at about 23% liquid (both water and gas or diesel). The tests were conducted such that the soils were all prepared to a 20% water level. However, this limited the amount of gas or diesel which could be mixed into the soil mixture.

At 20% water, the highest achievable BTEX concentration was about 3000 mg/kg. For diesel, at water content of 20%, the highest TPH concentration was 60,000 mg/kg.

The dose/response curves are plotted in Figures 3 and 4. A linear regression of the data yielded the following relationships for dose/responses:

Gasoline:

G = gasoline concentration, mg/kg

B = BTEX concentration (sum of benzene, toluene, ethylbenzene and

Eq. (2) $G = 13.33(B) - 375$

The correlation coefficient r, for this equation is 0.998.

Diesel:

Table 3
UST—Soil Washing Dose/Response Bench-Scale Tests

Job No	Soil (lb)	Water (ml)	Gasoline (ml)	Diesel (ml)	LAB DETERMINED		TPH Concentration (mg/kg)	Dose/Response Ratio
					BTEX Concentration (mg/kg)	TPH Concentration (mg/kg)		
1	100	100	0	2.500	0.000	0.00	0.0	15.0
2	100	100	20	14.020	30.107	20	2.100	33.7
3	100	100	50	37.050	50.345	50	4.420	53.2
4	100	100	10	7.410	14.544	20	1.101 (1300)	13.0
5	100	50	10	12.001	03.996	10	0.576	10.0
6	100	100	0	1.141	0.137	20	0.950	3.3
7	100	100	10	7.910	15.510	30	1.309	5.2
8	100	100	20	15.020	31.020	50	3.100	9.0
9	100	100	30	23.140	41.031	70	5.000 (47.000)	9.0

NOTES:
1) Analytical duplicate samples
2) Not tested

D = diesel fuel concentration, mg/kg

T = TPH concentration, mg/kg

$$\text{Eq. (3)} \quad D = 0.675(T) + 6268$$

The correlation coefficient r, for this equation is 0.995.

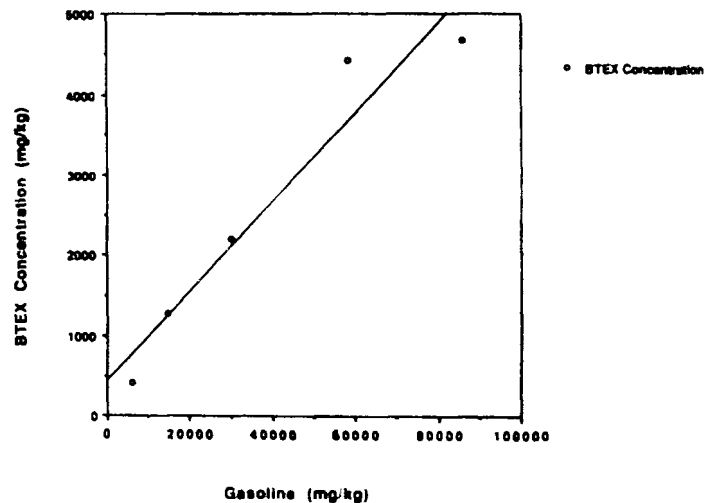


Figure 3
Dose/Response Values for Gasoline

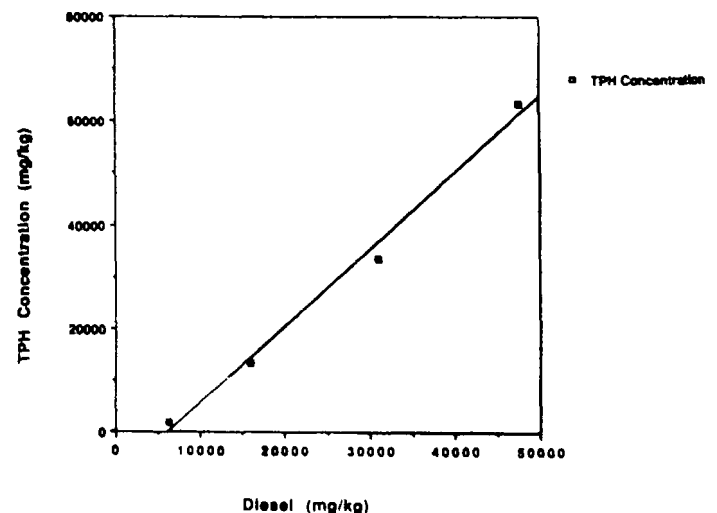


Figure 4
Dose/Response Values for Diesel Fuel

An additional experiment was conducted to determine if a higher level of BTEX could be achieved if a lower moisture content was used. In this experiment, a sample of soil was moistened to a 10% water content and then saturated with gasoline. The results, shown in Table 4 as "Jar 9," indicated that the BTEX content was increased to 4670 mg/kg.

The percent overdose required to achieve desired BTEX concentrations for gasoline are shown in Table 4. Theoretical BTEX added to the soil was calculated by assuming that the gasoline used for these tests consisted of 16% BTEX by weight, as referenced in Table 4. Theoretical amount of BTEX was compared to the lab data to obtain the percent overdose. The amount of overdose obtained based on the above assumption ranged from 80% to 194%.

Table 4
UST—Soil Washing Gasoline/BTEX Overdose Results

Jar No.	Theoretical Added BTEX Concentration** (mg/kg)	Lab Determined BTEX Concentration (mg/kg)	% Overdose
1	976	406	140
2	4,829	2,200	120
3	9,335	4,420	111
4	2,343	1,280	83
9	13,753	4,670	194

** This number represents 16% of the added gasoline concentration as referenced by Hoag, G.E.; Bruell, C.J.; Marley, M.C., 1984, A study of the mechanisms controlling gasoline hydrocarbon partitioning and transport in groundwater systems. Storrs, CT: Institute of Water Resources, University of Connecticut. Prepared for U.S. Department of the Interior, Geologic Survey Reston, VA. Project No. USGSG832-06, NTIS No. PB85-242907.

Equations 1 and 2 can be used to determine the amount of diesel or gasoline to add the SSM to reach the desired concentrations. Based on these calculations, estimates were made to determine the amount of gasoline and diesel fuel to add to the SSM to obtain the desired concentrations of BTEX and TPH for the bench scale experiments. The SSM blends were prepared in the U.S. EPA SSM Blending Facility in Edison, NJ in 50 lb batches for use in the bench scale soil washing experiments.

SUMMARY AND CONCLUSIONS

With the SSM being fully characterized and the dose/response tests completed, the next step was to conduct bench scale soil washing tests. These experiments involved washing the SSM spiked with gasoline, diesel fuel, or waste crankcase oil under several operating conditions to obtain sensitivity analysis curves on various parameters affecting soil washing efficiency.

The experiments were conducted by contacting approximately 1400 g of soil with varying amounts of washwater. The contact time varied according to experiment as did the rinsewater volume. The washing of the soils was conducted by shaking the soil and washwater in a 2-gallon jar in a shaker table operating with a stroke and frequency of 1.6 inches and 4 Hz respectively. The rinsing of the soils was performed in a Gilson Wet-Vac Model WV-1 which both rinsed the soils as well as separated the particles into three fractions using No. 10, No. 60 and No. 140 sieve trays. The process of the washing and rinsing yielded five distinct fractions - the soils on the three sieve trays, a washwater, and a rinsewater. All fractions were measured for mass (or volume) as well as contaminant concentration. A measure of total BTEX (benzene, toluene, ethylbenzene and o-, m-, and p-xylenes) was used on gasoline spiked soils, and total petroleum hydrocarbons (TPH) was used on diesel spiked soils.

Preliminary screening tests were conducted on soils spiked with diesel and gasoline to determine the optimum conditions for contact time, washwater volume, rinsewater volume and washwater temperature.

Figures 5 through 8 present some of the data obtained from the screening experiments. The results of the screening indicate that the optimal washwater parameters for SSM spiked with diesel and gasoline are: 20 to 30 minute contact time, 1:1 soil to washwater mass ratio, 3:1 rinsewater to washwater volume ratio, and ambient temperature for the washwater. These conditions resulted in a 90+% removal of TPH and BTEX in the No. 10 and No. 60 sieve fractions.

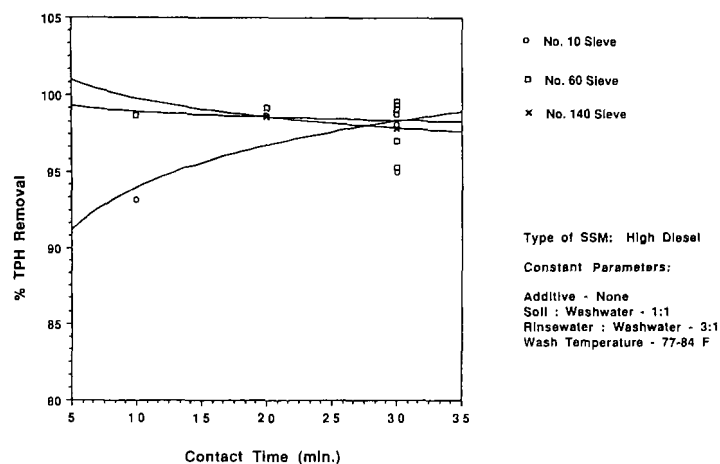


Figure 5
Contact Time Effect on Percent TPH Removal

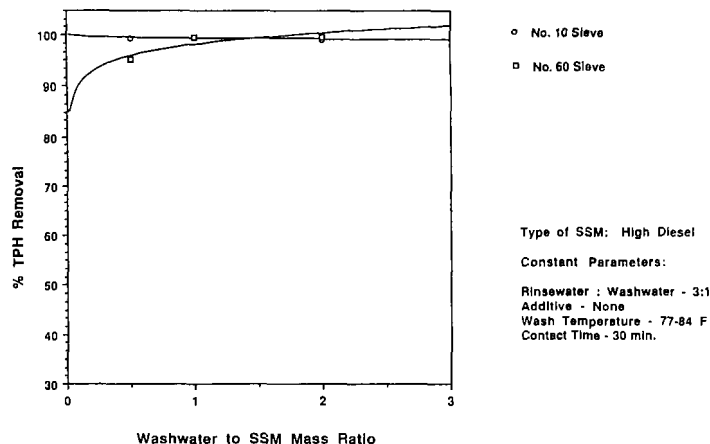


Figure 6
Washwater to Soil Ratio Effect on Percent TPH Removal

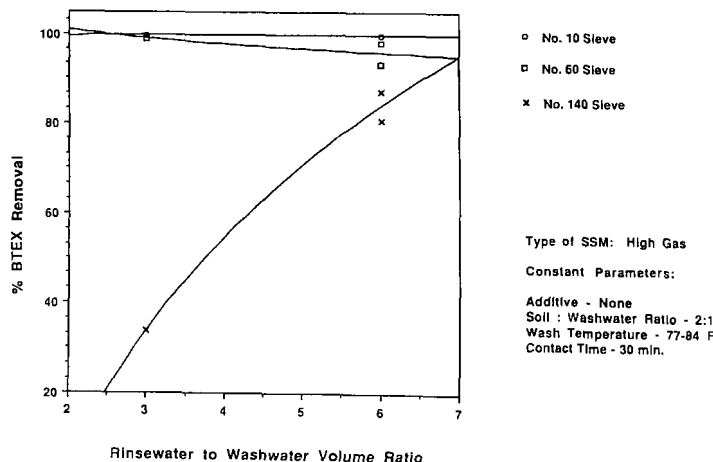


Figure 7
Rinsewater to Washwater Ratio Effect on Percent BTEX Removal

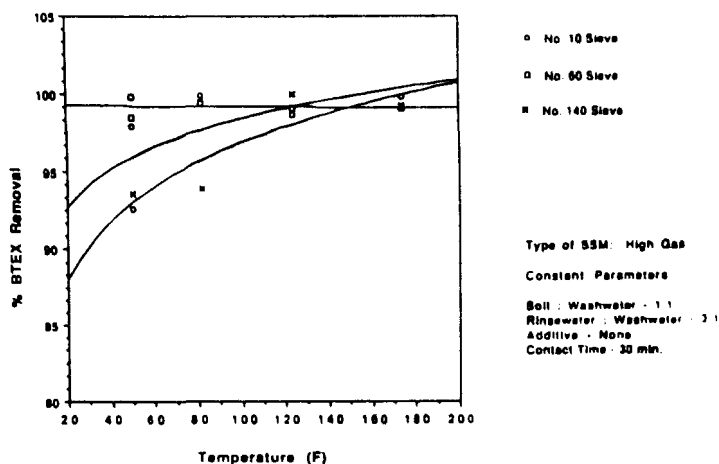


Figure 8
Temperature Effect on Percent BTEX Removal

It should be noted that the conditions stated above represent the most cost-effective operating conditions for bench scale treatment of SSM using soil washing technology. Operating conditions for each site soil may vary and should be determined on a case by case basis.

The SSM can be characterized as somewhat alkaline, sandy clay loam with a moderated CEC and low organic matter content. The alkaline nature of the SSM is due to the presence of dolomitic limestone. The clay formulation of the SSM is only partially represented by kaolinite and montmorillonite. The swelling of the SSM is minimal.

Soil washing of the SSM should decrease the pH and base saturation while removing a considerable amount of the Ca^{2+} and Mg^{2+} . As the limestone is removed, the texture of the SSM should become coarser. Organic carbon determinations should be made only after removal of the inorganic carbon.

The dose/response tests provided the necessary information to determine how much gasoline and diesel fuel should be added to the SSM to obtain the desired concentrations of BTEX and TPH respectively.

Preliminary soil washing bench scale screening tests indicate that removals of greater than 90% of BTEX and TPH can be obtained for soils in the No. 10 and No. 60 sieve fractions using the following operating conditions: 20-30 minute contact time, 1:1 soil to washwater mass ratio, 3:1 rinsewater to washwater volume ratio, and using washwater at ambient temperature.

Further work is being conducted to determine what, if any, effect additives to washwaters have on the removal of TPH on soils spiked with waste oils. The additives being investigated are CitriKleen (an organic-based solvent), and a surfactant. Bench scale experiments will also be conducted using actual site soils where leaking underground storage tanks have resulted in soils contaminated with gasoline and diesel. The results and conclusions of these experiments will be published in future papers.

These initial results show great promise in providing a feasible and cost-effective technology to the user community in the remediation of soil contaminated with petroleum hydrocarbons from leaking underground storage tanks, large buck storage tank farms, refineries and associated transportation and handling accidents. Stay tuned for further developments!

REFERENCES

1. Chiou, C.T., "Theoretical considerations of the partition uptake of nonionic organic compounds by soil organic matter." In B.L. Sawhney and Brown (eds.), "Reactions and movement of organic chemical in soil." *Soil Science Society of America, Inc. American Society of Agronomy, Inc. Madison, WI, 1989.*
2. Hoag, G.G. and Marley, M.C., "Gasoline residual saturation in unsaturated uniform aquifer materials." *J. of Env'l Eng., 112* (3): pp. 586-604, 1986.
3. Lindsay, W.L., "Chemical Equilibria in Soils." John Wiley & Sons, New York, NY, 1979.
4. Mishra, S., Parker J.C. and Singhal, N., "Estimation of soil hydraulic properties and their uncertainty from particle size distribution data." *J. of Hydrology, 108* pp. 1-18, 1989.
5. Nelson, D.W. and Sommers, L.E., "Total Carbon, and organic matter." In A.L. Page (ed.), "Methods of Soil Analysis Part 2, Agronomy monograph No. 9 (2nd ed.)." *Soil Science Society of America, Inc. Madison, WI, 1982.*
6. PEI Associates, Inc., "CERCLA BDAT SARM Preparation and Results of Physical Soil Washing Experiment." 1988.
7. Traver, R.B., "Development and Use of the EPA's Synthetic Soil Matrix (SSM/SARM)." U.S. EPA Releases Control Branch, Risk Reduction Engineering Laboratory, Edison, NJ, 1989.

Bench- and Pilot-Scale Case Studies for Metals and Organics Removals from CERCLA Site Soils

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ABSTRACT

Efforts are being made to devise technologies and treatment systems to remediate contaminated soil on site without generating significant wastes for off-site disposal. Two technologies under current study are washing excavated soils in above ground treatment units (soil washing) and flushing soils in place, without excavation (soil flushing). A recent bench-scale soil washing study was performed on soil samples with high organics and metals contamination obtained from a CERCLA site. The soil washing study demonstrated greater than 90% removal of a large number of the contaminants using various surfactant, organic solvent and acid washing solutions. For a second CERCLA site, a pilot soil flushing study is being conducted by passing water, or water with modifying additions, through columns of undisturbed soils. The three-phased soil flushing study has, to date, demonstrated significant removals of metal and organic contaminants. The pilot study has also yielded preliminary identification of relationships between various flushing process parameters, which will be confirmed in the third phase of the study.

INTRODUCTION

In concept, soil washing consists of applying a solvent solution to excavated soil placed in an above ground treatment system and processing the soil until adequate amounts of contaminants are removed. The process of soil washing, depicted in Figure 1, consists of segregating excavated soils into appropriate size fractions, feeding the soils into a tank containing a solvent and allowing the solvent to dissolve soil contaminants into the liquid solvent phase¹. The excavated soils may require dewatering to remove excess liquids prior to washing the soil solids. These steps are followed by separating the resulting solid phase for further treatment and/or disposal. The treated solids may require dewatering prior to disposal. Frequently, the used solvent (or soil washing solution) is collected and treated to allow recycle back to the treatment system to reduce costs.

Transfer of contaminants from the soil solids to the liquid phase can occur by dissolution, chelation or shearing of the contaminants bound to a soil matrix due to the action of the solution. The exact nature of the soil washing solution required depends on the chemical nature of the contaminants to be removed and the mineralogy of the soil.

Selection of the optimum washing process would be based on data derived from treatability studies, beginning with the type described in this paper, as well as pilot study for testing the most promising process options. Process options for consideration would include: a continuous-mix batch reactor, a high-pressure washer, a soaking system, a counter-current or concurrent flow system or any combination of these processes.

Soil flushing, as described in this paper, is the application of a solvent solution (usually water) to the ground surface (or at depth) of an unexcavated, undisturbed soil, allowing the solution to percolate downward

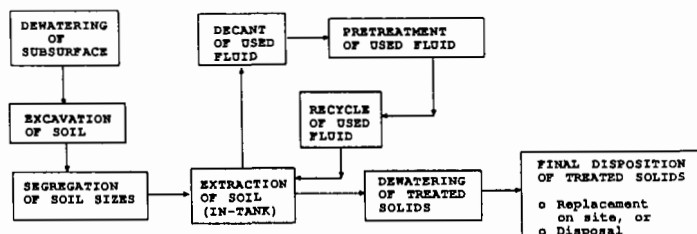


Figure 1
Concept for Soil Washing

and "flush" the entire soil contamination zone. A number of methods could be used to apply the solution, including infiltration by surface ponding, subsurface drainage fields, spray irrigation or pumping to the subsurface using wells or well points. At the base of the contamination zone, the flushing effluent is recovered at the groundwater table using subsurface drainage pipes, trenches, wells or well points. Frequently, the effluent from flushing is treated to allow recycle back to the flushing system. In the majority of cases, water is used as the flushing solution, although dilute acids or bases, chelating agents, selected minerals, aqueous surfactant solutions and organic solvents have been suggested.

In this paper, a soil washing and a soil flushing bench-scale study are discussed and the results from each are presented. Each study was conducted on soils from separate hazardous waste (i.e., CERCLA) sites.

SOIL WASHING STUDY

Site Conditions

The Soil Washing Study was conducted on soil from a non-operating commercial tract of land (approximately 6 ac) located within the Piedmont geologic province of New Jersey. As shown by the cross-section in Figure 2, materials encountered at successively lower depths in the subsurface are: (1) fill soil having variable compositions and particle sizes, (2) peat, (3) silt and (4) clay². Over the site area, the fill soil ranges from about 3 to 11 ft.

Figure 3 presents a representation of the fill soil components which include natural soil particles (including clay and peat) as well as waste fragment materials from site construction. The total volume of contaminated fill and peat is approximately 115,000 yd³ (c.y.). The site is covered with construction debris. A sludge disposal or spill area contains dark, greasy sludge underneath a dry soil crust. A 10,000-gal waste tank, which contains less than 20 c.y. of highly contaminated sludge, is present on-site.

Information from past site investigations indicates that there are three groundwater aquifers on-site: (1) a water table aquifer, (2) a till aquifer and (3) a bedrock aquifer. The water table is typically only 2 ft below

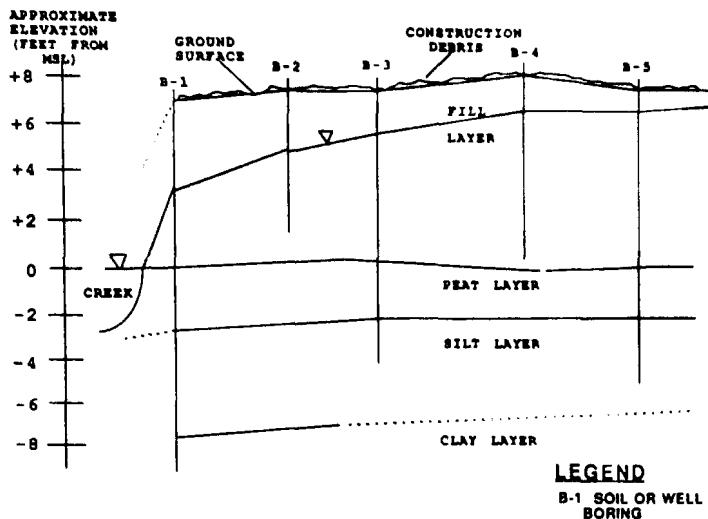


Figure 2
Cross Section of Site for Soil/Waste Washing Study
(Reference: ERM, Draft Feasibility Study)

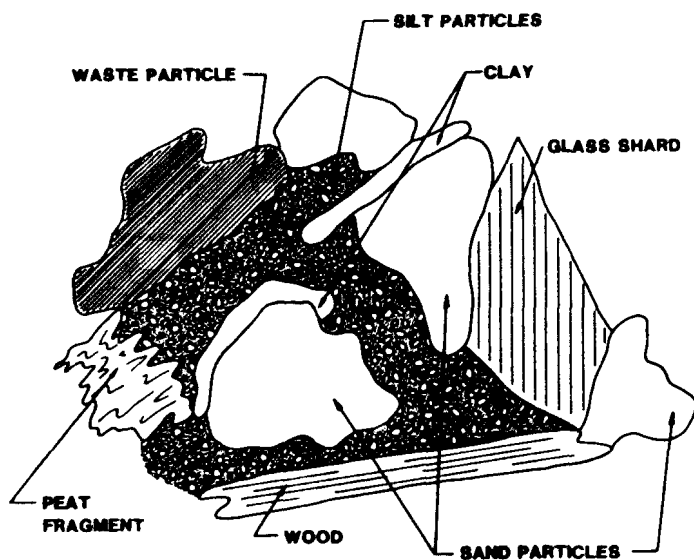


Figure 3
Representation of Fill Soil Components
(Enlarged)

the ground surface. To date, possible groundwater contamination in these aquifers has not been fully characterized.

Study Objectives

The overall objective of the Soil Washing Study was to make a preliminary evaluation of onsite soil washing technologies for remediating the contaminated fill soil, as well as tank and pit wastes, at the CERCLA site. Tank and pit wastes were evaluated since their relatively small volume may make them candidates for coprocessing with the soil. The specific objectives of the Soil Washing Study were to provide a preliminary indication of the following:

- The feasibility of extracting metals and organic chemicals from the site soil and waste
- The type(s) of solvents that may remove significant percentages of the soil/waste contaminants
- The types of contaminants that may be difficult to remove
- The solution contact time required for removal of contaminants and
- The levels of contaminants that may be transferred to the used solutions

Site Sampling

Sampling locations were selected to obtain soil and waste sample composites representative of the range of contaminant types and concentrations at the site. Composite samples were obtained to represent the highest detected concentrations of individual contaminants and overall site contamination. Consequently, soil washing tests were conducted on the following six soil and waste samples:

- A soil composite containing the highest concentrations of all soil contaminants ("High Contamination Soil")
- A soil composite for high lead contamination ("High Lead Soil")
- A soil composite for high PCB contamination ("High PCB Soil")
- A soil composite containing all soil contaminants, but at concentrations less than that for soil areas (i.e., "hot spots") with contamination similar in magnitude to that of the highest detected concentrations of contaminants ("Overall Soil Composite")
- A waste composite for high base neutral organics contamination ("High Base Neutrals Waste") and
- A composite of all wastes from the Waste Tank and the Waste Pit ("Overall Waste Composite")

These composite samples consisted of combined grab samples of soil and tank/pit wastes. Actual sampling locations and depths were selected based on a previous site investigation. Soil sampling depths varied between 0 and 5 ft below the ground surface. Grab samples were collected using back-hoes followed by shovels or hand trowels. One or more grab sample layers were placed in a Teflon-lined, plastic collection bag, depending on the type of composite sample required. Considerable amounts of rubble were present at some of the sampling locations. Rubble material was not included in the soil/waste samples.

Soil/Waste Characterization

All sample analyses in this study were conducted by a U.S. EPA-certified Contract Laboratory Program (CLP) laboratory. Analyses conducted are listed in Table 1. All analyses were reported as individual organic compounds (or elemental metals), except that petroleum hydrocarbons were reported as a total compound class. CLP protocol followed included the Statement of Work (SOW) 1086 for organics (with revisions through SOW 7/87 for inorganics). Either the CLP Low Concentration Method or the CLP Medium Concentration Method for solid samples was used in analyzing the study samples for organics. The High Concentration Method included in the CLP protocol was not used for this study, since it was not approved by U.S. EPA. At the time of the study, U.S. EPA had not approved any laboratories to perform the High Concentration Method.

All sample types had high organic chemical and heavy metal concentrations, even the sample type (Overall Soil Composite) which represented the average soil concentrations. Certain sample types contained fragments of concentrated organic solids or sludges. The High Contamination Soil Composite contained notably higher concentrations than the Overall Soil Composite of the following contaminants: copper, lead, cadmium, xylene, ethylbenzene, toluene and trichloroethene.

The High Base Neutrals Waste Composite contained no detectable levels of base neutral organic compounds. The lack of base neutrals may be due to either; (1) uncertainties in the data base used to select the sampling locations or, (2) a high variability in the contamination levels in the Waste Pit Area. The Tank/Pit Waste Composite contained high concentrations of total PCBs, total xylenes, lead, copper and chromium.

Selection of Solutions

In designing the Soil Washing Study, various chemicals and chemical solutions were evaluated for possible use. This evaluation was based on the results of a literature survey and direct communications with chemical vendors, various research and development branches of the U.S. EPA and investigators conducting similar studies. The solutions used in this study had been used at other sites to reduce organic and/or inorganic contaminant levels in soils. In the Soil Washing Study, higher solution strengths were used than those reported in the literature, since contaminant levels at the site were higher.

Table 1
Summary of Raw Sample Analyses for Selected Parameters

CONTAMINANTS	CONCENTRATION (in mg/kg) IN STUDY SAMPLES					
	HIGH CONTAMINATION SOIL	OVERALL SOIL	PCBs SOIL	LEAD SOIL	BASE NEUTRALS WASTE	OVERALL WASTE
PCBs						
Aroclor 1242	190	ND	ND	---	---	130,000
Aroclor 1254	22.0 J	ND	ND	---	---	16,000
Aroclor 1260	ND	ND	5.2 J	---	---	ND
Volatile Organics						
Methylene chloride	5.6 J	1.3	---	---	---	970
Acetone	64.0	2.4	---	---	---	2,100
trans-1,2-Dichloroethene	4.7 J	0.7	---	---	---	ND
Chloroform	140	3.8	---	---	---	4,800
1,2-Dichloroethane	93	ND	---	---	---	1,700
1,1,1-Trichloroethane	47	ND	---	---	---	600
Trichloroethene	270	ND	---	---	---	1,500
4-Methyl-2-pentanone	28.0 J	0.16	---	---	---	2,400
Trichloroethene	ND	1.8	---	---	---	1,500
Benzene	ND	0.45	---	---	---	970
Tetrachloroethene	210	7.6	---	---	---	70,000
Toluene	530	3.6	---	---	---	29,000
Chlorobenzene	7.3 J	0.45	---	---	---	ND
Ethylbenzene	88	1.2	---	---	---	3,000
Xylenes (total)	390	14.0	---	---	---	12,000
Base Neutral Organics						
Phenol	ND	ND	---	---	ND	4,000
1,2-Dichlorobenzene	17.0 J	ND	---	---	ND	16,000
Naphthalene	31.0 J	ND	---	---	ND	290
1,2,4-Trichlorobenzene	ND	ND	---	---	ND	920
2-Methylnaphthalene bis(2-Ethylhexyl) phthalate	15.0 J	ND	---	---	ND	140
Diethyl phthalate	15.0 J	ND	---	---	ND	2,800
Butylbenzylphthalate	ND	ND	---	---	ND	300
Phenanthrene	19.0 J	ND	---	---	ND	ND
Di-n-Butylphthalate	29.0 J	ND	---	---	ND	270
Metals						
Antimony	3.9	3.8	---	---	---	421
Arsenic	7.7	14.8	---	---	---	33.8
Beryllium	0.6	0.4	---	---	---	0.0
Cadmium	18.6	0.7	---	---	---	361
Chromium	81.3	89.8	---	---	---	6,060
Copper	1,790	399	---	---	---	4,020
Lead	979	596	---	1,540	---	59,700
Mercury	6.7	8.5	---	---	---	103
Nickel	20.8	26.4	---	---	---	35.6
Selenium	1.5	1.3	---	---	---	11.1
Zinc	612	874	---	---	---	2,510

NOTES: (1) Source: ERM, Draft Feasibility Study, 1989

(2) Study sample identifications are as follows:

PCB Soil	High PCBs Soil Composite
Lead Soil	High Lead Soil Composite
High Contamination Soil	High Contamination Soil Composite
Overall Soil	Overall Soil Composite
Base Neutrals Waste	High Base Neutrals Waste Composite
Overall Waste	Overall Waste Composite

(3) An unexpected result was the detection of no base neutral organics in the High Base Neutrals Waste sample, which was collected from previously identified sampling points. The cause of this result is unknown.

--- Not analyzed
ND Not detected

This study included soil and waste sample washing with four solutions: (1) a 5% (by weight) solution of aqueous surfactant (i.e., Triton-X-100), (2) a 10% (by volume) solution of hydrochloric acid and (3) both a 5% and (4) a 10% (by weight) solution of citrate solvent (i.e., Citrikleen). Water was used as a base for preparation of all wash solutions. Each wash solution was analyzed for the same contaminants as the soil samples. The Triton-X-100 surfactant did not contain any of the organic compounds detected in the soil/waste samples and the Citrikleen contained only one (i.e., acetone) of these compounds.

Total petroleum hydrocarbons were detected at levels of 5.2 and 4.1 mg/L in the 5% Triton-X-100 and the 5% Citrikleen solutions, respectively. The surfactant solution contained less than 0.5 mg/L each of copper, lead and zinc. The citrate solvent solution contained less than 0.5 mg/L each of copper, lead, zinc and chromium. These hydrocarbon and inorganic contaminants could have been introduced into the solution by the laboratory or by the manufacturers of the Triton-X-100 or Citrikleen. The hydrochloric acid solution contained trace amounts of inorganics but no organics.

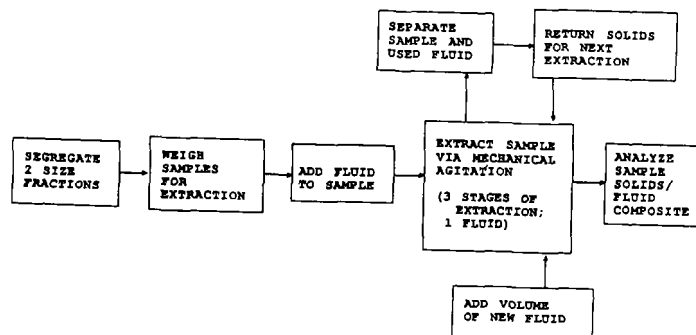


Figure 4
Soil Washing with One Fluid

Table 2
Soil Washing Study
Soil/Waste Process Trials

TABLE 2 SOIL WASHING STUDY SOIL/WASTE PROCESS TRIALS						
TYPE OF PROCESS TRIAL	SOLUTION TYPES/ STRENGTH	PROCESS TRIAL NUMBER	SAMPLE TYPE INVESTIGATED	SYSTEM CONTACT TIME	STAGE OF CONTACT TIME (MIN.)	NUMBER OF STAGES (MIN.)
Washing with One Fluid	Hydrochloric acid/ 10%	PT-1 through PT-12	High Lead Soil	45/90/180	15/30/60	3
			High Contamination Soil	45/90/180	15/30/60	3
			Overall Soil Composite	45/90/180	15/30/60	3
	Triton-X-100/5%	PT-13 through PT-24	High PCB Soil	45/90/180	15/30/60	3
			High Contamination Soil	45/90/180	15/30/60	3
			Overall Soil Composite	45/90/180	15/30/60	3
	Citrikleen/5%	PT-25 through PT-36	High PCB Soil	45/90/180	15/30/60	3
			Overall Soil Composite	45/90/180	15/30/60	3
			High Base Neutrals Waste	45/90/180	15/30/60	3
	Citrikleen/10%	PT-37 through PT-48	High PCB Soil	45/90/180	15/30/60	3
			Overall Soil Composite	45/90/180	15/30/60	3
			High Base Neutrals Waste	45/90/180	15/30/60	3
Washing with Multiple Fluids (Sequential)	Triton-X-100/5% Hydrochloric acid/10% Citrikleen/10%	PT-49 through PT-51	High Contamination Soil	270	90	3
			Overall Soil Composite	270	90	3
			Overall Waste Composite	270	90	3

NOTE: The fluid application ratio was maintained at a constant (10 g fluid: 1 g sample) for all process trials.

All solutions at their application strengths had relatively low viscosity. Both the surfactant and citrate solutions were opaque and tended to foam when agitated. The hydrochloric acid solution tended to emit acid fumes when agitated. The surfactant had a musty odor and the citrate solvent had an odor of oranges.

Soil/Waste Washing Trials Using One Solution

Figure 4 provides a simplified representation of the washing trials using one wash solution (i.e., process trials PT-1 through PT-48). Each trial consisted of three individual washes (or process stages) performed on the same, preweighed volume of a single sample type.

Most of the process trials run in this Soil Washing Study involved washing soil or waste samples with only one of the selected solutions. The limited time available for completing the trials (2 wk) and sample analyses (3 wk) required the study to focus on only two process variables: the type of washing solution and the total time in which a sample type was in contact with a solution (i.e., the "system contact time"). Forty-eight different trials were conducted using the six sample types, four different washing solutions and various system contact times. Table 2 contains a list of the different combinations used.

As shown, contact time varied among trials with the acid solution, the Triton-X-100 and the Citrikleen. For each sample and solution type, three process trials were performed, each with a different system contact time, to determine the effect of contact time on contaminant removal. The weight of sample per weight of solution (i.e., the "application ratio") was maintained at a constant (25 g of sample per 250 mL of solution) for all 48 trials.

Sequential Washing Trials Using Multiple Solutions

In addition to the process trials for testing a single solution type, three "sequential trials" were performed which consisted of successively washing a single sample type with more than one solution. Figure 5 provides a simplified representation of the three sequential trials: PT-49, PT-50 and PT-51. In each trial, the following three solutions were applied to the same sample volume, each solution being applied in a separate washing stage: 5% aqueous surfactant, 10% hydrochloric acid and 10% Citrikleen. Each solution was applied for 90 min in a single stage (unlike the earlier trials), so that three washing stages resulted. The same application ratio was used as for the previous 48 trials.

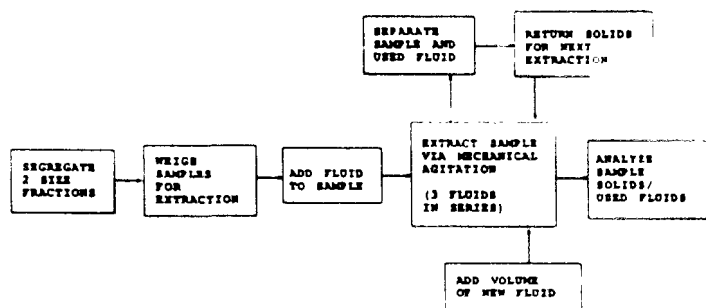


Figure 5
Sequential Washing with Multiple Fluids

Results of the Soil Washing Study

For the trials with a single solution, the process samples collected and analyzed included: (1) the treated sample solids prior to a final water wash, (2) the final, treated sample solids and, (3) a composite of the solution volumes used in each washing stage. For the three sequential trials, the process samples collected and analyzed included: (1) the final, treated sample solids, (2) the used aqueous surfactant from the first stage, (3) the used hydrochloric acid from the second stage, (4) the used Citrikleen solution from the third stage, (5) the water wash at the end of the second stage (6) the sodium carbonate wash following the second stage water wash and (7) the final water wash. The carbonate wash was used to neutralize the sample prior to washing with the citrate-based solution (the last stage). Table 3 summarizes the results of these process sample analyses.

The percent contaminant removals achieved in the washing trials are summarized in Table 3. As shown, washing with hydrochloric acid generally removed a high percentage of lead from all sample types investigated. The acid washing also removed a high percentage of copper, but a lesser percent of chromium. Washing with 5% surfactant removed a high percent of PCBs (between 66 and 78%) and total xylenes (between 87 and 99%). The 5% Citrikleen solution removed between 91 and 98% of a number of volatile and base neutral organics, but the degrees removal of PCBs with this solution could not be determined due to analytical difficulties. Table 5 summarizes some observations about how certain process variables affected contaminant removals.

This preliminary study did not attempt to remove the maximum possible contamination, but generally showed that high removals are possible. Used wash solutions contained high levels of metal and organic contaminants. Notable levels of selected contaminants, as detected in the used solutions, are summarized in Table 4.

Residual concentrations (i.e., following washing) of lead, copper and chromium of up to 733, 363 and 68 ppm, respectively, remained in the washed High Contamination Soil sample (Table 3). Between 80 and 450 ppm of lead residual was detected in the washed High Lead Soil. Residuals of PCBs, xylenes and toluene of up to 7.4, 9.6 and 4.8 ppm, respectively, remained in the High Contamination Soil sample. Residuals of xylenes and tetrachloroethene of up to 1.8 and 0.96 ppm, respectively, remained in the washed Overall Soil Composite. However, the degree of removal of PCBs, xylenes and toluene in this sample was inconclusive due to analytical difficulties.

Table 3
Summary of Percent Removals¹ for Selected Contaminants

CONTAMINANTS	PERCENT REMOVAL FOR STUDY SAMPLES ⁽²⁾					
	HIGH CONTAMINATION SOIL	OVERALL SOIL	PCB SOIL	LEAD SOIL	BASE NEUTRAL WASTE	OVERALL WASTE
Volatile Organics						
Tetrachloroethene	83-95	82-87	---	---	---	86-99
Xylenes (total)	87-98	87-92	---	---	---	81-99
Methylene Chloride	ND	99	---	---	---	92-96
Toluene	94-99	99	---	---	---	92-99
Ethylbenzene	86-97	99	---	---	---	80-99
Base Neutral Organics						
Phenol	ND	ND	---	---	NC ⁽³⁾	85-91
1,2-Dichlorobenzene	99	ND	---	---	NC ⁽³⁾	81-90
1,2,4-Trichlorobenzene	NC	ND	---	---	NC ⁽³⁾	82-92
Naphthalene	99	ND	---	---	NC ⁽³⁾	82
Bis(2-ethylhexyl) phthalate	75	NC	---	---	NC ⁽³⁾	61-89
PCBs						
Aroclor 1260	ND	ND	58-77	---	---	NC
Aroclor 1254	66-78	NC	ND	---	---	91-99.9
Aroclor 1242	73	NC	ND	---	---	ND
Total Petroleum Hydrocarbons	NC	NC	---	---	---	NC
Heavy Metals						
Chromium	43-66	55-63	---	---	---	63-71
Copper	80-95	78-84	---	---	---	72-82
Lead	25-89	86-95	---	70-98	---	75-81

NOTES: (1) Source: ERM, Draft Feasibility Study, 1989.
 (2) Study sample identifications are as follows:
 PCB Soil: High PCBs Soil Composite
 Lead Soil: High Lead Soil Composite
 High Contamination Soil: High Contamination Soil Composite
 Overall Soil: Overall Soil Composite
 Base Neutral Waste: High Base Neutral Waste Composite
 Overall Waste: Overall Waste Composite
 (3) An unexpected result was the detection of no base neutral organics in the High Base Neutral Waste sample, which was collected from previously identified sampling points. The cause of this result is unknown.
 ND: Not analyzed
 NC: Not detected
 NC: Not conclusive

Table 4
Soil Washing Study Contaminant Levels in Used Solutions

PROCESS TRIAL	WASHING SOLUTION (STRENGTH, %)	CONCENTRATION LEVELS (ppm)				
		LEAD	COPPER	CHROMIUM	TOTAL PCBs	PETROLEUM HYDROCARBONS
PT-1 to PT-12	Hydrochloric acid 10%	22-5,450	10-8,348	1-3,633	---	---
PT-13 to PT-24	Triton X-100, 5%	---	---	---	0-6,180	32-140
PT-25 to PT-36	Citrikleen, 5%	---	---	---	0-3,460	970-5,800
PT-37 to PT-48	Citrikleen, 5%	---	---	---	0-2,44	170-470
Not analyzed						

Suitability of CLP Methods

During sample analyses, significant analytical difficulties were encountered from the use of U.S. EPA CLP methods. These difficulties, listed below, often required the laboratory to report residual contaminant concentrations as less than between 10 and 2,500 ppm, rather than the lower, actual value expected.

- The methods did not include a procedure for analyzing samples containing surfactants. Consequently, a foam was generated during the preparation and analysis of samples previously washed with surfactant solution. The foaming problem interfered with the introduction of the preparation extract into the GC/MS and could only be mitigated by repeated sample dilutions.
- Contaminant concentration values were obtained for treated samples and used solutions in cases where contaminant levels were lowered to within the calibration range of the analytical instrument (i.e., the GC/MS). However, the methods frequently did not allow determination of precise contaminant concentrations in solid and liquid process samples. This problem is relatively common during contaminated soil analysis and was due to the high levels of multiple

Table 5
Observed Effects of Process Variables

PROCESS VARIABLES	GENERAL EFFECTS OBSERVED
FLUID TYPE	Higher PCB removals were achieved with citrate-based solvent that with surfactant (Triton-X-100) Similar removals of toluene, xylenes, ethylbenzene, and tetrachloroethene were achieved with the citrate-based solvent and with Triton-X-100.
SYSTEM CONTACT TIME (SCT) (1)	PCB removal via extraction with Triton-X-100 increased as the SCT was increased over 45 minutes. Removals of toluene, xylenes, ethylbenzene, and tetrachloroethene did not increase with increasing contact time, fo extractions with Triton-X-100. Lead removal via extraction with hydrochloric acid increased as the SCT was increased over 30 minutes. This trend was not observed for copper and chromium removal.
USE OF A WATER WASH	Overall metal removals increased after application of a final water wash. Overall organics removals were not increased by applying a final water wash.

NOTE: (1) The system contact time is the total time (over all washing stages) that the soil/waste sample was in contact with the extraction fluid.

contaminants, making high sample dilutions necessary to keep the chromatographic peaks for the contaminants within the instrument range.

SOIL FLUSHING STUDY

Objectives

The Bench-scale Soil Flushing Study was initiated at a hazardous waste (CERCLA) site to investigate and determine the feasibility of soil flushing as a remedial technology for subsurface soils. A second and related purpose was to determine the contaminant retardation characteristics of soils within the existing groundwater contamination plume of the site. This information is required for the design of facilities to recover and treat groundwater.

The flushing study was planned in three phases:

- Phase I - Preliminary Bench-scale Investigation
- Phase II Flushing Water Bench-scale Investigation
- Phase III Final Bench-scale Testing

In Phase I, a preliminary estimate of flushing feasibility were made. In Phase II, the effects of different additions to the water used for flushing were evaluated. The purpose of Phase III is to confirm the feasibility of flushing by bench-scale testing using the methods and procedures optimized in the first two phases.

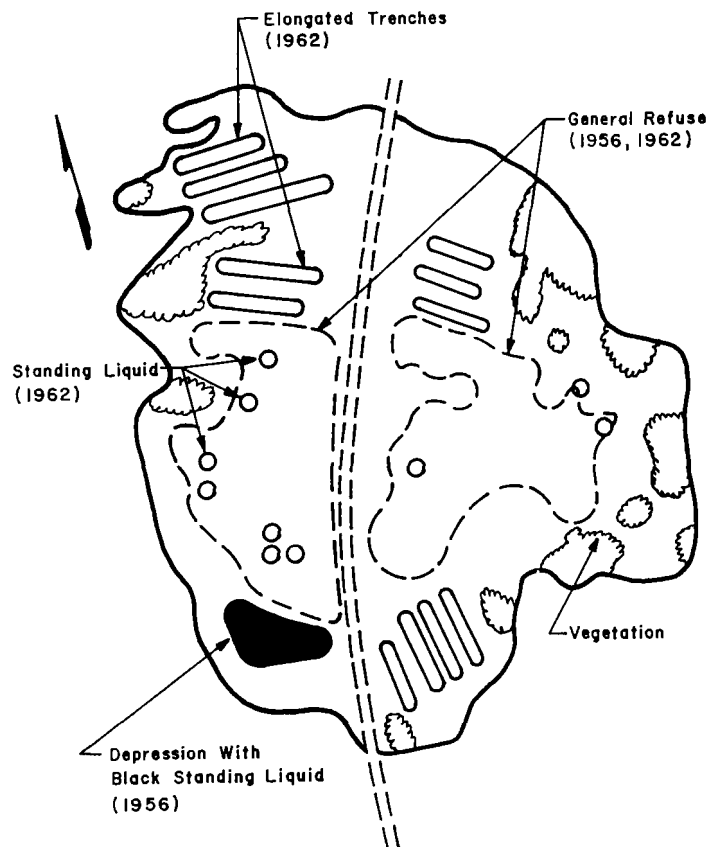
To date, Phase I and II have been completed and are the subject of this report.

Site Conditions

The hazardous waste site investigated is located within the Atlantic coastal plain of the eastern United States. The site was operated as an uncontrolled hazardous waste dump from the early 1950s to 1962. Wastes reportedly were dumped at the site in drums or as bulk liquids and either burned or buried in open pits or trenches. The surface of the site is characterized by the absence of vegetation, the presence of a black tar-like or asphalt-like material and areas containing corroded drums, broken glass and other debris. A composite view of waste disposal activity, taken from past aerial photography of the site, is shown in Figure 6.

The site has remained virtually unchanged since 1962. An initial investigation by the U.S. EPA in 1983 lead to the site being listed on the NPL. In 1986, a remedial investigation of the site was begun by the U.S. EPA. The U.S. EPA has issued a draft feasibility study for the

Figure 6
History of Waste Disposal



site, and a ROD for remedial action will be issued by the end of 1989.

The site topography is relatively flat with occasional small hills. The 32-ac denuded area of the site is surrounded by forest. Soils at the site and in surrounding areas consist of well drained, bleached, weathered sand underlain by a sandy loam subsoil containing minor percents of clay minerals. These soils have a low organic content, a low pH and exhibit a low cation exchange capacity (CEC). Unsaturated soils beneath the site range in depth from 16 to 18 ft.

The sandy aquifer beneath the unsaturated soils extends to a depth of over 180 ft until reaching the first confining layer. Groundwater flows with an average horizontal hydraulic gradient of approximately 0.003 ft/ft. The transmissivity of the sandy aquifer beneath the site ranges between 75,000 and 150,000 gal/day/ft. Groundwater quality is naturally acidic and contains high concentrations of iron, manganese, carbon dioxide, dissolved and suspended solids. The natural pH, iron and manganese groundwater concentrations exceed federal drinking water standards.

Disposal of waste materials in the 1950s and 1960s has contaminated the surface soil, subsurface unsaturated soils and groundwater. Plans for remediation of surface soils include off-site encapsulation and off-site treatment of liquid and semiliquid wastes unsuitable for encapsulation. Due to high transmissivity of the aquifer beneath and downgradient of the site, a groundwater contamination plume extends approximately 1 mi from the site. To accurately estimate the duration of treatment plant operation, site-specific information must be obtained regarding the retardation of contamination in the sandy aquifer. Contaminant retardation is expressed as the rate of groundwater flow versus the normally slower rate of contaminant movement in an aquifer.

One potential method of remediating subsurface unsaturated soils involves flushing these areas with treated groundwater to remove contamination from the soil. If feasible, in situ soil flushing could reduce subsurface remedial costs by at least 90% over other methods involving excavation. Bioremediation of this site had been previously evaluated by EEC⁴ and was determined to be only partially effective.

Some of the hazardous volatile and semi-volatile compounds found at significant concentrations (1 to 100 ppm) in subsurface unsaturated soils at the site are:

- Chlorobenzene
- Styrene
- 1,1,2,2-Tetrachloroethane*
- bis (2-ethylhexyl) phthalate*
- Toluene*
- bis (2-chloroethyl) ether*
- Chloroform*
- 4-methylphenol*
- 1,2-Dichloroethane*
- 2-methylphenol*
- Ethylbenzene*
- Naphthalene
- Trichloroethene*
- Phenanthrene
- Tetrachloroethene*
- Phenol
- Benzene*
- 1,2-Dichlorobenzene
- 2-Butanone
- 1,4-Dichlorobenzene
- Acetone
- DDT*
- Xylene
- DDD*

Compounds with an asterisk are those identified by the U.S. EPA as chemicals which pose a potential health risk and are, thus, of primary concern at the site. The distribution of contaminated subsurface soil is shown in Figure 7 as unsaturated contaminated soil thickness isopleths. Figure 7 also shows the edge of existing surface waste. As shown, contaminated soils extend to the water table in the west central portion of the site where standing liquids were observed in 1956 and 1962 (Figure 6).

Existing conditions at both sites indicate that in situ soil flushing may be feasible. Soils at the site are well drained and have a relatively low cation exchange capacity (CEC) and organic content, which limits their ability to retard contaminant flow. The results of site characterization work indicate areas of subsurface unsaturated soils which are con-

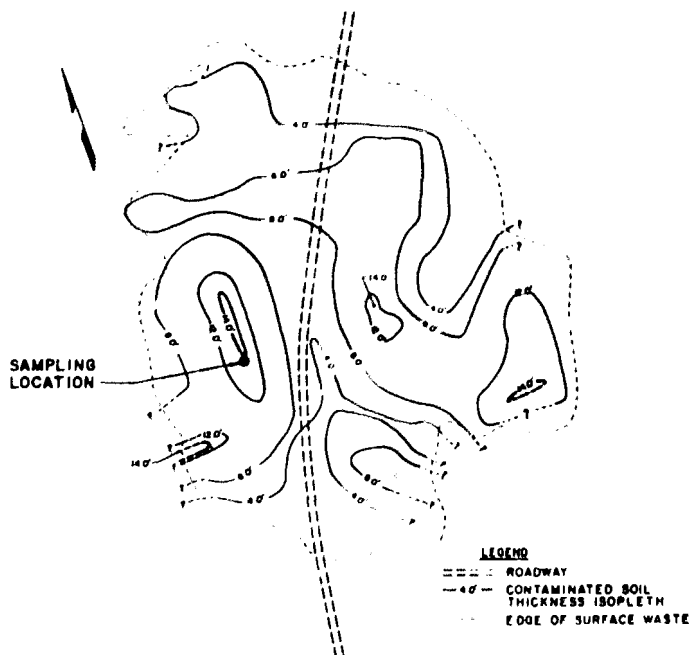


Figure 7
Contaminated Subsurface Soil Distribution

taminated with soluble organic compounds. Since the site has been "naturally flushed" by percolating rainfall for over 30 yr, the majority of soluble site contaminants should be located at depth, just above or in groundwater.

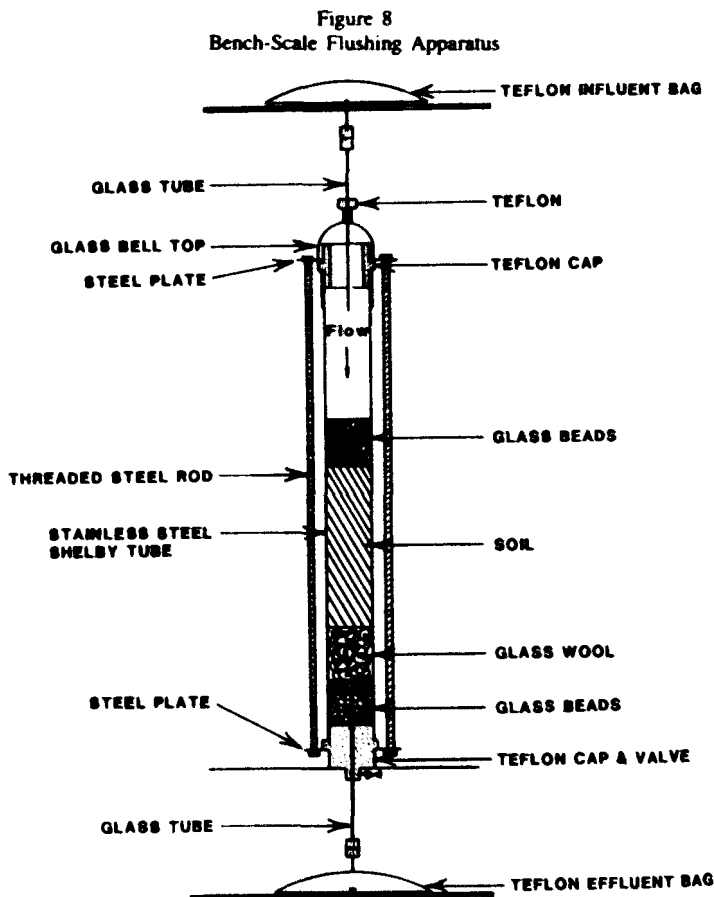
This assumption is partially confirmed by past site investigation which shows that groundwater beneath and downgradient of the site contains compounds at concentrations one order-of-magnitude less than those in contaminated subsurface soils. In addition, subsurface soil volatile organic contamination was found to be relatively widespread with the highest concentrations usually occurring at the groundwater table.

To assist in determining both the effectiveness of flushing subsurface soils and the time required for groundwater pumping and treatment plant operation, a bench-scale soil flushing study was conducted.

Phase I

Phase I of the Soil Flushing Study involved the collection of three contaminated-undisturbed soil columns for bench-scale testing. One soil column was obtained near the surface of the site and the remaining two from just above and just below the groundwater table at the location shown in Figure 7.

Soil flushing bench-scale testing of all three soil columns was conducted using the apparatus shown in Figure 8. As shown, the apparatus utilizes a stainless steel Shelby tube to obtain an undisturbed column of soil for testing. The only materials in contact with the soil or flushing water are Teflon, glass or stainless steel. A steel plate and rod assembly was used to seal the top and bottom Teflon end caps securely against the stainless steel Shelby tube. To aid in the prevention of water loss, Teflon tape was placed over the threaded ends of the Teflon connectors and Teflon O-rings were placed between connections. Prior to use, all parts of the apparatus were decontaminated.



The apparatus is air tight and uses Teflon gas bags for influent and effluent collection. Flow is under gravity conditions and is regulated by a valve in the bottom Teflon end cap. For Phase I, distilled water was used as influent. Effluent was sampled every 12 to 24 hr for analysis

of 12 subsurface site contaminants on U.S. EPA's Target Compound List (TCL). Effluent samples, as well as soil samples, were obtained from the soil columns for analysis of all TCL parameters at the beginning and end of the bench-scale test. Soil samples taken in the field adjacent to those used for bench-scale testing were analyzed for gradation (% sand, % silt and % clay) organic content, cation exchange capacity, pH, density and porosity.

Results from Phase I of the bench-scale flushing test show that effluent concentrations from flushing the two columns, taken just above and just below the groundwater table, significantly decreased during the test. This effluent concentration decrease, however, was directly correlated to a significant decrease in flow through the soil (i.e., permeability) also experienced during the test in the two columns taken just above and just below the groundwater table. Similar reductions in permeability during bench-scale testing did not occur with the soil column taken near the surface. Effluent concentration changes during bench-scale testing of the surface soil column were mixed, with some contaminant concentrations decreasing and others having wide variations during the test.

As previously indicated, subsurface soils at the site contain minor percents (2 to 4%) of clay minerals. Review of the Phase I soil flushing results indicated that flushing with distilled water removed double-valence, positively charged ions of calcium and iron as well as single-valence, positive ions of sodium from the soil matrix. Removal of these ions, specifically from the clay in the subsoil, may have induced dispersion and swelling of the clay which, in turn, reduced soil permeability.

As a result, three additional soil columns taken adjacent to those subjected to soil flushing, were tested for permeability. Permeability testing of these soil columns was conducted using tap water which contained approximately 43 parts per million (mg/L) of calcium, 35 mg/L of magnesium and 26 mg/L of sodium. This tap water permeant had a very limited capacity to remove either double or single-valent, positive ions from the soil matrix. Thus, permeability reductions from clay dispersion and swelling should have been prevented. Significant reductions in permeability, however, still occurred in the soil column taken below the groundwater table.

Based on Phase I testing, it became apparent that the phenomenon of permeability reduction during flushing was more complex than anticipated. Other factors which may have contributed to reduced permeability include dissolution and/or precipitation of inorganics in response to changes in pH or precipitation of iron in the presence of dissolved oxygen.

The pH of the water used to conduct soil flushing and permeability tests was approximately 7 and 8.3, respectively. Changes in pH may have induced the formation of metal complexes. Metal ions present within the soils can complex when a sufficient amount of hydroxide becomes available in solution. These complexes form within the interstices between soil grains and restrict flow. Soils at the site contain a significant amount of iron, which can precipitate and clog soil pores. A pH increase also produces additional negative charges on the clay particles present in the soils at the site. Increases in the negative charge of clay particles cause the clay to disperse and swell, whether the increase is from a rise in pH or removal of positive ions.

The water used for permeability and soil flushing tests had a dissolved oxygen content of approximately 6 and 7 mg/L, respectively. Groundwater at the site contains no measurable dissolved oxygen, but high amounts of carbon dioxide. Therefore, the addition of dissolved oxygen to the soil could easily result in the precipitation of iron from the soils. Reductions in soil permeability (clogging) may be a major impediment to the soil flushing process. Phase II of the Soil Flushing Study was designed to investigate additions to flushing water influent which may prevent reductions in soil permeability during flushing.

Phase II

Flushing influent variables which have been identified during Phase I are pH, dissolved oxygen content (DO) and calcium ion concentration (Ca). To determine the optimum combination of these variables economically, bench-scale testing in Phase II was planned using the

23 statistical experimental design of these variables, shown in Table 6.

Table 6
Phase II Soil Flushing Study Experimental Design

Soil Column/Solution Number	ACTUAL INFLUENT CONCENTRATION		
	Ca (ppm)	pH	DO (ppm)
1	39.32	4.2	1.19
2	381.37	4.2	1.17
3	39.31	5.7	1.16
4	383.26	5.8	1.16
5	38.52	4.2	8.35
6	386.94	5.5	8.70
7	42.13	5.6	9.14
8	387.26	5.6	8.96
9	0.00	6.3	9.30

As shown in Table 6, nine soil columns were tested during Phase II. Distilled water was applied to column 9 to match Phase I conditions. The solutions used for Columns 1 through 8 were made by adding the appropriate concentration of calcium chloride. Lower pH solutions were obtained with the addition of hydrochloric acid. Decreased DO was achieved by bubbling nitrogen gas through the solution.

Each soil column tested during Phase II was obtained from just below the groundwater table at the sampling locations used in Phase I. In Phase I, soil taken from just below the groundwater table clogged using both distilled and calcium enriched tap water. To determine the effects of different Ca, pH and DO influent concentrations on soil permeability as well as on contaminant removal, all soil columns for Phase II were taken from soil zones with as near identical conditions as possible. The horizontal and vertical location of samples were surveyed to match the Phase I location. In addition, each column contained 18 in. of soil.

The same apparatus used in Phase I was used for Phase II. As in Phase I, effluent was sampled every 24 hr for analysis of 12 TCL subsurface contaminants. To determine if the solutions used affected the soil matrix, effluent was also analyzed every 24 hr for total suspended solids, calcium, chloride, iron, silicon, sodium and zinc. As in the first phase of testing, soil samples were obtained from the soil column for analysis of TCL parameters at the beginning and end of bench-scale testing. Unlike Phase I, however, the actual soil in each column was analyzed for gradation organic content, cation exchange capacity, pH, density and porosity.

Throughout Phase II of the Soil Flushing Study, no reduction in soil permeability was evident. Flows through all nine soil columns remained consistent. Effluent concentrations of the 12 TCL compounds measured from Columns 1 through 7 decreased quickly as compared to Columns 8 and 9. After approximately 15 pore volumes, effluent concentrations of the volatile compounds monitored were reduced to nondetectable levels (<1 ppb). To determine if the influent solutions used inhibited contaminant removal and/or prevented a reduction in soil permeability, the influent of all nine soil columns was changed to distilled water after approximately 15 pore volumes. After changing the influent to distilled water, no additional contamination was removed and reductions in soil permeability did not occur. After Phase II bench-scale testing was completed, soil column concentrations of all site-related TCL volatile compounds were nondetectable.

To evaluate the effects of each solution on soil permeability, the inorganic effluent results obtained during solution testing were reviewed.

Although Column 9 showed no apparent signs of reduced permeability, it was the only column in which total suspended solids were removed during flushing. This indicates a breakdown of the soil matrix. Removal of sodium from the columns also indicates an increased potential for

dispersion and swelling of any clay present. Sodium was removed from all columns. A preliminary statistical analysis of the data, however, indicates that removal of sodium from the soil matrix is reduced using the higher calcium, low pH, low DO solutions.

To determine the effect of each solution on contaminant removal, soil contamination concentration data obtained from bench-scale testing were used to fit the following first-order decay equation.

$$\frac{C(V)}{C_0} = \exp^{-KV} \quad (1)$$

Where: V = Number of pore volumes

$C(V)$ = Soil contaminant concentration at pore volume V

C_0 = Soil contaminant concentration at zero pore volumes.

\exp = napierian base

K = Decay constant for a particular compound and soil

In Equation 1, the larger the value of K , the lower the number of pore volumes required to remove the contaminant. A statistical analysis program known as MINITAB¹ was used to fit Phase II experimental data to Equation 1 using multiple regression analysis. For each compound and each soil column, a regression coefficient, K , was determined.

The ranges of K for each compound found in the soil columns are shown in Table 7. In the gas chromatograph used for effluent analysis, 1,2-dichloroethane and bis(2-chloroethyl)ether coelute. Thus, the K values shown in Table 7 are for 1,2-dichloroethane and bis(2-chloroethyl)ether combined. As shown, K values for each compound have significant variations. Since effluent concentrations decreased quickly from Columns 1 through 7, K values were generally half an order-of-magnitude greater than for Columns 8 and 9.

Table 7
Phase II Soil Flushing Study Regression Coefficients

Compound	Regression K Value	Water Solubility ¹ @20°C(ppm)
1,2-Dichloroethane/ bis(2-chloroethyl)ether	0.196 to .991	8690/10200
Benzene	0.090 to 1.73	1780
Trichloroethene	0.125 to 1.17	1100*
Toluene	0.158 to 0.898	515
p-and m-Xylene	0.117 to 0.865	198**
o-Xylene	0.130 to 1.25	175
Ethylbenzene	0.089 to 0.585	152
1,1,2,2-Tetrachloroethane	0.314 to 1.06	150*

¹ From Verschueren, 1983, Handbook of Environmental Data on Organic Compounds

² 1,2-dichloroethane and bis(2-chloroethyl) ether coelute during effluent analysis. K values shown are for the combination of both compounds.

* At 25°C

** For p-Xylene at 25°C

To determine if K values were related to the influent solutions used, the regression K values were statistically compared to influent calcium, pH and dissolved oxygen content, as well as soil density, porosity,

percent sand, percent silt, percent clay and percent organic matter. In addition to influent and soil physical characteristics, regression K values also were compared to a total concentration of the 12 TCL compounds measured in each soil column (total C_0) and total bis(2-ethylhexyl)phthalate (BEHP) initially found in each soil column. BEHP is a common contaminant in each column and the only major semi-volatile present.

Preliminary results of this analysis indicate that:

- For relatively soluble compounds of 1,2-dichloroethane, bis(2-chloroethyl)ether and benzene, the regression K values are related to the Total C_0 in the soil column, the concentration of BEHP initially present and the dissolved oxygen content in the influent solution used for flushing. The regression K constants are larger for soils with low Total C_0 and BEHP concentrations and low influent dissolved oxygen concentrations.
- For moderately soluble compounds of trichloroethene, toluene, chlorobenzene, xylene, ethylbenzene and 1,1,2,2-tetrachloroethane, regression K values are directly related to the BEHP concentration initially present in the soil and the pH and/or dissolved oxygen content of the flushing influent. As with the higher soluble compounds, the regression K values are larger for soils with low initial BEHP concentration and low influent pH and dissolved oxygen concentrations.

These results are consistent with accepted theories of partitioning between the solid and solution phase $\frac{1}{2}$ (6) (i.e., soils with greater organic content tend to retain organics).

CONCLUSIONS

From results of the Bench-scale Soil Washing Study the following conclusions can be made:

- Removal of volatile and semi-volatile organics, petroleum hydrocarbons, PCBs and a variety of heavy metals is possible using soil washing methods.
- Both the aqueous surfactant and the aqueous citrate-based solutions are effective for high removals of all classes of organic compounds tested. The citrate-based solution appears to be slightly more effective than the surfactant for PCB removal.
- Chromium, nickel, mercury and arsenic are contaminants that may be more difficult to remove to acceptable levels using a hydrochloric acid solution.
- Single-stage soil washing is capable of removing high percents of contaminants. However, due to the level of residual concentrations in this study, a greater number of stages would be required to meet cleanup goals.
- Used solutions would require significant pretreatment for reuse due to their high contaminants levels. For the site investigated in the soil washing study, complete replacement of spent washing solutions with fresh solution volumes may be necessary during initial stages of soil washing. Complete replacement and disposal of used solutions may involve significant cost which, in turn, each impact the feasibility of soil flushing.
- The CLP protocol used for process sample analysis was not suitable due to the high constituent concentrations.

From results of the Bench-scale Soil Flushing Study, the following conclusions can be made.

- In situ removal, to nondetectable levels, of many volatile compounds from soils by soil flushing is possible.
- Soil flushing can cause reductions in soil permeability which, in turn, can prevent the removal of soil contaminants.
- Selection of soil flushing influent should be based on a review of site soil chemistry to prevent permeability reduction during flushing.
- The first-order decay equation (Eq.1) accurately expresses the reduction in volatile soil contamination during soil flushing. The decay constant is related to the initial total concentration of volatile and semi-volatile contaminants present in the soil.

Both studies require additional bench and/or pilot scale work to fully demonstrate feasibility of the soil remediation technologies.

REFERENCES

1. U.S. EPA, Handbook - *Remedial Action at Waste Disposal Sites* (revised). U.S. EPA-625/6-85/006, U.S. EPA, Cincinnati, Ohio, 1985.
2. Dames and Moore, *Remedial Investigation Report*, Sept. 1988. (Client maintained confidential for purposes of this paper).
3. U.S. EPA, 1988 and Penetone, Personal Communication with M.E. Kunze, EEC, Inc.
4. Gee, John R., "Feasibility of Bioremediation at Hazardous Waste Sites" *Proc of the Eleventh Annual Madison Waste Conference*, University of Wisconsin, Madison, WI, 1988.
5. Ryan, B.F., Joiner, B.L., Ryan, T.A., *MINITAB Handbook*, Second Edition. PWS-Kent Publishing Company, Boston, MA, 1988.
6. Lyman, W.J., Reehl, W.F., Rosenblatt, D.H., *Handbook of Chemical Property Estimation Methods*, McGraw-Hill Book Company, New York, NY, 1982.

Soil Stabilization/Solidification at the Tacoma Tar Pits

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ABSTRACT

The Tacoma Tar Pits Site is a Superfund site on the Puyallup River in Tacoma, Washington. Coal tar and hydrocarbon liquids are present in shallow ponds and as discontinuous lenses within site soils. Soils and shallow groundwater are contaminated with lead, PCBs and coal gasification products including phenols, polycyclic aromatic hydrocarbons, benzene, toluene and xylene. Portions of the site are covered with up to 3 ft of automobile shredder fluff and associated debris.

The principal remedial technique named in the ROD on for the site is on-site fixation (stabilization/solidification) of shallow soils and auto fluff. In a bench-scale soil fixation treatability study, site soil, coal tar and auto fluff were mixed in various proportions and fixed via a proprietary product. The resulting monoliths underwent testing for contaminant concentration, physical-engineering properties and leaching behavior. These properties were determined:

- contaminant concentrations as compared to site cleanup goals and other ARARs
- volume increase due to fixation
- wet/dry durability
- compressive strength as a function of time and monolith composition
- permeability
- the effect of wet-dry stressing on monolith strength, permeability and leaching
- effect of fixation on the TCLP leaching of five classes of contaminants
- ANS 16.1 leaching behavior, with and without wet-dry stressing.

Using calculated diffusivity values for the contaminants of concern, long-term leaching from a full-size monolith at the site was projected.

INTRODUCTION

The Tacoma Tar Pits is a Superfund site in the industrial district of Tacoma adjacent to the Puyallup River. A coal gasification plant operated on the 30-ac site from 1924 until 1956. Since 1967, a scrap-metal recycling facility has occupied most of the site. Current site features are shown in Figure 1.

RI/FS of the site has been conducted by the PRPs.^{1,2} The RI showed that wastes from the coal gasification and metal recycling operations are distributed over the entire site. Several acres are covered to a depth of 1 to 3 ft with decomposing auto fluff—the foam, rubber and non-ferrous metal products of an automobile shredder. There are approximately 5000 yd³ of coal tar within the shallow soil (chiefly in a "tar boil area") and in a small pit. Organic non-aqueous phase liquid (NAPL) forms lenses within the soil over much of the site.

These wastes are the source of several types of contaminants. Phenols, benzenes and polycyclic aromatic hydrocarbons (PAHs) are the chief components of the coal tar and NAPL. In the auto fluff and underlying

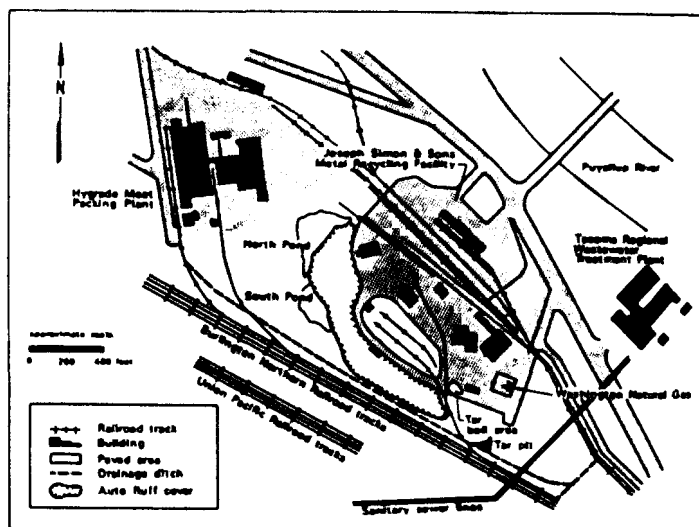


Fig. 1
The Tacoma Tar Pits Site.

fill, concentrations of inorganic contaminants (principally lead, mercury and arsenic) are elevated. PCBs are found in the auto fluff and the underlying fill. Varying levels of metals, PAHs, phenols and benzenes have been measured in the shallow aquifer on the site.

ROD for the Tar Pits Site established cleanup goals for site soil, surface water and groundwater.³ Goals were established in each medium for lead, benzene, total PCBs and PAHs [the sum of benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, dibenz(a,h)anthracene and indeno(1,2,3-cd)pyrene]. The ROD named stabilization/solidification of shallow soils and auto fluff as the principal component of site remediation.

Using materials from the Tar Pits site, a bench-scale treatability study was conducted. Its purpose was to test fixation as a treatment technique for multiple, physically heterogeneous waste matrices containing several classes of contaminants.

MATERIALS AND METHODS

Study Design

The study was designed not to optimize treatment parameters but, more fundamentally, to determine whether stabilization/solidification would even work on the waste matrices from the Tar Pits. Figure 2 shows the study design. The first phase of study planning established the properties of the raw and fixed wastes that would be tested in

assessing the success of the treatment.

Based on these properties, specific chemical, physical and leaching tests were chosen. The parameters chosen to track were the four contaminant classes named in the ROD, plus phenols. To assess the physical integrity of the monoliths, tests of permeability, durability and compressive strength were specified. The leaching tests selected were one regulatory test (the TCLP) and one test that would allow projections of long-term leaching (American Nuclear Society Test 16.1).

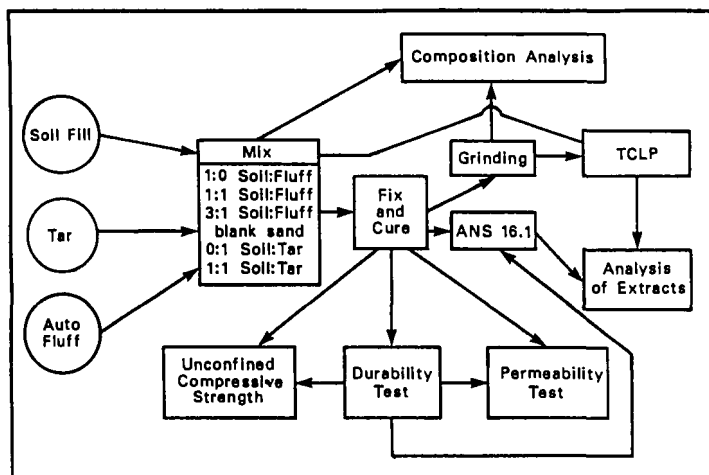


Fig. 2
Material Flow Through the Testing Procedure

The second phase of study planning involved (1) selecting the different waste materials and combinations of materials to be treated and (2) the degree of replication at each step. The number of samples that could be generated was constrained by the high analytical costs associated with the five contaminant classes. Six matrices were selected for testing: (1) site soil; (2) a 1:1(w/w) mix of site soil and auto fluff; (3) a 3:1 soil-fluff mix; (4) coal tar; (5) a 1:1 soil-tar mix; and (6) blank sand (a clean commercial sand). Although tar fixation was not proposed in the ROD, tar was chosen for testing to define the limits of fixation technology for site materials. This testing would also help determine what would happen if, during remediation, subsurface tar were encountered and inadvertently incorporated into the feed stream of the soil treatment unit.

Once the study design was finalized, additional planning steps included determining the appropriate sizes of the fixed coupons, calculating the needed volumes of site materials and devising the site sampling plan. The project workplan⁵ sets forth all of the methods used and the rationale for their selection.

Field and Laboratory Methods

The sampling and fixation experiments took place in January 1988. The sampling design was biased towards the collection of highly-contaminated material to provide maximum challenge to the fixatives. Site materials were collected over the full depth interval that would be excavated for site remediation. Seven soil samples were collected from pits 1 ft deep. They were composited on-site and screened through 3/8-in hardware cloth. Approximately 150 lb of field-moist soil were collected. Auto fluff was collected from four locations where the RI indicated NAPL contamination. The greatest thickness of fluff sampled was 2 ft. Particles larger than 3/8 in were screened out, and the fluff was homogenized on-site. Approximately 100 lb of fluff were sampled. A total of 3 gals of liquid tar were taken from the tar pit.

Before processing, site samples were stored at ambient temperature (40 to 50°F) for 5 days. Mixing and fixation took place at the U.S. EPA Region 10 laboratory in Manchester, Washington. All mixing was done in 2-kg batches using a Hobart rotary mixer. After site materials were mixed in the predetermined ratios, sub-samples of the unfixed materials were created for chemical analysis and TCLP extraction. Then the mixtures were treated by measured addition and mixing of tap water

and one or more proprietary reagents. Fixed mixtures were poured into small cylindrical molds of three different sizes, as required by the different tests. These were capped, labelled and stored at 100% relative humidity in closed plastic trays.

Materials to be tested for compressive strength were dispatched to the physical-testing laboratory the day after fixation. All other coupons were cured at ambient temperature for 28 days before further handling.

Phenol analysis was by colorimetry. All other chemical analytes were quantified according to Contract Laboratory Program methods by CLP laboratories. Physical/engineering tests were performed by U.S. EPA's Center Hill Laboratory according to its standard protocols for stabilized/solidified materials (6). Each type of monolith was tested for ultimate (28-day) unconfined compressive strength by a modification of ASTM D1633-84. The development of strength was traced by testing cylinders of the 3:1 soil-fluff mixture at 3, 7, 14, 22 and 29 days. Permeability was tested in a pressurized upflow apparatus by a method similar to EPA Method 9100-2.8(7). Durability was examined by a wet-dry stress test similar to ASTM D-559. The test entails 10 cycles of 6-hr immersion in deionized water followed by 18 hr of drying at 140°F(60°C). Seasonal wet-dry exposure of the full-scale monolith via shallow groundwater is possible at the Tar Pits site, and monolith strength and permeability might be affected. Therefore, two sets of fixed samples were subjected to wet-dry stressing, then one was strength tested and the second was tested for permeability.

Raw and fixed materials were crushed and leached by the TCLP. Both standard and zero-headspace extractors were used. Fixed materials were also extracted via a modification of the ANS 16.1 test. In this test, a cylinder was suspended in deionized water under quiescent conditions. After 1, 3, 5, 7, 14, 28 and 90 days, the leachant was replaced by fresh water and subjected to chemical analysis. A full set of fixed coupons underwent this testing. In addition, a set of 3:1 soil-fluff cylinders underwent wet-dry stressing (6, 14 or 24 days) followed by 90 days of standard ANS leaching. In these tests, the initial leachates were collected during the wet-dry stressing period.

Resource constraints prohibited a fully-replicated experimental and analytical design. Instead, precision was assessed at every step by testing triplicate samples of the 3:1 soil-fluff mixture.

Volatile compounds were analyzed in several types of samples, with the understanding that the reported concentrations may not be repre-

Table 1
Contaminants in Site Materials

Contaminant	Material	Concentration (mg/kg)		
		Reported from RI	Treatability Raw	Study Fixed
Lead	Soil	73-12,900	2490	877
	Fluff	2910-4700	3670 ^c	4663 ^c
	1:1 Soil-Fluff	---	3080	2770
	Tar	37	---	52
Phenols	Soil	<1	377	<1450
	Fluff	---	790 ^c	---
	1:1 Soil-Fluff	---	584	<1970
	Tar	150	200	<1050
Benzene	Soil	<0.001	0.002	---
	Fluff	---	---	---
	1:1 Soil-Fluff	---	<0.007	---
	Tar	430	---	---
Total PAHs ^a	Soil	1.1-<108	13.5	13.2
	Fluff	---	<1 ^c	---
	1:1 Soil-Fluff	---	5.6	<348
	Tar	2665	3240	2950
Total PCBs ^b	Soil	<0.7-135	6.2	6.6
	Fluff	11-204	58 ^c	26 ^c
	1:1 Soil-Fluff	---	32	16.2
	Tar	---	<198	<28

a. Sum of benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene and dibenz(a,h)anthracene

b. Sum of Aroclors 1016, 1221, 1232, 1242, 1248, 1254 and 1260

c. Calculated from the concentrations in the soil and 1:1 soil-fluff mixes

sentative. At no stage of sample handling was any attempt made to capture or quantify escaping volatiles.

RESULTS AND DISCUSSION

Chemical Concentrations

Contaminant concentrations in selected raw and fixed materials are summarized in Table 1 and compared with data from the RI. Concentrations in the raw materials generally fell within the previously-reported ranges. Lead concentrations in soil and fluff were 2000 to 5000 mg/kg. The soil collected for the treatability study was contaminated with NAPL, as evinced by the phenol and PAH values, but volatile contaminants were nearly undetectable. PAH concentrations in fluff were less than half those in soil (<1 vs 13 mg/kg), reflecting the fact that the auto shredder began operation long after the coal-gasification wastes were released on the property. The shredder fluff is the chief source of PCBs at the site, and total PCB concentrations in the sampled fluff exceeded 50 mg/kg (calculated from the soil-fluff mixes).

The dilution factor caused by adding fixation reagents to the raw materials was approximately 70%. The pre- and post-fixation concentration results do not reflect this factor closely (Table 1). The source of the variation is not clear; data from triplicate samples indicate that between-sample variation was 10 to 15%.

Physical Properties

Volume increases of site materials resulting from fixation ranged from 45 to 95%. These relatively large volume increases reflect the high bulk density of the in-place soil (about 130 lb/ft³) and the high reagent dosages used in the treatability study.

In the wet-dry stress test of fixed monoliths, durability was measured by monolith weight loss. There are no standard criteria for acceptable weight loss, but a weight loss of 5% or less generally is judged acceptable.⁸ In the treatability study, tar and tar-soil cylinders had weight losses exceeding 5% (11.8 and 9.2%, respectively). Among the soil and soil-fluff monoliths, one experienced a 5.3% weight loss; the average weight loss was less than 3%.

Figure 3 traces the development of monolith compressive strength over time. In concrete work, the 28-day strength is the measure of "ultimate strength." As shown in Figure 3, the 3:1 soil-fluff cylinders were still measurably gaining strength at 29 days. The inclusion of fluff and organic compounds probably slowed the development of strength; this phenomenon has been widely demonstrated.⁹ In such materials, a longer test (50 or 60 days) may give a more accurate measure of ultimate strength.

Figure 4 depicts the 29-day compressive strengths of the various monoliths. Water contents of all the mixes were similar. The mixes with higher proportions of soil developed greater strength; both auto fluff and tar detracted from monolith strength. Among unstressed cylinders, fixed soil had the greatest strength (895 psi) while fixed tar had the least (zero). For every material type, cylinders subjected to wet-dry stressing were stronger than unstressed cylinders. During the dry portions of the stressing cycles, cylinders were held at 140°F (60°C) which accelerated their curing. Because of this, effects due solely to cyclic wetting and drying cannot be distinguished.

There currently are no general standards for the strength of monoliths created during remediation of NPL sites. The Nuclear Regulatory Commission requires a strength of 150 psi in rigid waste materials. The proposed minimum strength for land-disposed RCRA solid wastes is 50 psi. At the Tar Pits, the overburden pressure on a full-size monolith would be 2 to 5 psi. Most of the tested mixes could readily support this load.

Figure 5 shows the permeabilities of the fixed materials. Among the unstressed materials, the most permeable was the 1:1 tar-soil cylinder (5×10^{-8} cm/sec); the least permeable was fixed tar (1.2×10^{-9} cm/sec). Permeabilities of the soil and soil-fluff monoliths were all within a factor of three, suggesting that the inclusion of fluff did not increase permeability. For every type of fixed material, wet-dry stressing increased permeability by more than an order of magnitude. This increase in permeability may have been an effect of accelerated curing. Alterna-

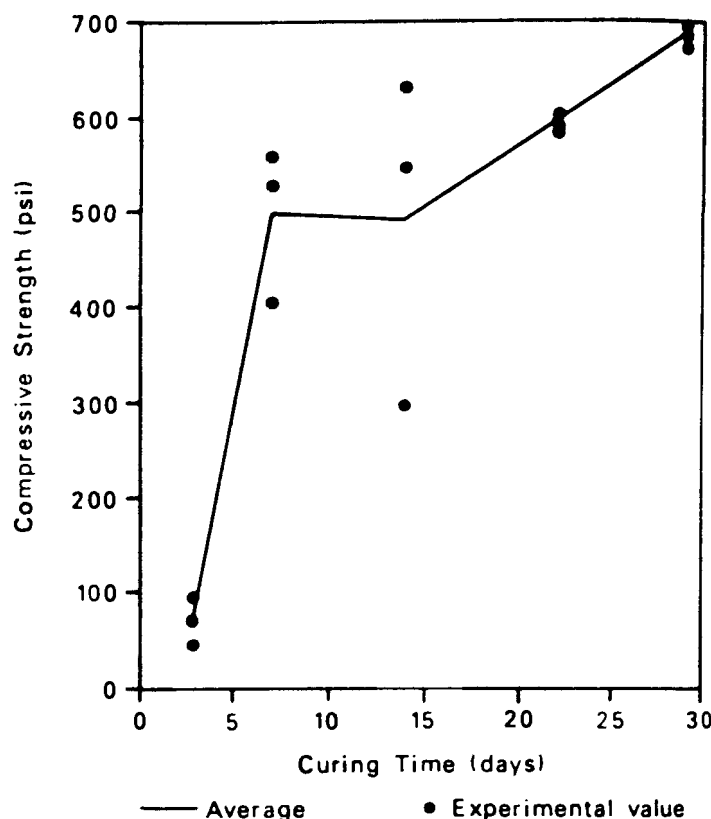


Fig. 3
Development of Compressive Strength in a
Fixed 3:1 Soil Auto Fluff Mix

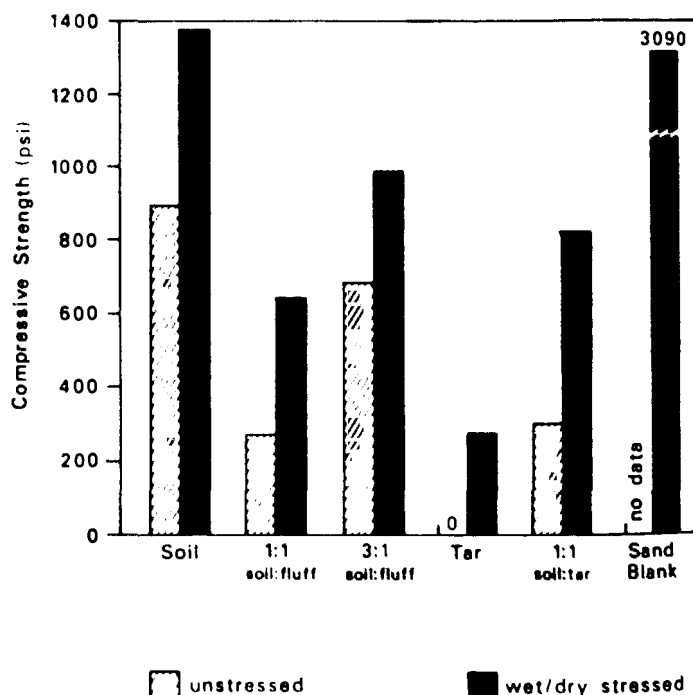


Fig. 4
Unconfined Compressive Strengths of Fixed Materials.
Results for 3:1 Soil:Fluff Mixture are
Means of Triplicates; All Others are
Single Determinations.

tively, it may have been caused by micropores near the cylinder surfaces, created through dissolution or other mechanisms. Leaching data (see below) indicate that such dissolution did occur. These results suggest that the physical integrity of an in-place monolith would be greatly enhanced by keeping it dry.

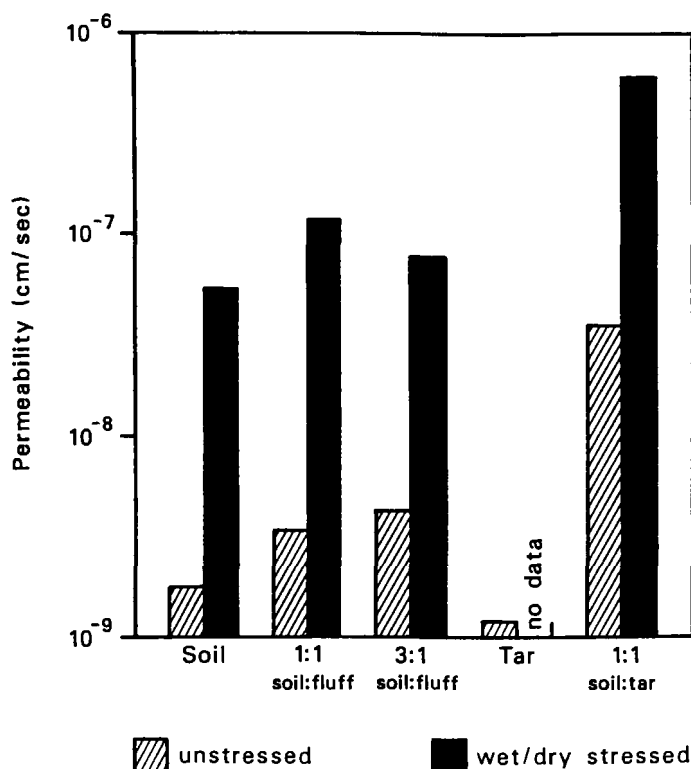


Fig. 5
Permeabilities of Fixed Materials.
Result for 3:1 Soil:Fluff Mixture are
Means of Triplicates; All Others
Are Single Determinations.

Leaching Properties

Table 2 summarizes the TCLP data for the contaminants of concern in leachates from selected materials. The data indicate that fixation was very effective in immobilizing lead, diminishing its leaching by more than 99%. Levels of lead greater than 10,000 ug/L leached from unfixed samples containing site soil, whereas leachate from fixed samples contained less than 50 ug/L lead. More than 5000 ug/L total phenols and 200 ug/L benzene were extracted from the raw tar; high concentrations of these contaminants also leached from fixed tar. As might be predicted from their solubilities, the PAHs and PCBs were found at very low levels in all leachates. The six individual PAHs of interest were undetectable at 26 ug/L, and total PCB levels were below 2 ug/L. Fixation did not inhibit the release of volatile compounds from cylinders in which they were very concentrated; benzene leached from fixed tar at 500 ug/L.

The Tar Pits ROD established the following cleanup goals for surface waters at the site boundary (all in ug/L): lead - 3.2; benzene - 53; PCBs - 0.2; PAHs - 5 to 30. If the TCLP leachates are considered without dilution, raw tar extract would exceed the benzene goal, and raw soil leachate would exceed the lead goal by three orders of magnitude. Both fixed tar and fixed soil would still exceed these standards. None of the TCLP leachates generated in this study would exceed the PAH or PCB standards.

Fixed cylinders of all types were subjected to the ANS 16.1 leaching test. Figure 6 shows representative leachate pH and conductivity trends for these tests. All of the fixed materials showed an initial release of alkalinity into the leachant (as indicated by high pH and conductivity)

Table 2
Summary of TCLP Results

TCLP Leachate Concentration (ug/L)			
Contaminant	Material	Raw Material	Fixed Sample
Lead	Soil	51,000	17
	1:1 Soil-Fluff	12,500	23
	Tar	165	<1
	1:1 Soil-Tar	---	<1
Phenols	Soil	<135	<418
	1:1 Soil-Fluff	<139	23
	Tar	5250	420
	1:1 Soil-Tar	---	1180
Benzene	Soil	<5	---
	1:1 Soil-Fluff	<5	---
	Tar	200	540
	1:1 Soil-Tar	---	59
Total PAHs ^a	Soil	<24	<72
	1:1 Soil-Fluff	<24	<78
	Tar	3	<72
	1:1 Soil-Tar	---	<72
Total PCBs ^b	Soil	0.06	---
	1:1 Soil-Fluff	<0.35	---
	Tar	<2.1	---
	1:1 Soil-Tar	---	---

a. Sum of benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene and dibenz(a,h)anthracene

b. Sum of Aroclors 1016, 1221, 1232, 1242, 1248, 1254 and 1260

which diminished after 2 wk. These results suggest that during the early portion of the tests alkaline oxides and hydroxides derived from the fixatives dissolved from the monolith surfaces. When the readily-soluble surface constituents were gone, leaching was limited by the low diffusion rate in the solid cylinders.

Selected leachability indices calculated from the ANS 16.1 data are summarized in Table 3. Each index is the inverse logarithm of the effective diffusivity, in cm²/sec, averaged over the seven leaching intervals. The index is calculated from the duration of the leaching interval, the time since the beginning of the test and the fraction of contaminant leached during that interval. Index values decrease with increasing leaching rate.

Table 3
Leachability Indices of
Selected Fixed materials

Contaminant	Average Leachability Index ^a			
	Soil	1:1 Soil-Fluff	Tar	1:1 Soil-Tar
Arsenic	>13.6	12.2	---	---
Lead	>12.2	>13.2	---	---
Phenols ^b	12.4	11.7	8.9	8.9
Naphthalene	>9.2	---	10.9	10.3
Pyrene	>12.5	>12.2	>13.2	>12.7
Benzo(a)pyrene	>13.1	---	>15.2	>14.7
Total PCBs	>12.1	>13.4	---	---

a. Average of seven leaching intervals totaling 90 days.

b. Initial concentrations in the fixed cylinders not quantified; assumed to be half those in the raw materials.

A leachability of 5 would indicate a fairly mobile compound, while a value of 15 would indicate a compound essentially immobile in this system¹⁰). Most of the contaminants of interest in the Tar Pits materials exhibited leachability indices greater than 10, indicating they were relatively immobile in the fixed coupons. Furthermore, there was no time trend in the leaching rates of most organic and inorganic contaminants (calculated leachability indices were the same for all seven leaching intervals). The sole exception was phenols: in all types of cylinders,

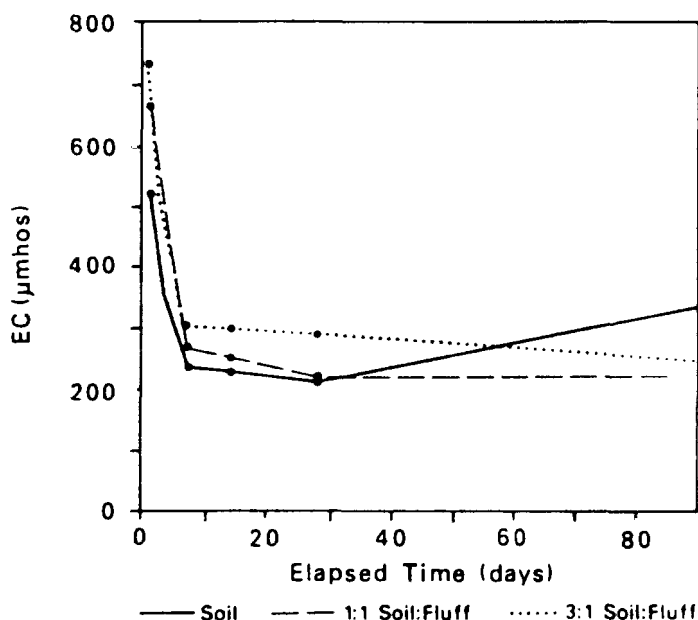
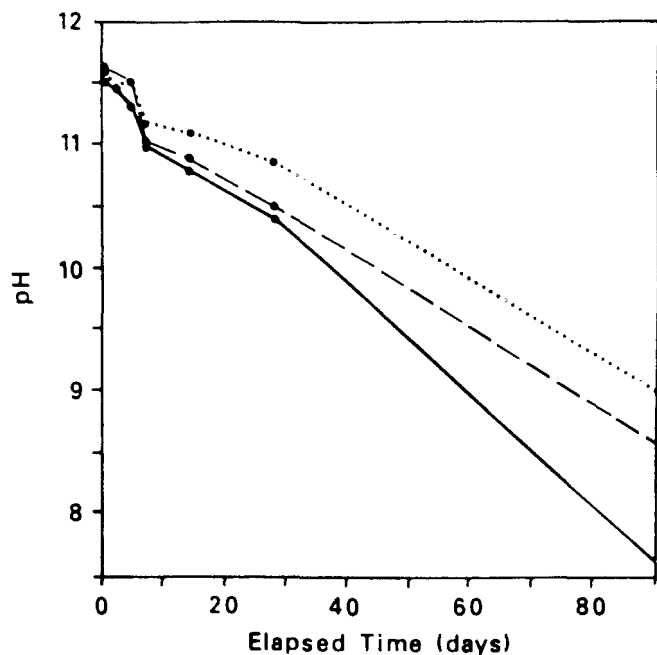


Fig. 6
ANS Leachate pH and Conductivity vs. Time.

phenol leaching decreased over time. Since phenols are weak acids, their concentration might have been expected to increase as leachate pH fell. The fact that it decreased instead suggests that diffusion through the solid cylinders was the factor limiting phenol leaching.

The leachability indices were used to make rough projections of contaminant release from a full-scale, on-site monolith. The projections assumed an unfractured monolith with the underside contacted by slowly-moving groundwater. Under these conditions, it was projected that less than 10% of the lead in the monolith would be released in 1000 yrs (Fig. 7). Leaching of organic compounds from a soil or soil-fluff monolith also would be less than 10% over 1000 yrs. On the other hand, phenols, naphthalene and possibly other PAHs were projected to leach from a soil-tar monolith at higher rates, such that 50% or more would be released over 1000 yrs. Hydrologic modeling would be required

to ascertain whether these compounds, very concentrated in the soil-tar monolith, would ever be present at measurable levels in the shallow groundwater.

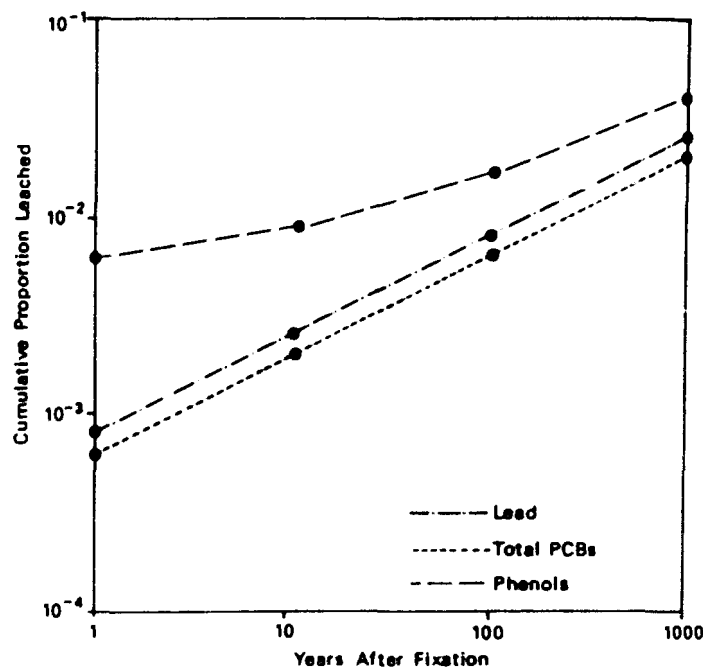


Fig. 7
Projected Leaching of a Full-Scale 1:1 soil-fluff Monolith at the Tar Pits Site.

Since a full-scale monolith at the Tar Pits is likely to undergo alternating periods of wetting and drying, one set of 3:1 soil-fluff cylinders was subjected to wet-dry stressing followed by ANS 16.1 leaching. Surface weathering of the cylinders (as expressed by leachate pH and conductivity) was accelerated by the wet-dry cycles (which were conducted at room temperature).

However, leachate concentrations of all individual contaminants were low, and calculated leachability indices were similar to those generated from simple ANS tests. There was no evidence for enhancement of contaminant leaching by wet-dry stressing.

CONCLUSIONS

In this study, various physical and leaching tests were used to ascertain whether stabilization/solidification is a viable remedial technology for the materials at the Tacoma Tar Pits site. Test results indicate that, for site materials not containing high levels of tar, stabilization is a promising technology. The physical tests suggest that a monolith of soil or a soil-auto fluff mixture would be sufficiently strong, durable and impermeable to meet site-specific remedial goals. A fixed 1:1 mixture of tar and soil probably would have sufficient physical integrity, but pure fixed tar probably would not.

TCLP results indicate that in most fixed materials the contaminants of concern could be immobilized effectively enough that the leachates would nearly meet cleanup goals without dilution. However, leachates from fixed tar could not readily meet the goals. Results of the ANS tests suggest that long-term contaminant leaching from a full-scale monolith would be very slow. Organic compounds leached from tar-rich monoliths might be measurable in slowly-moving groundwater.

ACKNOWLEDGEMENTS

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DISCLAIMER

Although the research described in this article has been supported by the U.S. EPA through assistance agreement CR 814701 to the University of Nevada, it has not been subjected to agency review and therefore does not necessarily reflect the views of the agency, and no official endorsement should be inferred.

REFERENCES

1. Applied Geotechnology, Inc., "Remedial Investigation, Tacoma Tar Pits, Tacoma, Washington," AGI, Bellevue, WA, 1987.
2. EnviroSphere Company, "Final Feasibility Study of the Tacoma Historical Coal Gasification Site." EnviroSphere Co., Bellevue, WA, 1987.
3. U.S. EPA, "Decision Summary and Record of Decision, Remedial Alternative Selection, Final Remedial Action, Tacoma Tar Pits, Tacoma, Washington." U.S. EPA, Region 10, Seattle, WA, 1987.
4. Rupp, G.L., "Bench Fixation of Soils from the Tacoma Tar Pits Superfund Site." Project Report. EPA/600/8-89/069.
- U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, 1989.
5. MSI Detoxification Inc., "Final Protocol for Bench Fixation Trials for Soils from the Tacoma Historical Coal Gasification Site." MDI, Bozeman, MT, 1988.
6. Center Hill Research Facility, "Summary Test Report, Tacoma Tar Pits." Technical Assistance for Evaluation of Solidification/Stabilization Treatment Technologies. University of Cincinnati, Cincinnati, OH, 1989.
7. U.S. EPA, *Test Methods for Evaluating Solid Waste*. EPA SW-846, 3rd Edition. U.S. EPA Office of Solid Waste and Emergency Response, Washington, DC, 1986.
8. Cullinane, M.J., Jones, L.W. and Malone, P.G., *Handbook for Stabilization/Solidification of Hazardous Waste*. EPA/540/2-86/001. U.S. EPA Hazardous Waste Engineering Laboratory, Cincinnati, OH, 1986.
9. Jones, L.W., "Interference Mechanisms in Waste Stabilization/Solidification Processes." U.S. EPA Hazardous Waste Engineering Laboratory, Cincinnati, OH, 1989.
10. PEI Associates, Inc. and Earth Technology Corporation, "Stabilization/Solidification of CERCLA and RCRA Wastes." U.S. EPA Risk Reduction Engineering Laboratory, Cincinnati, OH, 1986.

Evaluation of Chemically Stabilized/Solidified Soils Using the California Waste Extraction Test

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ABSTRACT

Contamination of soils with heavy metals is a significant problem at many uncontrolled hazardous waste sites. Chemical stabilization/solidification (CSS) has been proposed as a technology that reduces the mobility of heavy metals and other contaminants.

This paper presents the results of a bench-scale investigation of the capability to reduce the mobility of arsenic, cadmium, copper, lead and zinc from contaminated soils through application of CSS technology. Individual samples of contaminated soils were collected from three sites. Three generic CSS processes were evaluated: Portland cement, lime/fly ash and cement kiln dust. Physical strength of the specimens was evaluated using unconfined compressive strength (UCS). Contaminant mobility characteristics were evaluated using the State of California Waste Extraction Test (WET).

The results of UCS testing indicated substantial strength development for all binders tested. The results of the WET procedure indicated substantial reductions in leaching of all contaminants as a result of CSS. However, leachate concentrations for arsenic and lead exceeded the State of California's promulgated criteria.

INTRODUCTION

Chemical stabilization/solidification (CSS) is a process that involves the mixing of a contaminated soil with a binder material to enhance the physical and chemical properties of the soil and to chemically bind any free liquid¹. The CSS process involves the addition of water and binder material to the soil followed by mixing and a curing period. A schematic flowchart of CSS processing is shown as Figure 1. Typically, the binder is a cement or pozzolan. Proprietary additives also may be added. In most cases, the CSS process is changed to accommodate specific contaminants and soil matrices. Since it is not possible to discuss completely all possible modifications to a CSS process, discussions of most CSS processes are related directly to generic process types. The performance observed for a specific CSS system may vary widely from its generic type, but the general characteristics of a process and its products usually are similar. General discussions of CSS processes are given in Malone and Jones²; Malone, Jones and Larson³; and U.S. EPA⁴.

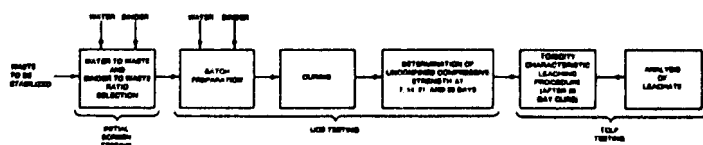


Figure 1

Schematic of the Chemical Stabilization/Solidification Process.

CSS systems that have potential application to contaminated soils include both Portland cement processes and pozzolan processes. Portland cement processes use Portland cement to produce a type of soil/concrete composite. Contaminant migration is reduced by microencapsulation of the contaminants in the concrete matrix and conversion of the metals to a less soluble form. Pozzolanic processes use the finely divided, noncrystalline silica in fly ash and the calcium in lime to produce low-strength cementation. Contaminant containment is produced by the same mechanisms in for the cement processes. Proprietary and non-proprietary admixtures, designed to enhance one or more properties of the mix, may be added to all CSS processes.

The specific objectives of this study were to determine if CSS techniques can be applied to soils contaminated with heavy metals to reduce contaminant leaching and to characterize the effect of CSS on the contaminated soils. Three solidification processes were used to stabilize/solidify the contaminated soil and are differentiated by the type of binder material used in the process. The three processes included: Portland cement, kiln dust and lime/fly ash.

MATERIALS AND METHODS

Materials of Interest

The materials of interest were contaminated soils obtained from three sites. Contaminants of interest included arsenic, cadmium, copper, lead, nickel, selenium and zinc. Analytical results from performing the California Waste Extraction Test (WET)² on the untreated soils are presented in Tables 1 and 2. The soils were generally classified as clay. The moisture content of the untreated soils was approximately 55, 25 and 27% for Soils 1, 2 and 3, respectively. A 5-gal composite sample of each soil was collected. The sample was collected from the top 12 in. of soil. Upon receipt at the laboratory, samples were placed in cold storage until implementation of the CSS evaluation protocol.

Table 1
Total Threshold Leaching Concentration (TTLC) Metals for Untreated Soil

PARAMETER	Criteria (mg/kg)	Detection Limit (mg/kg)	Soil 1 (mg/kg)	Soil 2 (mg/kg)	Soil 3 (mg/kg)
Arsenic	500	0.01	1500.0	93.0	37.0
Cadmium	100	0.005	9.2	250.0	42.0
Copper	2,500	0.025	170.0	1,550	1,000
Lead	1,000	0.2	10.0	37,800	19,600
Nickel	-	0.04	84.0	BDL	70.0
Selenium	100	0.005	3.0	12.0	7.4
Zinc	5,000	0.02	220.0	233,000	97,300

Table 2
Soluble Threshold Leaching Concentration (STLC)
Metals for Untreated Soil

Parameter	Criteria (mg/l)	Detection Limit (mg/l)	Soil 1 (mg/l)	Soil 2 (mg/l)	Soil 3 (mg/l)
Arsenic	5.0	0.01	16.0	1.8	1.1
Cadmium	1.0	0.005	0.1	7.6	2.7
Copper	25	0.025	1.3	61.0	68.0
Lead	5.0	0.2	BDL	370.0	500.0
Nickel	--	0.04	BDL	BDL	BDL
Selenium	1.0	0.005	BDL	0.21	0.36
Zinc	250	0.02	12.0	12,500	10,700

Initial screening test

The objective of the initial screening test was two-fold: the first objective was to determine the appropriate water to soil ratio (W/S or WSR), by wet weight, for each CSS process; the second objective was to narrow the range of binder to soil ratios (B/S or BSR) used for detailed evaluation. The soil was moist; however, it was necessary to add water to the contaminated soil to provide sufficient water for effective hydration. WSRs and BSRs selected for initial evaluation were based on the previous experience of testing personnel.

Determination of the appropriate WSRs and BSRs for detailed evaluation was based primarily on the results of the Cone Index Test (CI) performed on the initial screening test samples after they had cured for 48 hr. The CI measures the resistance of a material to the penetration of a 30-deg, right circular cone using the method specified in TM 5-530⁴. The CI value is reported as force per unit surface area, in psi, required to push the cone through a test material at a rate of 72 in./min.

Preparation of Specimens for Detailed Evaluation

Specimens were prepared by mixing water and binder with the contaminated soil in a Hobart K455S mixer. The resulting slurry was poured into 2-by-2 in. brass molds. Immediately after the slurry was placed in the molds, the molds were vibrated to remove voids. At the higher BSRs, the mixture was very viscous and vibration was an ineffective method for removing voids. These specimens were tamped according to ASTM C 109/86¹. The molded specimens were cured in the molds at 23°C and 98% relative humidity for a minimum of 24 hr. Specimens were removed from the molds when they developed sufficient strength to be free standing, and curing was continued under the same temperature and relative humidity conditions until further testing.

Unconfined Compressive Strength

Unconfined compressive strength (UCS) was used to define and characterize the effects of the CSS process on the physical characteristics of the soil. The UCS of the treated soil test specimens was determined using ASTM method C 109/86¹. UCS testing was performed on cubes after they had cured for 21 and/or 28 days. UCS was reported as the force per square inch, in psi, required to fracture the cube.

BSRs that exhibited UCS values greater than 50 psi were selected for evaluation of the contaminant-release characteristics of the treated soil. A UCS criterion of 50 psi was based on Office of Solid Waste and Emergency Response (OSWER) Policy Directive 9487.00-2A⁷.

Contaminant Mobility Testing

Since the sites under investigation are located in California, the California Waste Extraction Test (WET) procedure was used to evaluate contaminant mobility². The California procedure requires evaluation of both Total Threshold Leaching Concentration (TTLC) and Soluble Threshold Leaching Concentration (STLC). The TTLC/STLC analyses were performed by IT Corporation, Cerritos, California. Specimens selected for the extraction tests were forwarded to IT Corporation under chain-of-custody. TTLC and STLC extracts were analyzed for metals according to the methods and within the time constraints summarized in the *Federal Register*⁹ and specified in SW-846¹⁰.

DISCUSSION OF RESULTS

Initial Screening Test Results for Soil 1

In the initial screening test for the cement binder, WSRs of 0.1 and 0.5 were evaluated. The 0.1 WSR did not sufficiently hydrate the mixture, resulting in a dry, powdery specimen. At the 0.1 WSR and 0.4 BSR, the CI value was 647 psi after 48 hr of curing. Although the CI values were relatively high, the 0.1 WSR did not provide sufficient water for efficient hydration. In contrast, the 0.5 WSR resulted in very wet mixtures and yielded specimens with relatively low CI values, 93 and 260 psi for the 0.4 and 0.6 BSRs respectively. Based on past experience, observation of test specimens and the initial screening data, a WSR of 0.2 and BSRs of 0.2, 0.4 and 0.6 were selected for detailed evaluation.

The results of the initial screening test using kiln dust as the binder were similar to the cement binder results. Although relatively high CI values were obtained at the 0.4 and 0.6 BSR (693 and > 750 psi, respectively) at the 0.1 WSR, the samples were not adequately hydrated and dry, powdery mixtures were produced. Using a WSR of 0.5 and BSRs of 0.4 and 0.6, the samples were very moist and developed relatively low CI values (185 and 167 psi, respectively). Based on past experience, observation of test specimens and the initial screening data, a WSR of 0.2 and BSRs of 0.2, 0.4, 0.6 and 0.8 were selected for detailed evaluation.

The results of the lime/fly ash initial screening test were similar to cement and kiln dust binder results. At 0.1 WSR, the samples evaluated were not sufficiently hydrated and at 0.5 WSR the samples were too wet for efficient hydration. Based on past experience, observation of test specimens and the initial screening data, a WSR of 0.2 and BSRs of 0.2L/0.2F, 0.2L/0.4F, 0.4L/0.2F and 0.4L/0.4F were selected for detailed evaluation.

UCS Results for Soil 1

The results of the UCS tests for Soil 1 are shown in Figure 2 and discussed below.

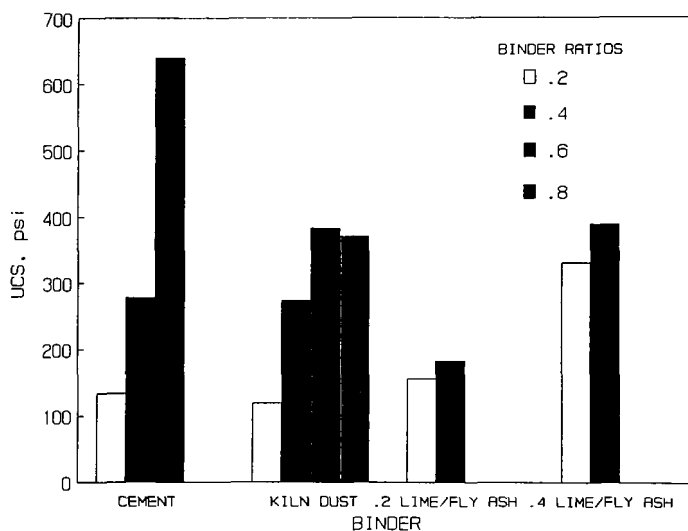


Figure 2
Twenty-eight Day UCS for Soil 1 Using Cement, Kiln Dust and Lime/Fly ash as Binders

For the cement binder, the 28-day UCS increased as the BSR increased, with the UCS doubling for each 0.2 increase in BSR. For example, at 0.2, 0.4 and 0.6 BSRs, the average UCSs were 134, 278 and 640 psi, respectively. Similar results were obtained when the UCS tests were run on 21-day cubes, indicating that the sample reached near maximum UCS at a 21-day cure time.

UCS results for the kiln dust binder were similar to those obtained with the cement binder. The 28-day UCS increased as the BSR was increased and a BSR of 0.8 developed three times the 28-day UCS of the 0.2 kiln dust BSR. The contaminated soil treated with a 0.2 kiln

dust BSR developed a 28-day UCS of 119 psi, and the 0.8 BSR developed a 28-day UCS of 370 psi. As the BSR increased, the UCS also increased but at a decreasing rate with each increase in the BSR. The 0.6 and 0.8 ratios had approximately equal 28-day UCS results, indicating little or no strength gain for BSRs greater than 0.6.

The interpretation of the lime/fly ash UCS data is more difficult than the cement and kiln dust UCS data because both the lime BSR and the fly ash BSR were varied. The 0.2L/0.2F BSR had UCS results, 155 psi, similar to the 0.2 cement and 0.2 kiln dust BSRs (134 and 119 psi, respectively). The average 28-day UCSs for 0.2L/0.2F and 0.2L/0.4F were 154 psi, and 182 psi, respectively. A 0.2 increase in the lime BSR resulted in doubling the UCS, with 0.4L/0.2F and 0.4L/0.4F UCSs of 330 psi, and 389 psi, respectively compared to 155 and 189 psi, for the 0.2L/0.2F and 0.2L/0.4F.

Extraction Test Results for Soil 1

As shown in Figure 2, all the binders, at the BSRs investigated, developed 28-day UCS well above the 50 psi, selection criterion, hence, the specimens with the minimum BSR were selected for WET analysis. The BSRs selected for extractions included: 0.2 cement, 0.2 kiln dust, 0.2 lime/0.2 fly ash. The results of the WET for treated Soil 1 are given in Table 3. The TTLC results reflect the dilution resulting from the addition of the binder material. The STLC results reflect substantial reduction in the apparent leachability of the contaminants. However, leachate arsenic concentrations for all binders exceeded the STLC arsenic criterion (5 mg/L) by a factor of three to seven. Other contaminants were less than their respective criteria. Of the binders evaluated, Portland cement appeared to perform the best, with kiln dust and lime/fly ash demonstrating roughly equal performance.

Table 3
Results of Solidification/Stabilization Studies on Soil 1

Contaminant	Standard		Untreated Soil		Cement		Kiln Dust		Lime/Flyash	
	TTLC (mg/L)	STLC (mg/L)	TTLC (mg/L)	STLC (mg/L)	TTLC (mg/L)	STLC (mg/L)	TTLC (mg/L)	STLC (mg/L)	TTLC (mg/L)	STLC (mg/L)
Arsenic	500.0	5.0	1500.0	10.0	1243.3	10.0	1504.67	20.67	1163.33	20.67
Cadmium	100.0	1.0	8.2	0.30	12.87	0.12	14.87	0.25	14.0	0.24
Copper	2500.0	25.0	170.0	1.3	230.0	7.30	306.67	13.33	246.67	8.0
Lead	1000.0	5.0	10.0	ND=0.2	148.87	ND=2.0	173.33	ND=2.0	14333.0	ND=2.0
Fluoride	---	---	84.0	ND=0.2	18.32	ND=0.4	21.67	ND=1.0	24.33	ND=0.4
Selenium	100.0	1.0	3.0	ND=0.05	4.0	ND=0.05	5.67	0.07	3.0	ND=0.05
Zinc	5000.0	250.0	220.0	12.0	283.33	0.37	306.67	5.67	303.33	1.03

Initial Screening Test Results for Soil 2

In the initial screening test for the cement binder, WSRs of 0.2 and 0.5 were selected for evaluation. A 0.2 WSR did not thoroughly hydrate the sample, but a 0.5 WSR provided a mixture of good consistency and adequate CI values. The 48-hr CI value at a 0.5 WSR and BSRs of 0.4 and 0.6 were 133 psi, and 467 psi, respectively. Based on past experience, observation of test specimens and the initial screening data, a WSR of 0.5 and BSRs of 0.4, 0.6, 0.8 and 1.0 were selected for detailed evaluation.

Based on the moisture contents and the results of the initial screening test for the cement binder, WSRs of 0.2 and 0.5 were also used for the kiln dust binder initial screening test. For the same reasons listed for the cement binder initial screening test, a 0.5 WSR was selected for detailed evaluation of kiln dust. Because the initial screening test results for a 0.5 WSR and 0.4 BSR were low, a 0.6 BSR was selected as the lowest BSR for detailed evaluation. Other BSRs selected for detailed evaluation were 0.8, 1.0 and 1.2.

For the lime/fly ash binder, WSRs of 0.2 and 0.5 were initially evaluated. Because both lime and fly ash are used, the mixtures using a 0.2 WSR were much dryer than the cement and kiln dust mixes prepared at a 0.2 WSR. A 0.5 WSR resulted in mixtures of good consistency and CI values, ranging from 125 to 517 psi, for the BSRs evaluated and was selected as the WSR for detailed evaluation. The 0.2L/0.2F BSR was selected as the lowest ratio for detailed evaluation because sub-

stantial strength was gained after only 2 days of cure. Based on past experience, observation of test specimens and the initial screening data, the BSRs selected for detailed evaluation were 0.2L/0.2F, 0.2L/0.4F, 0.2L/0.6F, 0.4L/0.2F, 0.4L/0.4F, 0.4L/0.6F, 0.6L/0.2F, 0.6L/0.4F and 0.6L/0.6F.

UCS Results for Soil 2

The results of the UCS tests for Soil 2 are shown on Figure 3 and discussed below.

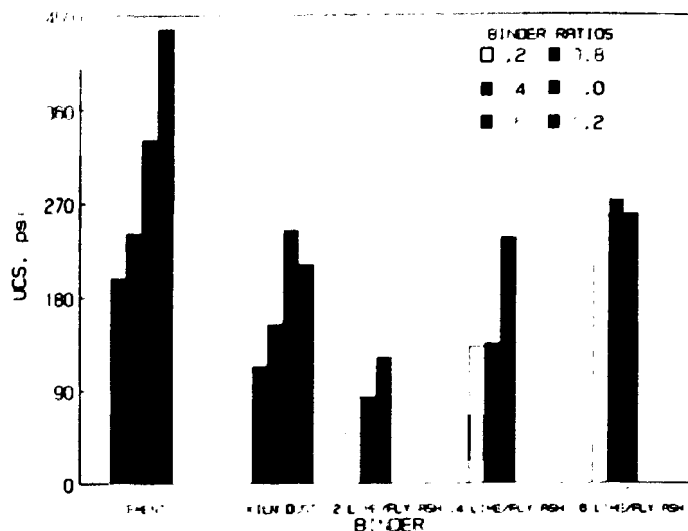


Figure 3
Twenty-eight Day UCS for Soil 2 Using Cement, Kiln Dust and Lime/Fly ash as Binders

Each BSR for the cement binder exceeded the 50-psi, criterion. At the lowest BSR, 0.4, the average UCS was 198 psi. The average UCS increased approximately 100 psi, with each 0.2 increase in the BSR.

Each BSR for the kiln dust binder exceeded the 50-psi, criterion. As expected, the 0.6 kiln dust BSR (114 psi,) did not develop as much strength as the 0.6 BSR for cement. As the BSRs were increased by increments of 0.2, the UCS also increased until the BSR reached 1.2. At this point, the kiln dust dehydrated the sample very quickly producing an extremely dry mixture, with a resulting decrease in UCS.

For the lime/fly ash binder, the average UCS did not increase significantly as the BSR was increased. At 0.2L/0.2F, the average UCS was 85 psi, and at the 0.6L/0.6F BSR the average UCS was 260 psi. The most significant increase in UCS was at the 0.4L/0.6F BSR, which exhibited an increase of 100 psi, over the 0.4L/0.4F BSR. Similarly to Soil 1 results, the increase in lime had more effect than an increase in fly ash.

Extraction Test Results for Soil 2

As shown in Figure 3, all the binders, at the BSRs investigated, developed a 28-day UCS well above the 50 psi, selection criterion. The BSRs selected for WET extraction included: 0.6 for cement, 0.8 for kiln dust and 0.2/0.4F for lime/fly ash. The results of the WET for treated Soil 2 are given in Table 4. The TTLC results reflect the dilution resulting from the addition of the binder material. The STLC results reflect substantial reduction in the apparent leachability of the contaminants. However, leachate lead concentrations for all binders exceeded the STLC lead criterion (5 mg/L) by a factor of seven to 22. Zinc exceeded the STLC criterion for the lime/fly ash binders by a factor of 10. Other contaminants were less than their respective criteria. Of the binders evaluated, Portland cement appeared to perform the best, with kiln dust and lime/fly ash demonstrating roughly equal performance.

Table 4
Results of Solidification/Stabilization Studies on Soil 2

Parameter	Standard		Untreated Soil		Cement		Kiln Dust		Lime/Flyash	
	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)
Arsenic	500.0	5.0	93.0	1.8	78.0	0.1	61.6	0.3	88.3	0.3
Cadmium	100.0	1.0	250.0	7.6	166.7	0.2	140.0	0.1	160.0	2.4
Copper	2500.0	25.0	1550.0	61.0	1303.3	10.7	976.7	16.7	1250.0	21.3
Lead	1000.0	5.0	37800.0	370.0	23100.0	64.0	19066.7	45.3	23666.7	76.7
Nickel	--	--	ND=200.0	ND=4.0	292.0	0.4	85.7	0.5	113.3	ND=0.4
Selenium	100.0	1.0	12.0	0.21	1.27	0.1	1.47	0.18	2.2	0.2
Zinc	5000.0	250.0	233000.0	12500.0	147333.0	213.0	119333.0	48.0	135333.0	2500.0

Initial Screening Test Results for Soil 3

The two WSRs evaluated for the cement initial screening test were 0.2 and 0.5. The 0.2 WSR resulted in samples that were not adequately hydrated resulting in a dry, powdery mixture. In contrast, the 0.5 WSR was very moist. The 0.5 WSR and 0.6 BSR had a CI value over 750 psi. At 0.5 WSR and 0.4 BSR, the CI value was 150 psi. These results indicated that by lowering the WSR, the BSR also could be lowered, while obtaining similar strength results. Based on past experience, observation of test specimens and the initial screening data, a WSR of 0.35 and BSRs of 0.2, 0.4 and 0.6 were selected for detailed evaluation.

WSRs of 0.2 and 0.5 were used for the kiln dust initial screening tests. The 0.5 WSR resulted in a very wet mixture, with low CI values of 33 psi, and 73 psi, at 0.4 and 0.6 BSRs, respectively. At a WSR of 0.2 and BSRs of 0.4 and 0.6, the CI values were much higher, 550 and 567 psi, respectively. Although the CI values for the 0.2 WSR were adequate, a WSR of 0.35 was chosen for detailed evaluation because laboratory notation indicated that the samples were not effectively hydrated at the 0.2 WSR. BSRs of 0.2, 0.4 and 0.6 were selected for detailed evaluation.

WSRs of 0.2 and 0.5 were used for the lime/fly ash initial screening tests. For the 0.2 WSR, CI values ranged between 490 and 533 for the BSRs evaluated. For the 0.5 WSR, CI values ranged between 63 and 343 psi. Like the cement and kiln dust, a 0.2 WSR as too low and a 0.5 WSR was too high. The 0.5 WSR did not achieve significant strength except at the highest BSR, 0.4L/0.4F, evaluated. A 0.35 WSR and BSRs of 0.2L/0.2F, 0.2L/0.4F, 0.4L/0.2F and 0.4L/0.4F were selected for detailed evaluation.

UCS Results for Soil 3

The results of the UCS tests for Soil 3 are shown on Figure 4 and discussed below.

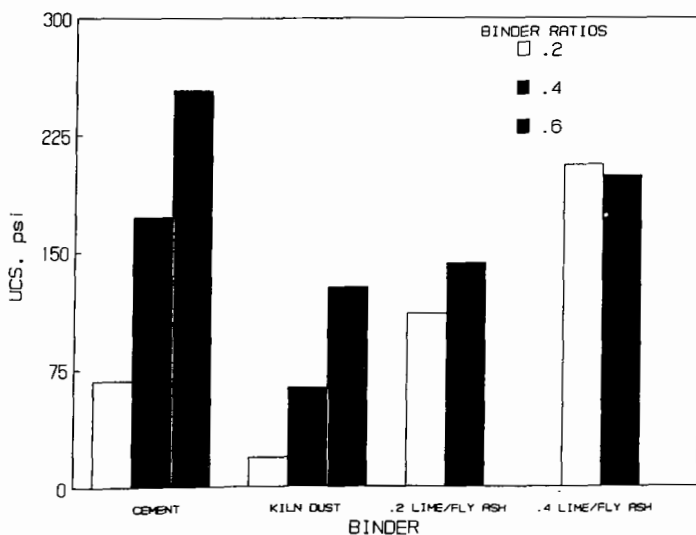


Figure 4
Twenty-eight Day UCS for Soil 3 Using Cement, Kiln Dust and Lime/Fly ash as Binders

For the cement binder, the UCS of the 0.2, 0.4 and 0.6 BSRs were 69 psi, 173 psi, and 254 psi, respectively. As the BSRs increased, the rate of increase in UCS decreased. From 0.2 BSR to 0.4 BSR, the UCS increased by 104 psi, but from 0.4 BSR to 0.6 BSR, the increase was only 81 psi.

The kiln dust binder results contrasted with those of the cement binder evaluation. The UCS of the 0.2, 0.4 and 0.6 BSRs were 19 psi, 64 psi, and 128 psi, respectively. The 0.2 BSR did not obtain enough strength, only 19 psi, to pass the 50-psi, criterion. As a result, 0.2 BSR was not evaluated further. The UCS increased with increases in the BSR, tripling from 0.2 BSR to 0.4 BSR and doubling from 0.4 BSR to 0.6 BSR. As expected, kiln dust was not as effective as cement in this segment of the solidification/stabilization of Soil 3.

The BSRs tested for lime/fly ash were 0.2L/0.2F, 0.2L/0.4F, 0.4L/0.2F and 0.4L/0.4F with a WSR of 0.35. The respective average UCSs were 111 psi, 143 psi, 206 psi, and 200 psi. Increasing the fly ash BSR by 0.2 resulted in a 30-psi, increase in UCS; however, increasing the lime BSR by the same amount doubled the UCS. Increasing both lime and fly ash caused the UCS to triple at 0.4L/0.4F.

Extraction Test Results for Soil 3

As shown in Figure 4, all the binders, except the 0.2 BSR kiln dust, developed a 28-day UCS above the 50-psi, selection criterion. The BSRs selected for extraction included: 0.4 for cement, 0.4 for kiln dust and 0.2L/0.4F for lime/fly ash. The results of the WET for treated Soil 3 are given in Table 5. The TTLC results reflect the dilution resulting from the addition of the binder material. The STLC results reflect substantial reduction in the apparent leachability of the contaminants. However, leachate lead concentrations for all binders exceeded the STLC lead criterion (5 mg/L) by a factor of nine to 46. Copper concentrations slightly exceeded the criterion. Other contaminants were less than their respective criteria. Of the binders evaluated, Portland cement appeared to perform the best, with kiln dust and lime/fly ash demonstrating roughly equal performance.

Table 5
Results of Solidification/Stabilization Studies on Soil 3

Parameter	Standard		Untreated Soil		Cement		Kiln Dust		Lime/Flyash	
	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)	TTLC (mg/kg)	STLC (mg/l)
Arsenic	500.0	5.0	37.0	1.1	32.33	0.167	32.0	0.13	53.0	0.4
Cadmium	100.0	1.0	42.0	2.7	37.33	0.07	35.0	0.21	35.7	0.06
Copper	2500.0	25.0	1000.0	68.0	890.0	15.4	853.0	30.0	876.7	33.0
Lead	1000.0	5.0	10600.0	500.0	13967.0	106.4	14600.0	66.0	13666.7	220.0
Nickel	--	--	70.0	ND=4	64.0	0.4	69.7	ND=0.4	72.7	ND=0.4
Selenium	100.0	1.0	7.4	0.36	ND=0.5	0.07	1.4	0.27	1.1	0.3
Zinc	5000.0	250.0	97300.0	10700.0	71200.0	136.7	76933.0	83.0	74033.3	46.3

CONCLUSIONS

A laboratory study was conducted to investigate the effects of three CSS processes on a contaminated soil. Both UCS and WET tests were performed on the stabilized/solidified specimens and based on the results of these tests, the following conclusions can be drawn:

- Small quantities of binding agents produce materials with UCS well above the 50-psi, criterion.
- Water must be added to the contaminated soil in order for the binders to develop strength.
- The binders can be easily mixed with the contaminated soil.
- The stabilized/solidified soil sets within 24 hr and no free liquid was observed after this 24-hr period.
- The CSS processing of the soil effectively reduced the mobility of the contaminants in the soil.
- Because of the high concentrations of the contaminants and/or the aggressiveness of the WET procedure, none of the CSS processes produced a product that meets the California Department of Health Services TTLC/STLC criteria.

REFERENCES

1. American Society for Testing and Materials, *Construction; Cement; Lime; Gypsum*, Vol 0401, *Annual Book of ASTM Standards*, Philadelphia, PA, 1986.
2. California Administrative Code, "California Hazardous Waste Regulations," Department of Health Services, Section 66700, July 29, 1985.
3. California Department of Health Services, "California Site Mitigation Decision Tree," Sacramento, CA, 1986.
4. Headquarters, Department of the Army, "Materials Testing," Technical Manual No. 5-530, Section XV, Washington, DC, 1971.
5. Malone, P. G. and Jones, L. W., "Survey of Solidification/ Stabilization and Technology for Hazardous Industrial Wastes," EPA-600/2,79056, U.S. EPA, Cincinnati, OH, 1979.
6. Malone, P. G., Jones, L. W. and Larson, R. J., *Guide to the Disposal of Chemically Stabilized and Solidified Waste*, SW-872, Office of Water and Waste Management, U.S. EPA, Washington, DC, 1980.
7. U.S. EPA. Office of Solid Waste and Emergency Response (OSWER) Policy Directive 9487.00-2A, Office of Solid Waste and Emergency Response, Washington, DC, 1986.
8. U.S. EPA. *Handbook for Stabilization/Solidification of Hazardous Wastes*, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1986.
9. U.S. EPA. *Federal Register*, 51, No. 142, Office of Solid Waste, Washington, DC, Nov. 7, 1986.
10. U.S. EPA. *Test Methods for Evaluation Solid Waste: Physical/Chemical Methods*, SW-846, 3rd ed., Office of Solid Waste and Emergency Response, Washington, DC, 1986.

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In Situ Remediation of Groundwater and Soils: Seminar Outline

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BRIEF HISTORY

- 1946 - CE Zobell publication: Hydrocarbon Microbiology
- 1950s - Single cell protein development showed relationship of bacteria/oil/water
- 1967 - Focus on ocean oil spills and bacterial degradation: first environmental focus
- 1970s - Microbial enhanced oil recovery technology showed relationship of bacteria/oil/water/mineral
- 1972 - First application of in situ aquifer bioremediation, Sun Oil Company under the guidance of Paul Yaniga (Groundwater Technology, Inc.)
- 1980s - Bioremediation technologies shown to be a proven and cost-effective remediation strategy for many organic waste contaminated sites.

BIOMECHANISM OF ORGANIC CHEMICAL DEGRADATION

- Aerobic Oxidation
 - Use of oxygen as terminal electron acceptor
 - Most rapid biomechanism for degradation of most organic wastes
 - Products are oxidized intermediates, carbon dioxide and water
- Co-oxidation
 - Use of co-metabolite to degradation of an otherwise recalcitrant compound.
 - Harder to control than simple aerobic oxidation.
 - Rates vary greatly depending upon pollutant, co-metabolite, etc.
- Anaerobic Dehalogenation
 - Simple biologically mediated redox reaction
 - Requires very anaerobic condition
 - Simply dehalogenates substrate, not mineralized

BIODEGRADABILITY OF ORGANICS

- Unsubstituted Hydrocarbons
 - Rapidly degrade
 - Multiple ring structures are more resistant
- Resistance imparted by substitution
 - Halogens
 - Ethers
 - Methoxy groups
 - Etc.
- Molecular Complexity
 - Greater the complexity - greater resistivity

BACTERIAL ATTACHMENT TO ORGANIC POLLUTANTS

- Cell surface hydrophobicity
 - Hydrophile - lipophile balance of cell surface

- Oil/water partitioning
- Biosurfactant production
 - Activity of cell surface
 - Surface activity of biomolecules
 - Action on pollutants
- Forms of pollutants available to bacteria
 - Droplets
 - Dissolved molecules
 - Microemulsions

BACTERIA CAPABLE OF IN SITU BIODEGRADATION

- Dependent upon pollutant
- Dependent upon environmental factors
- New organisms being discovered regularly

BACTERIA FOR USE IN AN IN SITU DECONTAMINATION SYSTEM

- Genetically engineered strains
- Not likely due to regulatory constraints
- Acclimated strains
 - Generally unnecessary for most applications
 - Almost impossible to use effectively in subsurface groundwater systems.
- Stimulation of indigenous strains
 - Generally best way to approach bioremediation
 - Appropriate bacteria generally present

NUTRIENTS NECESSARY FOR IN SITU AEROBIC BIOREMEDIATION SYSTEMS

- Oxygen
 - Air spargers
 - Hydrogen peroxide
 - Soil aeration
- Nitrogen
- Phosphorous
- Trace elements
- pH
- Temperature

NUTRIENTS NECESSARY FOR CO-OXIDATION BIOREMEDIATION

- Same as for Aerobic System with the Systems Addition of a co-metabolite.

NUTRIENTS NECESSARY FOR ANAEROBIC DEHALOGENATION SYSTEMS

- Same as aerobic oxidation systems except:

- No oxygen should be added
- Need supplementary carbon sources

IN SITU BIOREMEDIATION SYSTEM DESIGN

- Saturated Zone
 - Hydraulic control
 - Infiltration
 - Closed loop recycle
 - Nutrient system
 - Monitoring
- Unsaturated zone
 - Soil aeration system
 - Forced air
 - Negative pressure
 - Nutrient percolation
 - Soil pore moisture
 - Monitoring

ON-SITE BIOREMEDIATION SYSTEM DESIGN

- Soils/Sludge treatment
- Cell construction
 - Aeration
 - Nutrient addition
 - Off-gas treatment
 - Monitoring

CASE STUDIES

CASE #1

In Situ Bioremediation: A Case Study through Closure.

- Contaminated site setting
- Bioremediation system design
- Performance of system/site data
- Post-closure monitoring
- Associated costs of project versus other treatment technologies

CASE #2

In Situ Bioremediation: Unsaturated zone and Saturated Zone.

- Contaminated site setting
- Bioremediation feasibility study
- Comprehensive system design
- Performance of system/site data
- Associated costs of project

CASE #3

On-Site Bioremediation of Heavy Oil Contaminated Soils.

- Site setting
- Feasibility study
- Site excavation/construction
- Nutrient amendment
- Performance data
- Associated costs of project versus other treatment technologies

Appendix I

FOCUS

In Situ Bioreclamation: A Cost-Effective Technology to Remediate Subsurface Organic Contamination

by Scott B. Wilson and Richard A. Brown

Abstract

In situ bioreclamation is a proven technology that cost-effectively treats organic contamination in subsurface environments. As a remediation strategy, it reduces both the contamination dissolved in ground water, as well as residual soil-bound contamination.

To maximize biodegradation, the technology is applied after conducting laboratory studies. Application of the technology involves infiltrating necessary nutrients to the contaminated subsurface.

Results of a specific case study indicate excellent performance with rapid cleanup of petroleum hydrocarbon contamination from soils and ground water.

Costs associated with in situ bioreclamation technology showed a savings of approximately 50 percent over simple pump-and-treat technology. Time frame for cleanup was shown to be approximately 30 percent of the projected time frame of simple pump-and-treat technology.

Introduction

The basis for all bioreclamation technologies as applied to hydrocarbons and organic pollutants is hydrocarbon microbiology, a field of study that was first reviewed by C.E. Zobell (1946). Zobell showed that the ability of microorganisms to use hydrocarbons was dependent upon environmental factors, as well as the chemical makeup of the organic substrate. The application of hydrocarbon-degrading bacteria is not new and literature is readily available on related topics, such as the production of surfactants in hydrocarbon fermentation (Suzuki et al. 1969) and the bacterial extraction of bitumens from tar sands (Gerton and Zajac 1977 and Wyndham and Costerton 1981). Atlas (1981) has presented an excellent review of environmental perspectives of hydrocarbon microbiology.

The application of hydrocarbon-degrading bacteria to remediate ground water contamination was first suggested by Davis et al (1972) who recommended in situ bioreclamation by inorganic nutrient stimulation as a method of restoring ground water quality. Today, the technology is a proven component of ground water remediation programs with bioreclamation having the ability to restore subsurface environments at a fraction of the time and costs necessary with simple "pump-and-treat" systems.

In Situ Bioreclamation as a Remediation Strategy

There is no single remedial approach that will be universally applicable to every site and contaminant

Choice of particular treatment processes should be determined by an understanding of the transport and persistence of the contaminant. The reactivity of a contaminant either chemically or biologically and its ultimate fate determine whether an in situ treatment process can be used or whether containment or physical removal is more appropriate. The feasibility of a remediation process is determined by matching available technology with an understanding of contaminant transport and reaction.

Subsurface Contamination

Organic contaminants potentially exist in the subsurface as a vapor phase and three condensed phases: (1) mobile free product (phase separated), (2) residually contaminated soil (sorbed phase), and (3) contaminated ground water (dissolved phase). The distribution of contaminants into these different phases, while a result of dynamic transport, is ultimately a function of their physical and chemical properties and the hydrogeological and geochemical characteristics of the formation. One must examine the phase distribution in terms of the volume of the subsurface impacted by a phase and the amount of the contaminant within a phase.

Table I represents the estimated phase distribution of a gasoline spill in a medium sand aquifer (Groundwater Technology Inc. 1983). There are several generalizations that can be made from this. First, ground water flow is the primary long-term mechanism for the spread of contamination once the free product layer has achieved flow equilibrium. Because of the high mobility of ground water, the volume of ground water contaminated is greater than the other phases. This phase, however, contains only

TABLE I
Phase Distribution of a Typical 30,000-Gallon Gasoline Spill*

Phase	Contaminated Volume Cu. Yd.	% of Total	Contaminant Volume (Gallons)	% of Total
Free phase	700	1.0	16,500	62
Adsorbed (soil)	250,000	30.0	10,000	33
Dissolved (water)	900,000	79.0	333	1.5

*Medium sand aquifer, depth to water approximately 15 feet.

a small fraction of the total product (1 to 5 percent). Most of the contaminant (62 percent of the amount spilled) is present as free-phase material.

The second observation to be made is that the amount of material in the ground water is small compared to that retained in the soil matrix (33 percent). Laboratory studies have shown (Brown et al. 1987) that gasoline residual saturation capacity in dry soils varied from 32.0 mg gasoline/kg soil (32,500 ppm) for coarse sand (i.e., 2.0 mm average particle diameter) to 122.3 mg gasoline/kg soil (122,000 ppm) for fine sand (i.e., 0.25 mm average particle diameter). Sands at field capacity moisture content had lower residual saturation capacities than dry sands.

At field capacity moisture content, residual saturation capacities ranged from 26.5 mg gasoline/kg soil for medium sand (i.e., 0.85 mm average particle diameter) to 44.1 mg gasoline/kg soil (44,200 ppm) for fine sand. These values demonstrate the importance of addressing the adsorbed phase, as well as ground water, because the residually contaminated soil is a continuing source of dissolved ground water contamination. In a study of the water extraction of various residually contaminated soils, it was found that 46 pore volumes of water effectively removed only 1.6 percent of adsorbed gasoline fractions. After 500 pore volumes of water, soil contamination was still high (in the range of 1400 ppm) (Brown et al. 1987). Therefore, after phase-separated product recovery, the focus of remediation should be on the reduction of residual soil contamination, thereby reducing dissolved-phase pollutants simultaneously.

Bacterial Action in the Subsurface

The target of in situ bioreclamation is both the adsorbed phase and the dissolved phase. By stimulating the proper bacteria to proliferate in the subsurface, organic contaminants are reduced by bacterial attack. Bacteria can attach directly onto contaminant droplets held within the porous matrix of the subsurface soils and/or adsorbed onto the surface of soil particles. This occurs due to the cell surface hydrophobicity of many organic chemical degrading bacteria (Rosenberg et al. 1980, Dahlback et al. 1981). This characteristic forces the bacterium to partition onto the hydrophobic surface of adsorbed or trapped organics, thus putting the degrading bacterium in direct contact with the polluting chemical.

Another mode of bacterial attack is the production of biosurfactants, which are surface-active compounds that aid in the dispersal of the contaminant. Biosurfactants

are broadly grouped into categories based upon their chemical components including carbohydrate-containing, amino acid-containing, phospholipids, fatty acids, and neutral lipids (Wilson 1985). Production of biosurfactants is often stimulated by the presence of organic chemicals (Suzuki et al. 1969), and it has been shown that they play an important role in hydrocarbon and organic chemical transfer to aqueous media (Velankar et al. 1975). Contaminants within the porous matrix of the subsurface incorporate into micelles and macroemulsions in the presence of surfactants and are dispersed into the aquifer waters. Chemical transfer from micelles or macroemulsions to the bacterial cell is readily performed because biosurfactants and many cell surface components are compatible (Gerton 1985).

The uptake of dissolved organic contaminants directly from the aqueous phase is also a mode of bacterial attack upon subsurface contaminants. This is a mechanism that is well understood as it has been studied with regard to common waste-treatment technologies such as trickling filters. Here the contaminating organic chemicals are scavenged from the aqueous phase by fixed subsurface bacteria (those adhering to the aquifer matrix) and those suspended in the soil pore moisture and aquifer waters.

By stimulating the appropriate bacteria in the subsurface, contamination is attacked and degraded by the previously described mechanisms in place in a true in situ treatment process. This is the only in situ treatment method proven to date that addresses both the dissolved contaminants, as well as its source, the residual soil contamination.

Principles of Application

The proper application of in situ bioreclamation requires the integration of hydrogeology, geochemistry, microbiology, and engineering. For bioreclamation to be successful there must be an appropriate bacterial community, the hydrology must allow for timely transport through the subsurface and the soil and water chemistry must be compatible with the introduction of necessary nutrients.

Laboratory Pilot Study

Prior to the field application of any in situ bioreclamation system, an assessment should be made of the ground water and soil quality across the site with respect to chemical and physical parameters, as well as bacterial enumeration and contaminant concentrations. A labora-

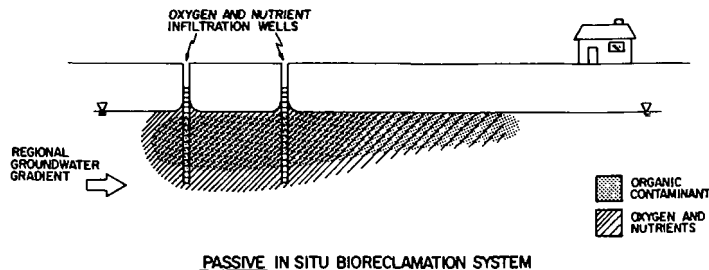


Figure 1. Passive in situ bioreclamation system.

tory pilot study should be conducted to discern the biodegradability of the contaminants and the subsurface parameters necessary to stimulate maximum degradation. This is accomplished by a microcosm evaluation, which consists of a soil/water slurry of site material designed to emulate the site environment. Inorganic nutrient (e.g. nitrogen and phosphorous sources) and oxygen (where applicable) concentrations are adjusted to give the greatest rate of degradation. In complex mixtures, the rates and sequences of specific compound degradation should be evaluated. Based on the microcosm studies, an estimate of remediation time can be derived under these optimum conditions. Once this is accomplished, an engineering evaluation should be conducted to determine the feasibility of obtaining these conditions in the subsurface and to define potential problems that could arise during the implementation of the in situ program.

Conceptual System Design

Proper design of an in situ bioreclamation system provides for mass transfer into and out of the contaminated area. This can be achieved through a passive system by simply infiltrating nutrients into the contaminated

subsurface (Figure 1). Often, however, at sites where ground water is being recovered, reinfiltration of augmented site water is performed in a dynamic system design (Figure 2). The advantage of a dynamic system design is that induced hydraulic gradients can be created to control flow and thus movement of nutrients and contaminants.

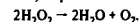
It is generally unnecessary to add bacteria to the subsurface. Bacteria capable of degrading a wide range of organic contaminants have been shown to exist in subsurface environments (McKee, et al. 1972, Litchfield and Clark 1973) and can be stimulated to degrade the contaminants of concern as indicated by positive laboratory pilot study results.

Oxygen Supply

For those systems requiring aerobic microbial processes, oxygen is generally the limiting factor to the bioreclamation process. Support for this is shown in reports by many workers including a study by Wilson et al. (1985), in which it was concluded that oxygen supply was limiting creosol biodegradation in contaminated aquifer material. One method of supply is the feeding of atmos-

pheric oxygen through air spargers. These spargers, generally of silicon carbide, have the capacity to diffuse atmospheric air into ground water at a rate of up to 10 cubic feet of air per minute when placed in wells and driven by an adequate air compressor. Problems associated with this approach to aeration, however, can be critical. Biofouling (sliming) of the sparging surface occurs in the presence of the induced aeration, often inhibiting flow of air outward into the well bore. Biofouling of the well's filter pack can also occur, decreasing flow and diffusion into and out of the native soils. Remedying these problems generally entails the laborious pulling of the spargers for cleaning and the treatment of biofouled wells with an appropriate chemical.

Oxygen can also be supplied to ground water chemically by the use of hydrogen peroxide solutions. Hydrogen peroxide decomposes naturally in the presence of heavy metal catalysts and certain microbial enzymes (e.g., catalase) to produce water and oxygen:



This decomposition is completed over time and has been shown to present no hazards to ground water (Texas Research Institute 1982). Although used as an antiseptic at high concentrations (i.e., 3 percent solution), hydrogen peroxide can be supplied to hydrocarbon-utilizing bacteria at up to 2500 ppm without showing cytotoxic effects (Texas Research Institute 1983). The proper application of hydrogen peroxide to the subsurface allows for adequate oxygenation of the contaminated ground water while controlling the biofouling of the infiltration points.

Nutrient Supply

The nutrients necessary to stimulate bacterial degradation in the subsurface should be studied and defined at the laboratory pilot study stage. Generally, however, nutrient requirements consist of phosphorous and nitrogen. Phosphorous can be supplied in one of several forms but common sources for ground water augmentation are orthophosphate and polyphosphate salts. It should be recognized that phosphates are readily adsorbed onto soils and if improperly applied can precipitate from solution, affecting the hydraulic conductivity of contacted strata.

A wide range of nitrogen sources have potential for use in situ. Common supplies are ammonium salts, as these are inexpensive, easy to handle, and the ammonium ion is readily assimilated in bacterial metabolism. Any time a nitrogen source is added to ground water (particularly when inducing aerobic conditions) it is important to monitor levels of the inorganic nitrogen species, including ammonia, nitrite, and nitrate. This allows for an understanding of the total quantity of inorganic nitrogen available and of the subsurface oxidation-reduction potential.

Trace elements, by and large, are available in sufficient quantities in ground water environments. These include calcium, magnesium, manganese, iron, sulfur, etc. However, in situ biodegradation systems have been applied where native ground water quality was augmented with trace elements to ensure maximum biodegradation as defined in initial laboratory pilot studies.

Monitoring and Analysis

The proper operation of any in situ bioreclamation system includes the monitoring of ground water quality with regard to dissolved oxygen, pH, inorganic water chemistry, organic water chemistry, and bacterial enumeration. Particularly critical is the initial startup period when infiltration of nutrients (and oxygen) is begun. Such shakedown monitoring establishes subsurface transport patterns, nutrient transport times, oxygen consumption rates, and contaminant release and degradation rates. Throughout operation, monitoring should be conducted to ensure optimum conditions are being maintained in the subsurface to affect maximum degradation rates. Monitoring of the system may also be necessary to ensure that any hydraulic control requirements are being met to contain contaminant and nutrient migration.

Case Study

The case study to be discussed is the remediation of a gasoline contamination site. The leak was estimated at a volume of 900 gallons of leaded gasoline, the dissolved fraction of which was impacting a municipal water supply. The soils impacted were calcareous silty sandy clays and calcareous argillaceous silty and/or gravelly sands. This was underlain by a highly fractured and solution-channelled impure limestone and dolomite aquifer of high productivity. The areal extent of the dissolved contamination within the aquifer was within a 100-foot radius of the spill site.

After adequate assessment of the site conditions, a comprehensive ground water remediation program was undertaken. The program involved hydraulically controlling the initially observed dissolved hydrocarbon contamination using a water-table depression pump. This central pumping point served as a collection for phase-separated hydrocarbons using a dual-pump system (Yaniga 1982). Recovered water was treated via a counter-current flow air stripping system. The total amount of phase-separated product recovered was approximately 100 gallons, with excavation of contaminated soils removing an estimated 50 gallons of hydrocarbons. The balance of contamination was bound in the soil as the adsorbed phase and dissolved in the ground water.

A laboratory pilot study showed a hydrocarbon degrading consortium of bacteria present within the contaminated aquifer (approximately 1.0×10^4 cfu/mL). This consortium was shown to provide maximum biodegradation of the contaminants under aerobic conditions with ammonium chloride and sodium phosphate nutrient augmentation. The geochemistry of site soil and water appeared to be compatible with this mixture of inorganic salts, showing no effects upon soil permeability or infiltration even when subjected to hydrogen peroxide feed.

An in situ bioreclamation system was implemented at the site. Recovered water treated through the air stripper was augmented with ammonium chloride and phosphate salts, as well as hydrogen peroxide and reintroduced to the contaminated subsurface through an infiltration gallery in a dynamic-type in situ bioreclamation system.

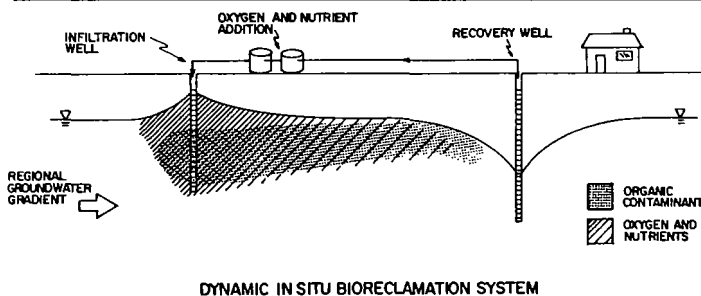


Figure 2. Dynamic in situ bioreclamation system.

Additional loading of nutrients and peroxide was conducted by batch feeding of strategic wells.

After 18 months of operating the in situ bioremediation system, approximately 99 percent of the residual soil-bound and dissolved hydrocarbons had been degraded, water quality in the recovery well indicated 1.0 part per billion total petroleum hydrocarbons (Figures 3, 4, 5). This represents more than 650 gallons of petroleum hydrocarbons biodegraded, compared to only 50 gallons of reduction attributed to air stripping of the recovered water.

Associated Cost

The cost-effectiveness of in situ bioremediation over other treatment technologies is the result of two factors. First, bioremediation will treat both the soil and the ground water, thus eliminating the source of contamination, as well as the symptom. Second, the bioremediation process is more rapid than extraction and thus the time of treatment is significantly less. Because of increased effectiveness and decreased operation time, in situ bioremediation is generally a very cost-effective option (Yamaguchi and Smith 1985).

The costs for applying bioremediation at a given site reflect (1) the physical setup (e.g., number of wells), (2) amount of equipment, (3) the nutrients consumed, and (4) the services required, both analytical and managerial. The factors that affect these costs are:

- The type and amount of contaminant present
- Site hydrogeology (permeability, ground water flow, etc.)
- The level of remediation

The first two factors are ultimately quantifiable and are dependent upon site conditions. The third factor is somewhat nebulous and is dependent on regulatory interaction. Table 2 shows how these factors impact a remediation project.

The case study presented in the previous section represents a typical in situ bioremediation program in terms of associated costs relative to other treatment options. Because this site remediation included a pump-and-treat system (air stripping tower), an analysis can be made of the cost benefit of employing in situ bioremediation over the cost associated with pump-and-treat technology alone. Presented in Figure 6 is an additive cost curve showing all cumulative costs that were associated with implementing the in situ bioremediation program in combination with the pump-and-treat technology. Also shown are projected cumulative costs for remediating the same site by pump-and-treat technology alone (based on a detailed review of pump-and-treat systems operating in similar contaminated site conditions).

This comparison demonstrates that in situ bioremediation was very effective, achieving cleanup in approximately two years. The projected time frame associated with operating the pump-and-treat system alone in this case was at least eight years, which is conservative when compared to other generalized estimates (Engineering Science Inc. 1986).

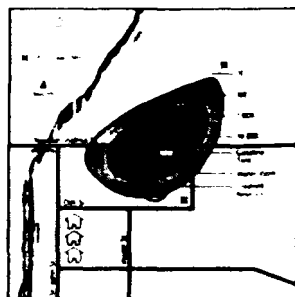


Figure 3. Extent of initial ground water hydrocarbon contamination (ppm).

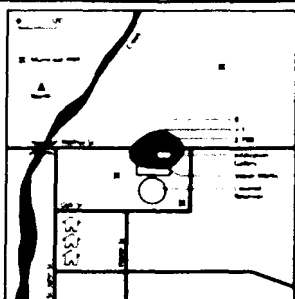


Figure 4. Extent of contamination 18 months following in situ bioremediation with air stripping of produced water.

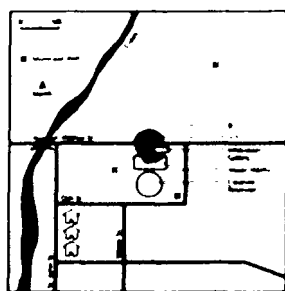


Figure 5. Extent of contamination after 34 months of in situ bioremediation with air stripping of produced water.

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TABLE 2
Factors Influencing the Cost of In Situ Bioremediation

Factor	Design Element	Impact
Contaminant type	Nutrients consumed	N,P,O demand per lb contaminant
	Service required	Project time
Contaminant amount	Nutrients consumed	Total nutrient demand
	Physical setup	Number of wells, equipment
Areal extent of contamination	Service required	Project time
	Physical setup	Number of wells, equipment
Water table depth	Physical setup	Cost of wells
Remediation level	Service required	Project time

The greater initial costs of implementing the in situ bioremediation system would have been exceeded after an additional operating time of two years by pump-and-treat technology alone. However, at this point (four years operation) the pump-and-treat technology would have operated only one-half of the minimum time necessary to achieve remediation of the site, representing a final cost of at least \$425,000. It should be noted that this projected pump-and-treat cost is based on an average per-year operating cost and is therefore conservative. It does not reflect the present worth of operations (capital and operation and maintenance costs over operation time at a

projected interest rate) or projected cost attributed to inflation.

Summary

In situ bioremediation is a proven technology that when properly applied, can greatly reduce treatment time and associated costs of contaminated soil and ground water cleanup.

To successful application requires the integration of the hydrology, chemistry, and microbiology of the site. For bioremediation to be successful there must be an appropriate bacterial community, the hydrology must

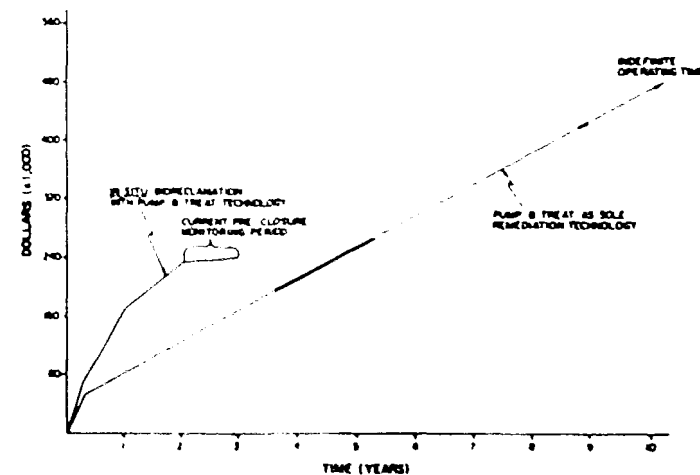


Figure 6. Cost comparison: in situ bioremediation vs. simple pump-and-treat.

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allow for timely transport of nutrients, and the soil and water chemistry must be compatible with the nutrients introduced.

Proper system design includes a laboratory pilot study to discern the biodegradability of contamination under site conditions and an engineering evaluation to study effects of implementation upon site soils and the aquifer itself. Nutrients (and oxygen where applicable) can be added to the subsurface both passively and in dynamic systems requiring recovery and infiltration of water.

In situ bioreclamation rapidly attacks the residual contaminants trapped within site soils, as well as dissolved within the aqueous phase. Because of this simultaneous reduction of both the symptom, as well as the source of contamination, in situ bioreclamation has proven to be a very cost-effective remediation alternative.

References

- Atlas, R.M. 1981. Microbial degradation of petroleum hydrocarbons: An environmental perspective. *Microbiol. Rev.*, v. 45, no. 1, pp. 180-209.
- Brown, R.A., G.E. Hoag, and R.D. Norris. 1987. The Remediation Game: Pump, Dig, or Treat. Water Pollution Control Federation Conference. Oct., Philadelphia, Pennsylvania.
- Dhalback, B., M. Hermansson, S. Kjelleberg, and B. Norkrans. 1981. The hydrophobicity of bacteria—an important factor in their initial adhesion at the air-water interface. *Archives of Microbiology*, v. 128, pp. 267-270.
- Davis, J.B. 1972. *The migration of petroleum products in soil ground water: Principles of countermeasures*. American Petroleum Institute Publication No. 4149, Washington, D.C.
- Engineering-Science Inc. 1986. *Cost model for selected technologies for removal of gasoline components from groundwater*. American Petroleum Institute Publication No. 4422, Washington, D.C.
- Gerson, D.F. 1985. The biophysics of microbial growth on hydrocarbons: Insoluble substrates. *Int. Biore-sources J.*, v. 1, pp. 39-53.
- Gerson, D.F. and J.E. Zajic. 1979. Bitumen extraction from tar sands with microbial surfactants. *Canada - Venezuela Oil Sands Symposium*, pp. 195-199.
- Groundwater Technology Inc. 1983. Estimation of lost product distribution in the subsurface. Confidential Client, GTI, Chadds Ford, Pennsylvania.
- Litchfield, J.H. and L.C. Clark. 1973. *Bacterial activities in ground waters containing petroleum products*. American Petroleum Institute Publication No. 4211, Washington, D.C.
- McKee, J.E., F.B. Laverty, and R.N. Hertel. 1972. Gasoline in groundwater. *J. Water Poll. Cont. Fed.*, v. 44, pp. 293-302.
- Raymond, R.C., V.W. Jamison, J.O. Hudson, R.E. Mitchell, and V.E. Farmer. 1978. Field application of subsurface biodegradation of gasoline in a sand formation. Final report submitted to American Petroleum Institute, p. 137.
- Rosenberg, M., E. Rosenberg, and D. Gutnick. 1980. Bacterial adherence to hydrocarbons. R.C.W. Berkeley, J.M. Lynch, J. Mellings, P.R. Rutter, and B. Vincenti (ed.) *Microbial Adhesion to Surfaces*. Ellis Horwood,

- Chichester, England, pp. 541-542.
- Suzuki, T., K. Tanaka, I. Matsubara, and S. Kinoshita. 1969. Trehalose lipid and alpha-branched beta-hydroxy fatty acids formed by bacteria grown on n-alkanes. *Agric. Biol. Chem.*, v. 33, no. 11, pp. 1619-1626.
- Texas Research Institute Inc. 1982. *Feasibility Studies on the Use of Hydrogen Peroxide to Enhance Microbial Degradation of Gasoline*. American Petroleum Institute, Washington, D.C.
- Texas Research Institute Inc. 1983. Progress Report: *Biostimulation Study*. February.
- Velankar, S.K., S.M. Barnett, C.W. Houston, and A.R. Thompson. 1975. Microbial growth on hydrocarbons - Some experimental results. *Biotech. Geoen.*, v. 17, pp. 241-257.
- Wilson, S.B. 1985. In situ biosurfactant production: An aid to the biodegradation of organic ground water contaminants. In *Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection and Restoration*. National Water Well Association/American Petroleum Institute, Houston, Texas, pp. 436-444.
- Wyndham, R.C. and J.W. Costerton. 1981. In vitro microbial degradation of bituminous hydrocarbons and in situ colonization of bitumen surface within the Athabasca oil sands deposit. *Appl. Environ. Microbiol.*, v. 41, pp. 791-800.
- Yaniga, P.M. 1982. Alternatives in the decontamination of hydrocarbon contaminated aquifers. In *Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring*. National Water Well Association, Dublin, Ohio, pp. 47-57.
- Yaniga, P.M. and W. Smith. 1985. Aquifer restoration: In situ treatment and removal of organic and inorganic compounds. *Groundwater Contamination and Reclamation*. American Water Resources Association, pp. 149-165.
- Zobell, C.E. 1946. Action of microorganisms on hydrocarbons. *Bacteriol. Rev.*, v. 10, pp. 1-49.

Biographical Sketches

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microorganisms to proliferate; these materials must already be present or be supplied in the proper form and ratios to the requisite microorganisms. Extremes of temperature, pH, salinity, and contaminant concentrations can also markedly influence the rates of microbial growth and substrate utilization. The nature of the limiting environmental factor(s) will often help dictate the strategy in applying biotechnology to hazardous waste treatment.

In most cases the organic pollutants themselves are able to supply the carbon and energy required to support heterotrophic microbial growth. However, the introduction of carbonaceous materials to soils and groundwater aquifers can cause an imbalance in the natural biodegradation processes, limiting the microbial transformation of the organic pollutant. For example, when labile carbon is introduced to an aerobic aquifer, the microorganisms consume oxygen along with the carbon substrate. An anaerobic aquifer can be expected whenever the rate of aerobic respiration exceeds the rate of oxygen input to the site. To sustain aerobic microbial growth, oxygen, therefore, must be supplied to the subsurface microorganisms.

The importance of oxygen supply to in-situ biodegradation was well documented recently in a study of a wood treating site in Conroe, Texas (5). A downgradient portion of the contaminant plume was characterized by low levels of organic pollutants and dissolved oxygen, while inorganic contaminants (i.e., chloride), which were associated with the organic wastes, remained at elevated concentrations. The authors suggested that oxygen was consumed during the aerobic metabolism of the organic contaminants by the indigenous micro-organisms. Hydrocarbons persisted in areas of the plume where oxygen levels were insufficient to support aerobic biological activity.

Artificially increasing the oxygenation of subsurface environments will dramatically increase the growth of heterotrophic bacteria. In a study of petroleum hydrocarbon degradation, sand columns were used to determine the effect of oxygen supply on bacterial growth and degradation of gasoline.

Several columns were prepared under identical conditions using 50 mL of wet sand sieved to 40-60 mesh. Fifty milliliters of gasoline were added to each column and allowed to drain through. An average of 4.3 mL of gas was retained. The columns were then washed with 2 liters of nutrients made up in groundwater. Different levels of oxygen were supplied to the columns by using air, oxygen or hydrogen peroxide dissolved in groundwater. The columns were treated for two weeks. At the completion of the experiments the columns were drained, and analyzed for gasoline content, total organic carbon (TOC), total bacteria and gasoline utilizing bacteria.

Bacterial counts in the interior of the column showed a very strong dependence on the oxygen level:

DEPENDENCE OF BACTERIAL GROWTH ON AVAILABLE OXYGEN

Bacteria, Colony Forming Units (CFU) / Gram Dry Soil

Available Oxygen, ppm (Ave.)	Heterotrophic Bacteria (x 10 ⁶)	Gasoline Utilizing Bacteria (x 10 ⁶)
8	.05	.0001
40	5.5	.7
112	75	27
200	207	31
Correlation w D.O.	.979	.933
Ratio of counts @ 200 ppm D.O.: 8 ppm D.O.	4 x 10 ³	3 x 10 ⁵

Appendix II

OXYGEN SOURCES FOR BIOTECHNOLOGICAL APPLICATIONS

Richard A. Brown, Groundwater Technology, Inc.

It is well recognized that microorganisms play prominent roles in the transformation and degradation of organic chemicals in virtually every major habitat except the atmosphere. Microbial communities in nature exhibit a truly impressive biochemical versatility in the number and kinds of synthetic organic compounds that they are able to metabolize (1,2).

Virtually the only natural transformation of polluting chemicals that can result in complete mineralization occurs via microbial metabolism. However, there are limits to the metabolic versatility of microorganisms. Many xenobiotic substrates are transformed so slowly that they cause some degradation of environmental quality. This resistance to biodegradation, though, is not a feature that is strictly associated with exotic chemical compounds. Decomposition is a function of the a) structure of the particular contaminant, b) the existing environmental conditions, and c) the physiology of the requisite microorganisms (3,4). Of these, the environmental limitations are the easiest to rectify.

In order to grow, microorganisms need a suitable physical and chemical environment. Microorganisms, like all other forms of life, are primarily composed of C, H, O, N, P, S, although a variety of other elements are also found in trace amounts. These substances are required to varying degrees in order for

As can be seen from the data, the bacterial counts increased dramatically with increasing available oxygen. Gasoline utilizing bacterial are even more sensitive to oxygen levels than are general heterotrophic Bacteria.

DEPENDENCE OF GASOLINE DEGRADATION ON OXYGEN LEVEL

Available Oxygen	Gasoline Bio- degraded		Gasoline Flushed Out		Total Gasoline Removed		
	<u>PPM (Ave.)</u>	<u>GRAMS</u>	<u>g'</u>	<u>GRAMS</u>	<u>g'</u>	<u>GRAMS</u>	<u>g'</u>
8		.388	12.9	.71	23.6	1.098	36.6
40		.508	16.9	.77	25.6	1.278	42.6
112		.773	25.8	.59	19.6	1.363	45.4
200		1.272	42.4	.49	16.3	1.762	58.7
Correlation w D.O.		.994		-.93		.974	
Ratio gas degraded θ		3.27		.69		1.60	
μ ppm D.O.: 8 ppm D.O.							

Based on average of 3.0 g originally present.

Several things should be noted from this data. First, the more oxygen that was supplied, the more gasoline that was biodegraded. Second, the rate of biodegradation under highly oxygenated conditions was greater than the rate of physical removal/dissolution.

These sand column studies demonstrate that bacterial growth and metabolism are very dependent on oxygenation. As a result, an important part of the biological treatment of hazardous waste is oxygen supply.

There are basically two methods of oxygen supply - physical and chemical. Physical supply involves forcing air and/or pure oxygen into the contaminated matrix. Chemical oxygen supply involves the addition of substances which can be converted to oxygen, such as hydrogen peroxide (6); or substances which can act as terminal electron acceptors directly such as nitrate (7,8). All of these methods have been used in treating contaminated soils and aquifers.

The choice of an oxygenation method depends on several factors. Basically, one wants to achieve maximum efficiency in oxygenation. Too little oxygen supply relative to the amount of contamination results in much longer remediation times. Too much oxygen relative to the amount of contamination being treated can result in elevated remedial costs. The principal is to balance oxygen supply with oxygen demand. The factors that must be considered in achieving this demand are:

- oxygen mass transfer, pounds per unit time, supplied by each method
- contaminant load and location
- ease of transport/utilization

First, considering oxygen mass transfer, it is easy to calculate the amount of oxygen supplied by the different methods. The more oxygen supplied per unit time, the greater the potential level of bioremediation.

Air sparging, one of the simpler techniques, provides oxygen by diffusing air/oxygen into a well bore. This is accomplished by using a porous stone, acintured metal or fitted glass diffuser. The water in the well bore is saturated with oxygen and diffuses out into the formation. The amount of oxygen supplied is a function, therefore, of the rate of water flow by the well bore. This, in turn, is a function of the hydraulic conductivity, the gradient and the surface area of the formation affected by the well bore. The following matrix calculates the pounds of oxygen per

day an air sparger provides per well for different hydraulic conductivities and gradients. The table assumes a 30 foot saturated thickness and that the lateral influence of the well is 3 ft.

POUNDS PER DAY OXYGEN SUPPLIED BY SPARGING, SINGLE WELL

Hydraulic Conductivity gals / Day / ft	(high)		Hydraulic Gradient ft/ft		(low)	
	(air)	(oxygen)	(medium)	(oxygen)	(air)	(oxygen)
10 ⁴ (gravel)	6	30	.6	3.	.06	.3
10 ³ (medium sand)	.06	.3	6x10 ⁻³	3x10 ⁻²	6x10 ⁻⁴	3x10 ⁻³
10 ⁻¹ (silt)	6x10 ⁻³	3x10 ⁻²	6x10 ⁻⁵	3x10 ⁻⁴	6x10 ⁻⁷	3x10 ⁻⁶

As can be seen air sparging is a limited source of oxygen. Sparging pure oxygen instead of air will increase the pounds per day by a factor of five so that the maximum on the matrix would be 30 lbs. oxygen per day instead of 5.

A second system is to pump air/oxygen saturated water into a contaminated aquifer. The pounds per day of oxygen supplied is a function of injection rate:

POUNDS PER DAY OXYGEN SUPPLIED BY AERATED/OXYGENATED WATER INJECTION SINGLE WELL

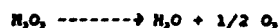
Injection Rate, gpm	aerated water 10 ppm D.O.	oxygenated water 50 ppm D.O.
1	.12	.60
10	1.2	6.0
100	12.0	60.0

Air venting systems are an efficient means of supplying oxygen through unsaturated contaminated soils. This technique is used in treating vadose zone contamination or in treating excavated soil piles. Air can be added by either injection or by withdrawal. In vadose zone treatment, the common method is vacuum withdrawal. This method has the added advantage of physically removing volatile contaminants in addition to supplying oxygen. The amount of oxygen supplied is a simple function of the air flow rates. The following table uses a 20% oxygen content for air to calculate air supply:

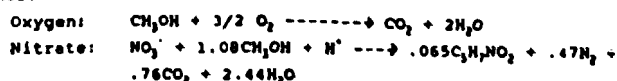
POUNDS PER DAY OXYGEN SUPPLIED BY VENT SYSTEM (UNSATURATED SOILS) SINGLE WELL

air flow rate SCFH	oxygen supply lbs / Day
1	23.3
5	116.6
10	233.3
20	466.6
50	1,166.4
100	2,332.8

Finally, there are two chemical carrier systems - Hydrogen peroxide and nitrate. While both of these materials are highly soluble, their common use rate is about 1000 ppm (.1%). The number of oxygen equivalents supplied is dependent on the chemistry involved. Hydrogen peroxide is converted through decomposition to oxygen:



Each part of hydrogen peroxide supplies .47 parts of oxygen. Nitrate is, on the other hand, directly utilized as a terminal electron acceptor. Its oxygen equivalents can be calculated by comparing the amount of nitrate required to oxidize a substrate versus the amount of oxygen. Take, for example, the oxidation of Methanol:



Based on these above equations, one part of nitrate is equivalent to .84 parts of oxygen.

The oxygen equivalents supplied by these two chemical carriers is a simple function of injection rate.

**POUNDS PER DAY OXYGEN EQUIVALENTS SUPPLIED
BY CHEMICAL CARRIERS, SINGLE WELL
@ 1000 PPM**

Injection rate gpm	H ₂ O ₂ (.47 equiv O ₂ /part H ₂ O ₂)	NO ₃ ⁻⁻⁻ (.84 equiv O ₂ /part NO ₃)
1.0	5.6	10.0
5.0	28.0	50.0
10.0	56.0	100.0
20.0	112.0	200.0
50.0	280.0	500.0

The second factor in considering an oxygen source is the contaminant load and location. Contaminant location is important in that vent systems require unsaturated environments and will, therefore, be excluded in treating contaminants below the water table. Contaminant load, on the other hand, impacts all means of oxygen supply, in that it determines oxygen demand. What drives contaminant load is the phase distribution.

Petroleum hydrocarbons exist in the subsurface as three condensed phases: mobile free product (phase separated), residually saturated soil (adsorbed phase), and contaminated ground water (dissolved phase). The distribution of hydrocarbons into these different phases, while a result of dynamic transport, is ultimately a function of their physical and chemical properties, and the hydrogeological and geochemical characteristics of the formation. One must examine the phase distribution by two means: the areal extent of contamination or the volume of the subsurface impacted by a phase and the severity of contamination or the amount of the contaminant within a phase, measured as either total weight or concentration. The following table gives the phase distribution for a gasoline spill in sand and gravel:

PHASE DISTRIBUTION OF GASOLINE IN SAND AND GRAVEL

Phase	Extent of Contamination		lb.	Mass Distribution	
	Volume, cu. yd.	% of Total		Conc. ppm	% of Total
Free phase ¹	780	5.3	126,800 ¹	---	90.9
Adsorbed (soil)	2,670	18.3	11,500	2,000	8.2
Dissolved (water)	11,120	76.3	390	15	0.3

¹ Actual value recovered from site

There are several generalizations that can be made from the above data concerning the distribution of petroleum hydrocarbons between the different phases. First, groundwater flow is the primary long term mechanism for spread of the contamination once the free product layer has achieved flow equilibrium. Thus, the areal extent of groundwater contamination is typically greater than that for other phases. However, the amount of material in the groundwater is small compared to that retained in the soil matrix, less than 5%. The residually saturated soil, if untreated, is a continuing source of groundwater contamination.

In looking at the contaminant load, the presence of and the distribution between the different phases is an important factor. The following table gives the pounds per cubic yard of aquifer for dissolved and adsorbed phase contamination. The calculation assumes a porosity of 30% and a dry soil bulk density of 2700lb/yd³. The soil levels are generally two orders of magnitude higher than dissolved levels.

**COMPARISON OF CONTAMINANT LOADING
DISSOLVED AND ADSORBED PHASE
/ yd³ OF AQUIFER MATERIAL**

Dissolved Phase #	#/yd ³	Adsorbed Phase #	#/yd ³
1 ppm	5x10 ⁻⁴	100 ppm	.27
10 ppm	5x10 ⁻³	1,000 ppm	2.7
100 ppm	5x10 ⁻²	10,000 ppm	27.0

From this data it is obvious that contaminated soil drives the contaminant load. The more the volume of contaminated soil and the higher the level of contamination, the greater the contaminant load. One cubic yard of soil contaminated at only 100 ppm contains as much contaminant as 5.4 yd³ of contaminated aquifer material (dissolved phase).

The third factor in considering an oxygen source is the ease of transport and utilization. This involves the means of application, the maintenance of system, and the rate/degree of utilization.

An air sparger system uses a small compressor able to deliver ~1CFM per well. The sparger itself is either a porous stone, a scintured metal diffuser, or a fritted glass diffuser. Power consumption is minimal. The transport of the aerated water is limited by the rate of groundwater flow. The most significant operating cost is an air sparger system is maintenance of the compressor and of the diffuser and well screen. Biofouling or inorganic fouling of the diffuser and well screen can be significant and well therefore require a high degree of maintenance. Bacterial utilization of the dissolved oxygen is very high.

Injection of aerated/oxygenated water is a relatively simple system. The simplest approach is to use an air stripper to aerate the water. Often in treating a contaminated aquifer, groundwater is recovered and air-stripped to achieve hydraulic control of the contaminant plume. ReInjection of the stripped groundwater, can therefore, be accomplished for relatively low cost. The main cost of operation is controlling fouling of injection system. Transport of the oxygenated water is dependent on the geology (hydraulic conductivity). Bacterial utilization of the injected dissolved oxygen is very good.

Venting systems, while limited to unsaturated soils, are very efficient means of oxygen supply. The primary capital cost is the vacuum pump(s) needed to drive the system. Maintenance of the pumps is fairly simple and power consumption is minimal. The efficiency of the vent system is enhanced by volatile removal. The largest potential cost with a vent system is treatment of the vapor discharge. This can be accomplished by using disposable carbon, regenerable carbon or catalytic oxidation. Regenerable carbon and catalytic oxidation are capital systems.

A hydrogen peroxide system is generally a low capital, easy to maintain system. It does entail a fairly high O&M cost due to the chemical cost of the hydrogen peroxide. The cost of hydrogen peroxide is dependent on the volume used. Small quantities cost more per pound than do large quantities. On a per pound of oxygen basis, the cost will range from \$1.50 to \$2.50. The biggest cost factor involved with hydrogen peroxide is how quickly it decomposes. There are two mechanisms of decomposition - Biological and metal catalysis. Ideally, one would like minimal metal catalyzed decomposition. In some soils, however, that contain high levels of iron or manganese, metal catalyzed decomposition can be severe. In such cases the solubility of oxygen is rapidly exceeded and the water phase degassed, losing available oxygen and drastically reducing the efficiency of the system.

Finally, nitrate systems are a potential electron acceptor alternative. Operationally, these systems have not been proven. Capital costs for a nitrate system would be fairly low consisting, as with peroxide, of a supply tank and metering pump. Chemical costs for nitrate are \$.60 - .70 / lb oxygen equivalent. The issue with nitrate, however, is not the cost or ease of addition, but instead the biochemistry of utilization and the regulatory issues. In a recent test of nitrate utilization, it was found that even with an extremely labile substrate such as sucrose, there was a significant lag phase in the utilization of the nitrate when oxygen

was also available at low levels. It would appear that nitrate utilization requires low oxygen conditions. If the biochemistry of nitrate is complicated, the regulatory issues become significant. Nitrate levels in ground water are regulated at 10 ppm. If nitrate is not rapidly utilized, injection would have to be tightly controlled and may be precluded.

To put the above costs and analyses into perspective, one can compare the operation of the different systems for a sample gasoline problem. The site characteristics are as follows:

Area of contamination

soil - 100 x 50 x 5 ft (3 ft above; 2 ft below water)
groundwater 250 x 70 x 5 ft

Contaminant concentrations

soil - 1200 ppm
groundwater - 18 ppm

Aquifer characteristics

hydraulic conductivity 5×10^7 gal/day/ft²
hydraulic gradient .08 ft/ft
pumping rate/well 35 gpm
saturated thickness 25 ft.
DTW 15 ft.

Contaminant distribution

soil 2500 lb. (1500 lb above/1000 lb below)
GW 30.0 lb.
Total 2530 lb.

The configuration of the systems would vary. The basic layouts would be as follows:

Air Sparging: Sparging would be through 15 wells spaced through-out the plume. There would be no recovery wells.

Water Injection: The system would consist of 2 recovery wells pumped at 35 gpm each. Each well would have a 25 ft. cross-gradient capture radius. The 70 gpm water would be air stripped through a 2 ft. x 18 ft. air stripper and reinjected through two upgradient galleries.

Vent System: Venting would be through 4 wells placed on 40 ft. centers. Each well would be pumped at 40-45 CFM. The system would require a single 2 H.P. high vacuum blower. Vapor discharge would be treated through a catalytic oxidizer.

Peroxide System: Hydraulic control is maintained by 2 down gradient recovery wells each operated at 35 gpm. Of the 70 gpm recovered, 35 gpm would be reinjected through a gallery and 2 upgradient injection wells. Peroxide would be added at 1000 ppm. Excess water would be air stripped and severed.

Nitrate System: Because of the concern with off site migration of nitrate, there would be 4 downgradient recovery wells. Two of the wells, on the leading edge of the plume, would be operated at 35 gpm each. This water would be amended with nitrate (1000 ppm) and reinjected

through 4 upgradient wells and an injection gallery. The two additional recovery wells would be placed 50 ft. downgradient of the plume to create a barrier to migration of nitrate. They would be operated at 30-40 gpm.

Using this data, the capital and operating costs for each system can be calculated. The following table gives a comparison of the different systems.

As can be seen, there is a wide variance in both cost effectiveness and in treatment effectiveness. In terms of cost performance, the order is:

Venting > peroxide > nitrate > air sparger > water injection

In order of treatment effectiveness the order is:

Peroxide = nitrate > water injection > venting > air sparging

While venting is a very cost effective method it is limited to treating the vadose zone. Consequently, its treatment effectiveness is limited.

This above analysis is given for a situation with extensive contamination. If the degree of contaminants is changed so that the soil contamination is minimal, the analyses would change. Assuming that there is no soil contamination above the water table and that the soil levels are <100 ppm, the performance of the different systems would be as follows, all other factors remaining constant:

COST/PERFORMANCE, LOW DEGREE OF CONTAMINATION

System	lb\$/day Q ₂	Time of Treatment days	\$ lb oxygen used
Air sparging	6	180	43.55
Water Injection	8	330	89.55
Venting	Not Applicable		
Peroxide	190	180	38.39
Nitrate	211	240	47.39

When the degree of contamination is less, simpler systems such as air sparging become more cost effective. When the contamination is only the dissolved phase, an air sparger system is the best choice. The following table summarizes the best choices for different contamination situations.

The choice of an oxygen supply is dependent on the contaminant load, the mass transfer and the ease of transport/utilization. Depending on what the degree of contamination is, different systems will be most effective.

REFERENCES

- Alexander, M., 1981. Biodegradation of Chemicals of Environmental Concern. SCIENCE, 211:132-138.
- Kobayaski, M. and B.E. Rittmann, 1982. Microbial Removal of Hazardous Organic Compounds. ENVIRON SCI TECHNOL, 16: 170a-183a.

Cost/Performance Comparison for Various Oxygen Systems
High Degree of Contamination

System	Costs			Performance				
	Capital	Operation	Maintenance	Lbs/Day Oxygen	% Site Treated	Utilization Efficiency %	Time of Treatment	\$/Lb oxygen Used
Air Sparging	\$35,000	\$800/month	\$1200/month	6	41	70	858 days	\$25.80
Water Injection	\$77,000	\$1200/month	\$1000/month	8	75	50	1580 days	\$28.62
Venting System	\$88,500	\$1500/month	\$1000/month	4000	60	5	132 days	\$ 3.82
Peroxide System	\$60,000	\$10,000/month	\$1500/month	190	100	15	330 days	\$18.60
Nitrate System	\$120,000	\$6500/month	\$1000/month	211	100	12.5	335 days	\$22.06

Prioritization of Systems for Different Contaminant Situations

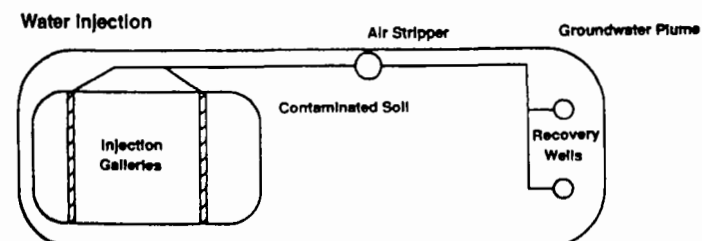
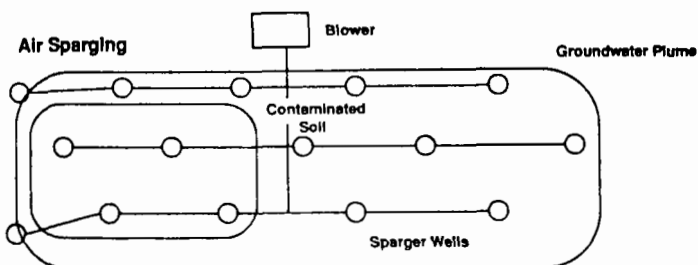
(1=Best)

Types and location of Contamination

System	Dissolved Only	Dissolved and Soil Below Water	Soil Above and Below Water Table and Dissolved	Soil Above Water Table
Air Sparger	1	2	3	
Water Injection	3	3	2	3
Vent System				1
Peroxide	2	1	1	2
Nitrate	(Not Recommended at present)			

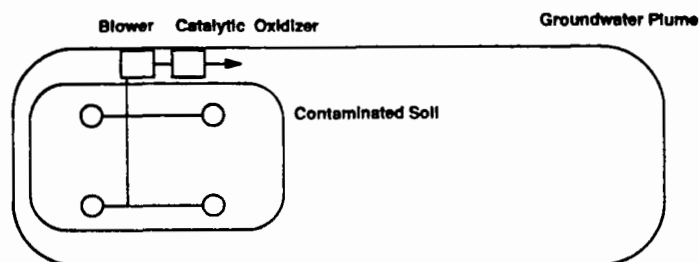
- 3) Alexander, M., 1965. Biodegradation: Problems of Molecular Recalcitrance and Microbial Fallibility. ADV APPL MICROBIOL, 7:35-80.
- 4) Alexander, M., 1973. Nonbiodegradable and Other Recalcitrant Molecules. BIOTECH BIOENGINEER, 15:611-647.
- 5) Wilson, J.T., J.F. McNabb, J.W. Cochran, T.H. Wang, M.B. Tomson and P.B. Bedient, 1985. Influence of Microbial Adaption on the Fate of Organic Pollutants in Ground Water. ENV TOXICOL CHEM, 4:743-750.
- 6) Brown, R.A., R.D. Norris and R.L. Raymond, 1984. Oxygen Transport in Contaminated Aquifers. Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water-Prevention, Detection and Restoration. Nov. 5-7, 1984, Houston, TX.
- 7) "Use of Biotechnics in Water Treatment: Feasibility and Performance of Biological Treatment of Nitrates," A. Leprince, Y. Richard, Aqua Sci. Tech. Rev., 1982 (5), pp. 455-62.
- 8) "Nitrogen Removal in a Subsurface Disposal System," A. Andreoli, R. Reynolds, M. Bartilucci, R. Forgione, Water Science Tech. 1981, 13 (2), pp. 967-76.

System Layout

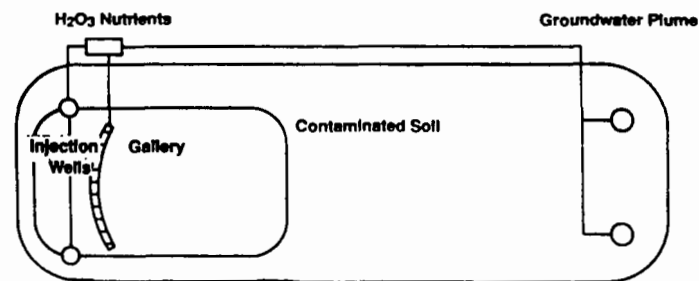


System Layout

Venting

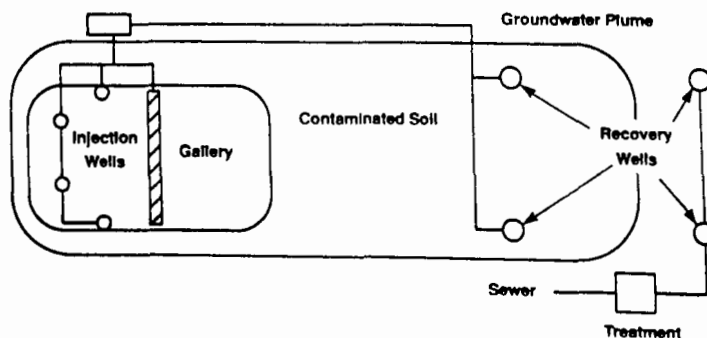


Peroxide



System Layout

Nitrate



AQUIFER RESTORATION, IN SITU TREATMENT AND REMOVAL
OF ORGANIC AND INORGANIC COMPOUNDSPaul M. Yedje and William Smith¹

ABSTRACT: Recovery of the appreciable quantities of free floating hydrocarbons has become a proven reliable technology for minimizing the spread of impact from subsurface hydrocarbon leaks. Removal of the free floating phase does not however mitigate all of the associated impacts, one does not return the aquifer to usable condition. In specific situations where aquifer use, or potential use, dictate otherwise or cleanup to natural conditions, the subsurface leaks require degradation of organics by native hydrocarbon utilizing bacteria becomes a cost-effective alternative.

Subsurface contamination from hydrocarbons predominantly exists in three phases of free floating or mobile hydrocarbons, product adsorbed onto the soil matrix, and hydrocarbons dissolved in the aquifer environment.

The latter two phases of adsorbed and dissolved hydrocarbon contamination affect a greater area within the formation. The symposium impacts, although less intense than the free product, are more persistent.

This paper discusses a three-year abatement program implemented to address hydrocarbons adsorbed/dissolved into the groundwater system. The treatment program consisted of a combined physical chemical/biodegradation approach to reduce aquifer degradation and supply interim potable water to the impacted well owner.

The bioremediation phase consisted of: 1) introduction of clean aerated water from beyond the contamination plume, 2) addition of dissolved oxygen by mechanical air spargers, 3) utilization of hydrogen peroxide for the dissolved oxygen and subsequent phase out of air spargers, and 4) addition of nutrients at subsurface down and laterals. The net results of the work program are a 70-80 percent reduction of total hydrocarbons within the aquifer.

(KEY TERMS: aquifer remediation; groundwater degradation; bioremediation; dissolved organic; hydrogen peroxide.)

INTRODUCTION

Many of the organic compounds which were developed in the late 1920's and 1930's to serve the needs of evolving technological societies have found their way into our environment. These compounds originally developed to serve mankind have become his nemesis. The increasing awareness of soil and groundwater degradation by organic compounds is now widely recognized as a problem of international dimension. The source and vehicle for the entry of these diverse compounds into the soil and groundwater system are as varied

as the contaminants. Historically, deliberate and sometimes sanctioned disposal of waste solvents, sludges, and off-spec product into landfills have come to generate significant problems of environmental degradation. Today, an even more common, yet equally, unintentional source of loss of organic chemicals to the soil and groundwater system presents itself in the form of leakage from below ground transmission lines and tanks used for containment of these compounds. By the means of the following case history, one such problem of soil and groundwater degradation by benzene, toluene, xylene, and certain associated inorganic parameters is discussed in terms of its treatment and abatement.

The key to the treatment and abatement of this particular cleanup is the application of an in situ bioremediation technique, which utilizes existing native hydrocarbon utilizing bacteria via addition of nutrients and oxygen to the ground water system. This paper presents information showing the superiority of oxygen transmission to the groundwater system via the use of dissolved oxygen of hydrogen peroxide over traditional mechanical air spargers.

The aquifer clean up and abatement program also incorporates a comprehensive physico-chemical treatment system for water neutralization and removal of metallic components.

BACKGROUND

In this case history, the contamination problem occurred when an undetermined amount of gasoline leaked from a below ground storage tank. The area of the loss is underlain by approximately 6 to 7 feet of red-brown, heavy clay loam, which in turn, is underlain by a fractured red-brown shale and silt stone. The groundwater table is found within the bedrock system at a depth of 30 to 35 feet below grade. The gasoline migrated through the overburden into the bedrock ground water system.

The resulting significant impacts of the loss included soil contamination by adsorbed concentrations of gasoline type hydrocarbons which proved to be a continuing source of

organic vapors and contamination sources of low level water soluble organic compounds to groundwater. Associated changes in geochemistry also led to increased concentrations of iron and manganese. The resulting impacts affected the quality and use of the domestic water supply wells. The impacts that were observed are typical of leaks of such materials, with the exception that a free floating phase was absent (Figure 1).

PROBLEM ASSESSMENT

The areal extent and magnitude of the organic contamination was determined via a combined program of sampling and analysis of domestic wells and the installation of routine additional observation wells.

This reduction showed a plume of dissolved organics and inorganics that extended approximately 300 to 350 feet in a north-south direction and 300 to 350 feet in an east-west direction. The east-west plume elongation proved a function of local geologic structure and direction of groundwater movement (Figures 2 and 3). Contaminant concentrations ranged from less than the detection limit (10 ppb), to greater than 15 ppm for gasoline type hydrocarbons, iron and manganese concentrations ranged from 0.1 mg/l to 4.7 mg/l and 0.2 mg/l to 12.0 mg/l, respectively (Figures 3a and 3b).

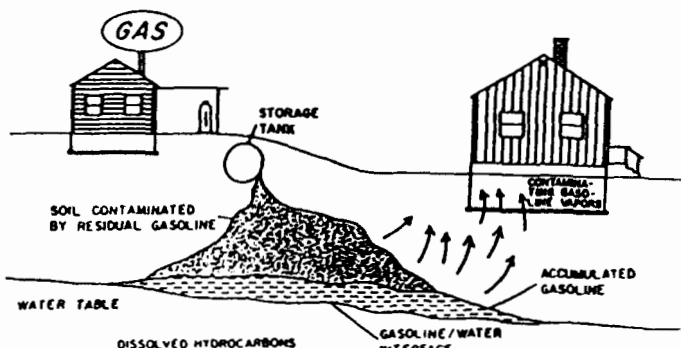


Figure 1. Typical Impacts from Loss of Organic Chemicals

150

Yedje and Smith

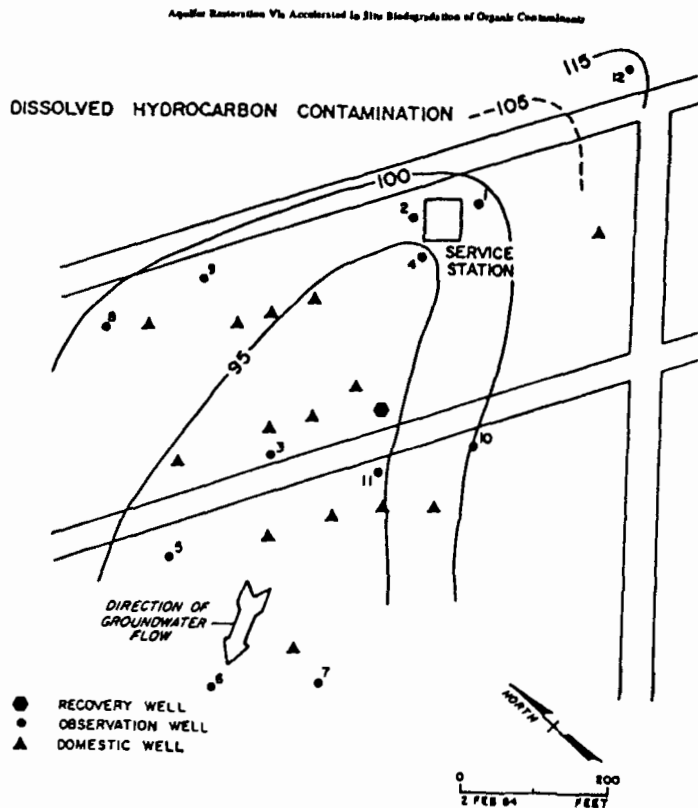


Figure 2. Water Table Contour Map (data taken from Groundwater Technology monitoring wells, September 18, 1983).

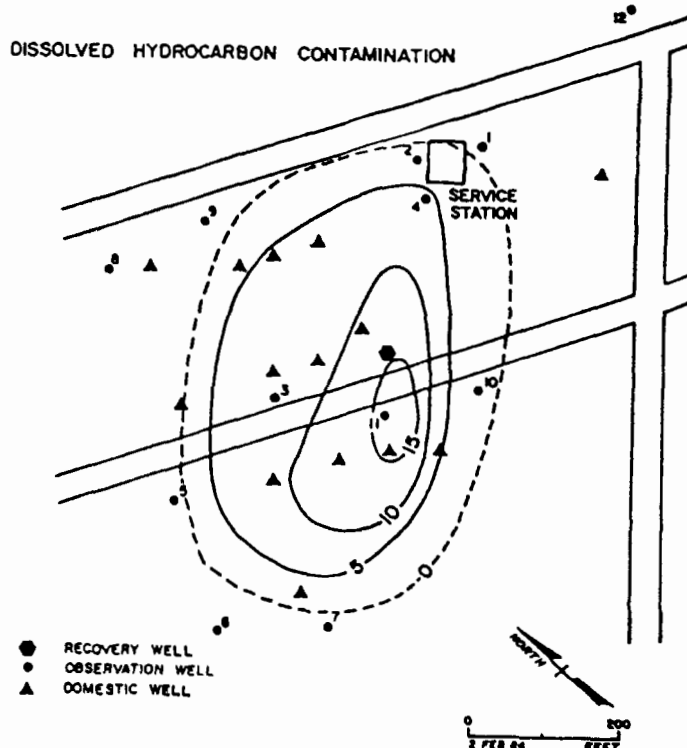


Figure 3. Isopleth Map of Hydrocarbon Contamination (ppm) of Domestic Wells, September 9, 1981.

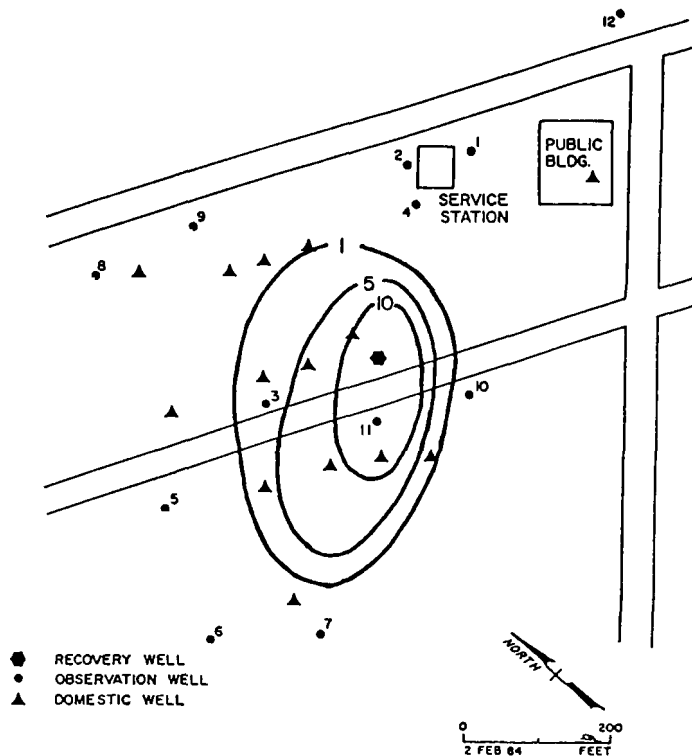


Figure 3A. Isocon Map Manganese Concentration (ppm), November 1981.

DISSOLVED HYDROCARBON CONTAMINATION

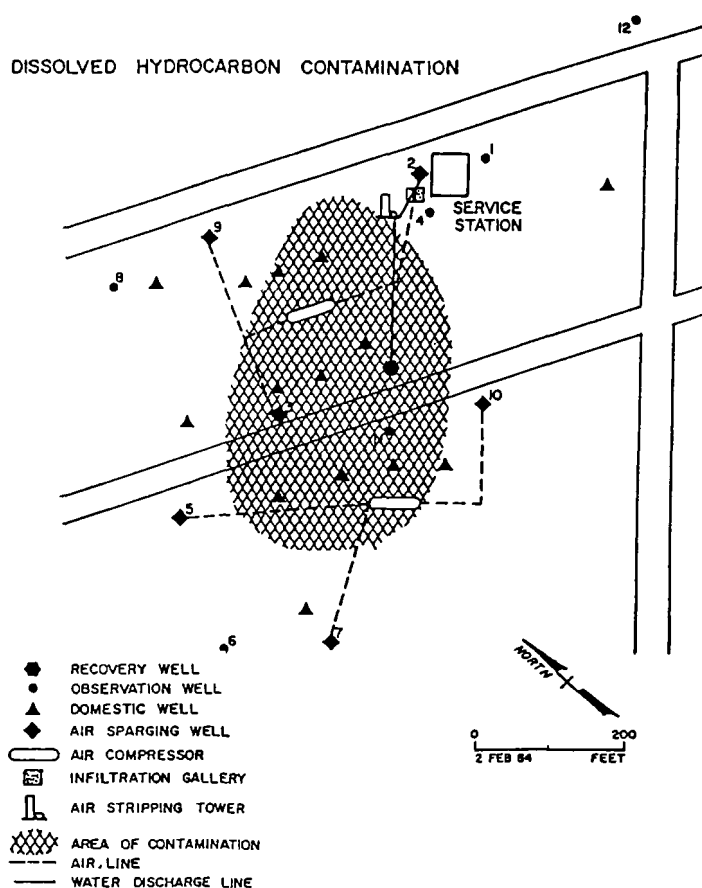


Figure 4. Schematic of Bioreclamation System.

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Further analysis, beyond organic scans, showed a need to address inorganic, as well as, organic compounds. The analytical results dictated the development of a physico/chemical treatment process that relied on neutralization, carbon adsorption, ion exchange, and biologic control (Figure 5). This combination of treatment steps produced aesthetically usable water, which was free of any residual dissolved organic compounds.

INITIATION OF ABATEMENT/AQUIFER RESTORATION

In implementing the designed program, a practical approach was kept in mind that took into account the nature of the problem, the source, the configuration of the plume, the nature of the groundwater system, and the character of the community. The program development was carried out in a logical sequence which included:

- Development, installation and shutdown testing of the physico-chemical water treatment systems on domestic wells.
- Excavation and disposal of highly contaminated soil in the tank pit area.
- Conversion of the tank pit, via backfill with crushed stone, to an infiltration gallery.
- Construction of a pumping well located in the center of the plume to control the water table and movement of contaminated groundwater.
- Pump test of the central well to allow calculations of the expected radius of influence, to assess the well's capability to control the migration of the plume.
- Construction and erection of an air stripper for volatile organic removal.
- Development of nutrient mix ratios for addition to the groundwater system to accelerate hydrocarbon-utilizing bacteria for reduction of the fugitive organics.
- Development of mechanical means of air supply and air sparging to deliver oxygen into the groundwater system. Previously existing observation wells were used as air sparging and nutrient addition points.
- Development and construction of a nutrient mix tank in the area of the infiltration gallery for batch feed of nutrients to the contaminated tank pit area.
- Shutdown testing of the system to ensure operational efficiency in the control of the organic plume.

The system, as designed, was to initiate pumping at the central well, inducing water in the plume to flow radially inward from the periphery. The recovered contaminated water was then passed through an air stripping tower where volatile organics were removed and oxygen was added. Nutrients were then added to the hydrocarbon-free/oxygen-rich water, which was then passed through the contaminated soils and groundwater system thus accelerating the in-situ reduction of organic compounds via the increased number of hydrocarbon-utilizing bacteria. The control of the spread of nutrients/oxygen and biologic community was maintained by the central pumping well, which had redirected groundwater movement to that point. The treatment for the organics was enhanced via the addition of oxygen and nutrients on the periphery of the

plume. This water was then pulled back through the contaminated zone to the central pumping well.

RESULTS OF THE ABATEMENT PROGRAM

The results of the aquifer restoration program were quite good. The physico/chemical treatment system for the domestic wells functioned well, producing a reliably usable water supply (Figures 5a and 5b). As the total aquifer clean-up program moved forward, decreased frequency of treatment media exchange was required, thus attesting to overall contaminant reduction. The central pumping well contained and controlled the plume configuration like an in-situ treatment vessel (Figure 6). The air stripping tower, subsequent to shutdown testing, performed as designed with greater than 98 to 99 percent efficiency for removal of volatile organics (Figure 7). The designed infiltration gallery, located in the former tank pit, proved functional in accepting the 30,000 to 35,000 gallons per day of treated oxygen and nutrient rich water. Heavy spring rains and recharge caused some concern regarding overtopping of the gallery, which, however, did not occur.

The air sparging system, consisting of mechanical air compressors, air lines, and down well diffusers, proved to be effective to partially effective in delivering needed oxygen to peripheral areas of the plume outside the infiltration gallery. Major limitation focused on the maximum quantity of oxygen that could be induced into the groundwater system (10 ppm) at the sparging point and the fouling/plugging of the sparging points by the development of thick biologic growths. These two items precluded optimum oxygen transfer to the fractured bedrock system and required frequent mechanical cleaning.

Despite this non-optimum condition overall efficiencies of clean-up over the first eleven months showed a general 50 to 85 percent reduction in organic contaminants. Several wells proved to be absent of any organic contaminants at this point (Figure 8 and 9).

While pleased with the overall results, the specifics of oxygen transfer rates were limiting biologic community growth and lengthening the project restoration timeframe; therefore, a program to accelerate this problem was developed. The program involved a comprehensive approach that included:

- laboratory research,
- field studies,
- further hydrogeologic and engineering assessment, and
- information/educational meetings and contact with representatives of the community and regulatory agencies.

The results of the applied efforts was the development of a comprehensive approach to deliver increased quantities of oxygen to the groundwater system via the trickle feed and dissolution of dilute quantities of hydrogen peroxide. Laboratory studies conducted jointly by Mr. Richard L. Raymond and FMC (Richard A. Brown) showed that inducing dilute concentrations of hydrogen peroxide did not kill desired hydrocarbon utilizing bacteria. On the contrary, this increased their numbers and the rate of hydrocarbon reduction. Field studies by R. L. Raymond also showed similar

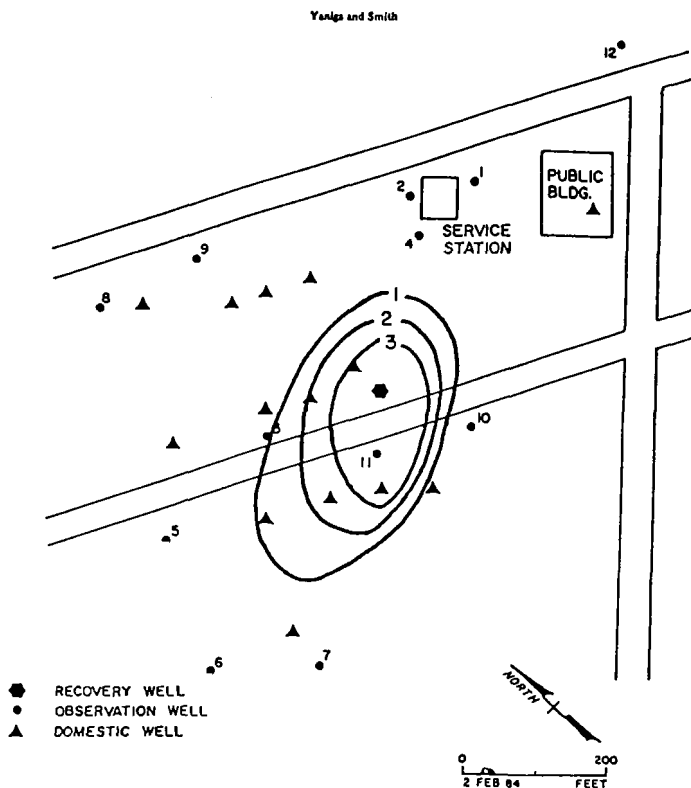
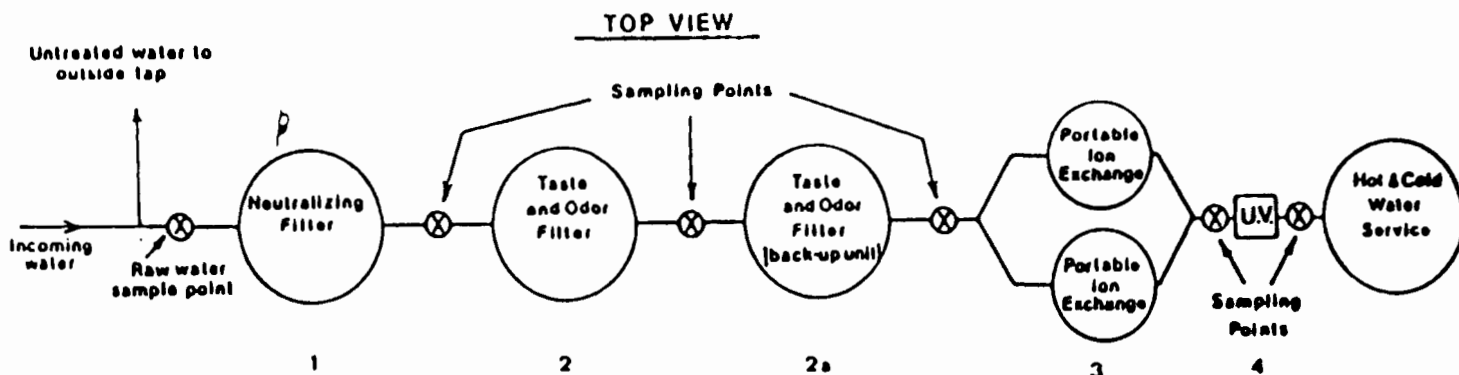


Figure 3B. Isocon Map Iron Concentration (ppm), November 1981.



Notes:

1. Neutralizing filter; preliminary sediment, iron, and manganese removal.
- 2 & 2a. Taste and odor filter; activated charcoal with high surface area for removal of taste and odor (removal of hydrocarbons).
3. Portable ion exchange units (in parallel); removal of hardness and further iron and manganese removal.
4. Ultra violet light; bacteriological treatment unit for coliform treatment.

Figure 5. Schematic: Water Treatment System to Improve Aesthetic Water Quality in Residences Affected by Suspect Hydrocarbon Contamination.

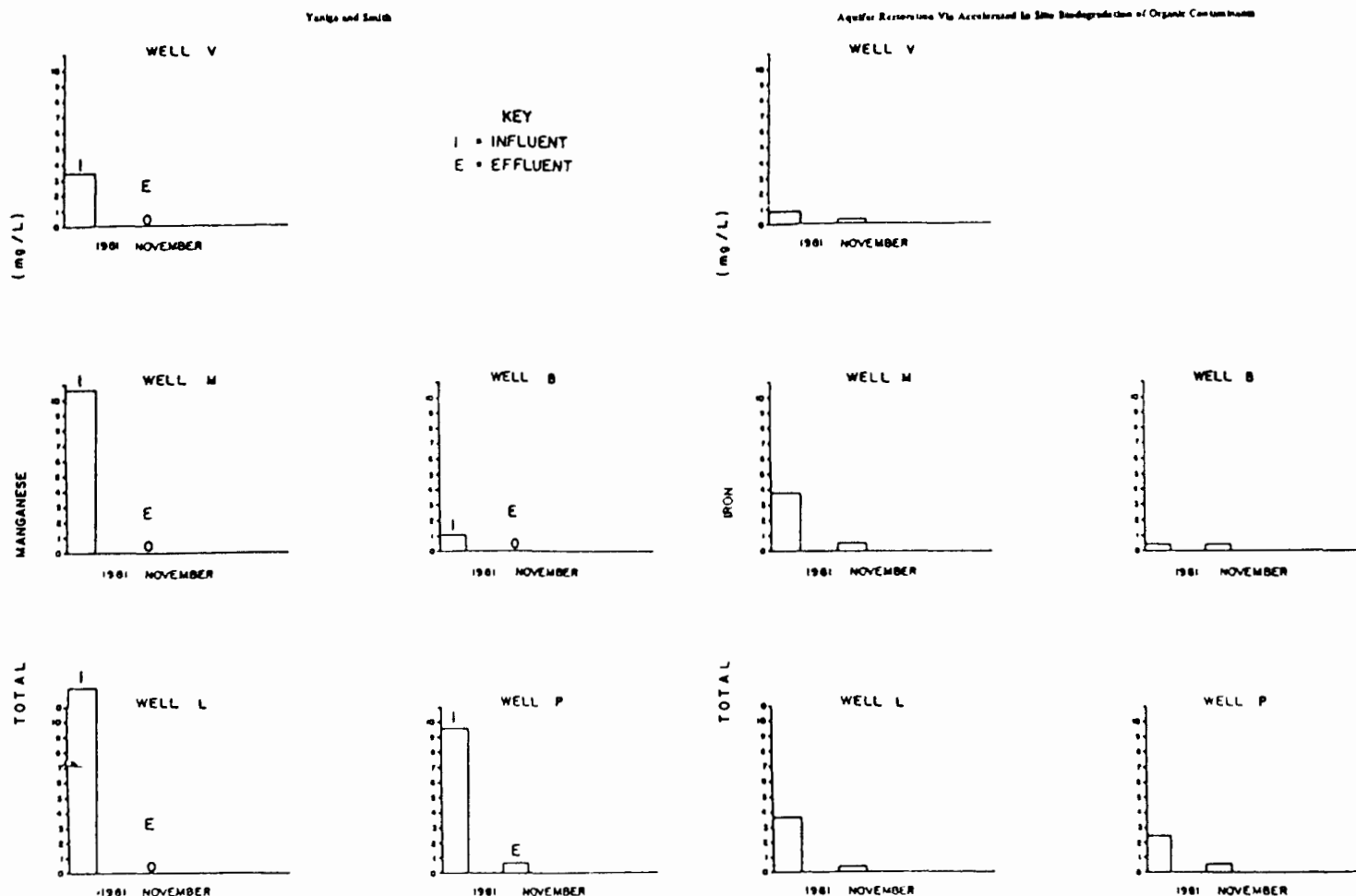


Figure 5A. Manganese Concentration Pre and Post Physical-Chemical Treatment.

Figure 5B. Iron Concentrations Pre and Post Physical-Chemical Treatment.

DISSOLVED HYDROCARBON CONTAMINATION

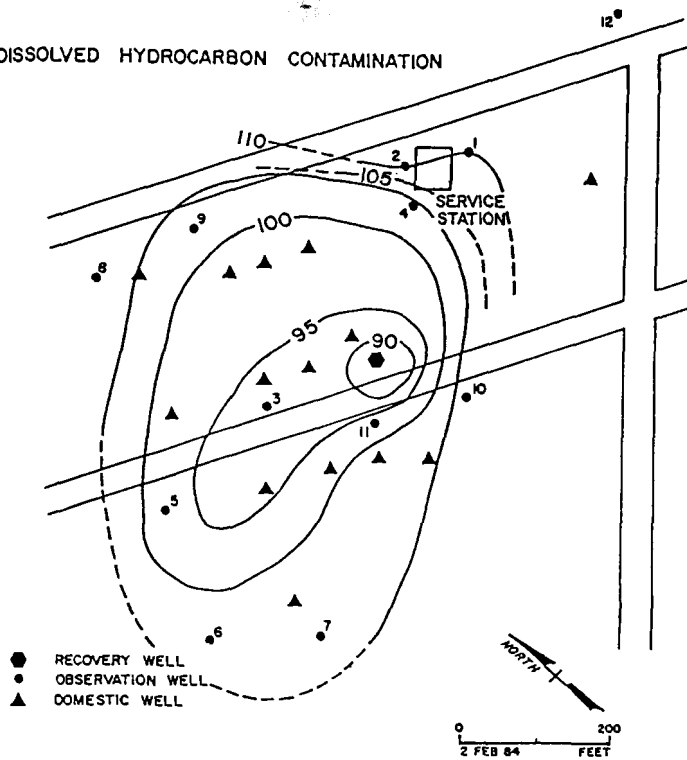


Figure 6. Water Table Gradient (data taken from Groundwater Technology monitoring wells, April 1, 1982).

NOTE: SAMPLES WERE RETRIEVED BUT NOT ANALYZED DURING SEPT TO DEC 1982. MONTHLY SAMPLING AND ANALYSIS PROGRAM WILL CONTINUE IN JAN 1983.

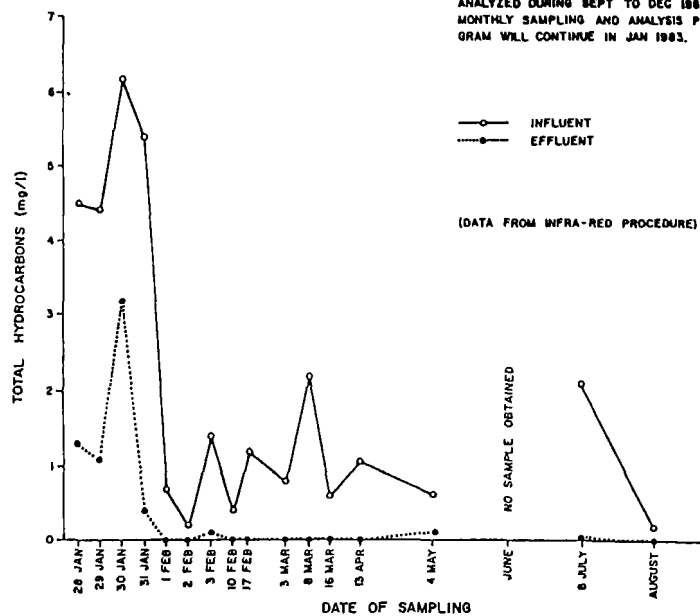


Figure 7. Total Hydrocarbon Concentrations for Air Stripping Tower.

results. In the development of the handling, delivery, and application techniques for hydrogen peroxide, the experience of FMC Corporation was most valuable.

Laboratory and specific field trials at the project site showed marked results. One specific area of the site, located in a down dip area from the origin of the contamination, proved troublesome in maintaining a sufficiently high dissolved oxygen rate to support the aerobic biodegradation of the fugitive organics. As a means of testing the new oxygen diffusion technique under worst case conditions, a 5-gallon batch of peroxide at a 100 ppm concentration was added to a point on the periphery of the plume, which was approximately 40 feet from the closest sampling location toward the pumping well. The test was initiated with the central pumping well in operation, to induce flow of water and hydrogen peroxide to it and the intermediate observation points. The results showed an acceptable increase, from 0.5 ppm dissolved oxygen to 8.0

ppm dissolved oxygen in a 24-hour period. The increase in dissolved oxygen also stimulated an increase in microbiologic activity and a decrease in hydrocarbon concentrations.

The concentration of hydrogen peroxide used in the on-going program for enhanced bioreclamation is 100 ppm, yielding 50 ppm of dissolved oxygen for uptake and utilization by the microbiologic community. Hydrogen peroxide is currently being added to the groundwater system at the site, both at the infiltration gallery and former air sparging wells. An added benefit of the hydrogen peroxide use in the wells is that when introduced to the well bore at 100 ppm, it keeps the well free of heavy biogrowth, thus allowing more equal and quicker transmission of needed oxygen to the impacted areas of the groundwater system. The most recent results from the site show overall hydrocarbon concentration levels to have declined in the core area, with only five homeowner wells still showing degradation (Figure 10).

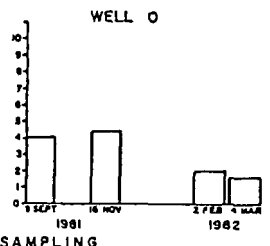
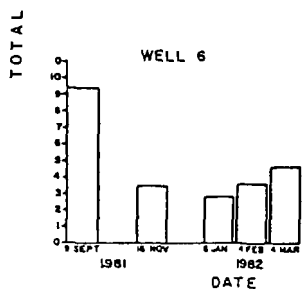
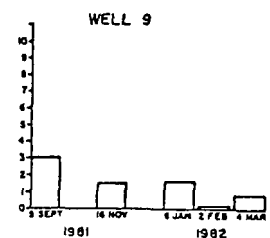
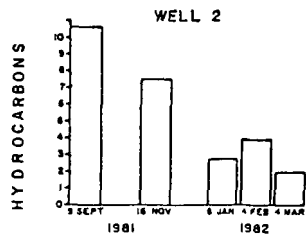
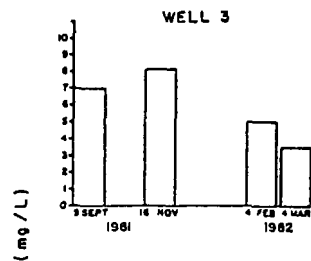


Figure 8. Total Hydrocarbon Concentrations for Core Homes.

Aquifer Restoration Via Accelerated In Situ Biodegradation of Organic Contaminants

DISSOLVED HYDROCARBON CONTAMINATION

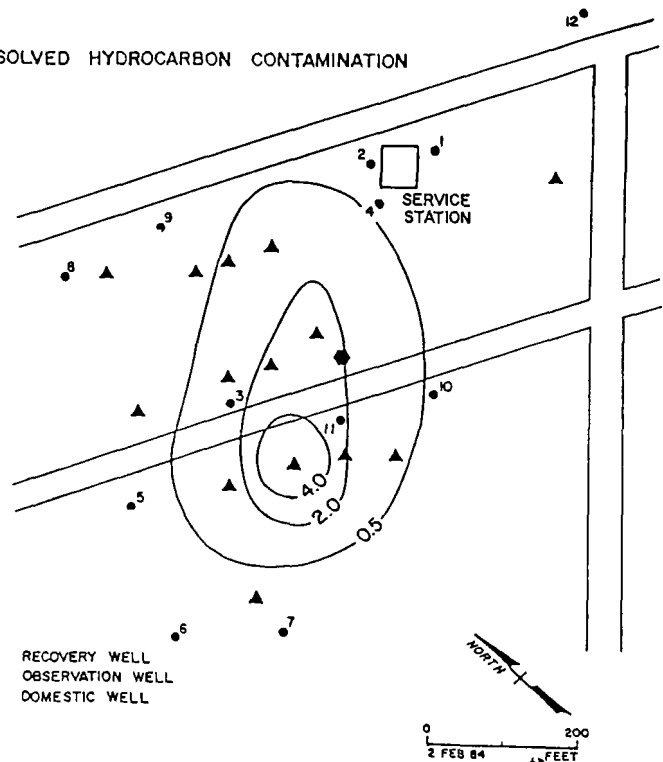


Figure 9. Isocon Map of Hydrocarbon Contamination (ppm) of Domestic Wells, December 1, 1982.

SUMMARY

The applied techniques of physical/chemical treatment of domestic well water combined with groundwater manipulation via a pumping well, air stripping for volatile organic removal, and enhanced biostimulation/bioremediation of groundwater systems contaminated by organic compounds proved a most applicable and cost-effective technique. Limitations of oxygen transfer critical to aerobic decomposition of the organic contaminants can be overcome by the application of a superior oxygen donor, such as hydrogen peroxide, when applied in a comprehensive, scientific manner.

RELATED LITERATURE

- American Petroleum Institute. 1972. The Migration of Petroleum Products in Soil and Groundwater - Principles and Considerations. API Publication No. 4149.
- De Pauwreth, T. C., Y. Barndt, A. Chiswell, and D. Farnell. 1979. Pollution of Groundwater from Oil Pollution. Conference on Marine, Netherlands, pp. 1-16.
- Jambona, V. W., R. L. Raymond, and J. O. Rodman. 1976. Biodegradation of High Octane Gasoline. Proceedings of the Third International Biodegradation Symposium, Applied Science Publishers.

- Kramer, William M. Groundwater Pollution from Gasoline. Ground Water Monitoring Review 3(2).
- Luskfield, J. M. and L. E. Clark. 1973. Bacterial Activity in Groundwater Containing Petroleum Products. API Publication No. 4211.
- Raymond, R. L., V. W. Jambona, and J. O. Rodman. Bioremediation of Bacterial Activity in Groundwater Containing Petroleum Products.
- Somesh, Inc. 1978. Vapor Liquid Solvent Bioremediation Process Cleans Up Groundwater. Petroleum Marketing (July/August).
- Wheatley, L. 1983. Cleanup Taps. Pollution Engineering (February).
- Yaniga, P. 1992. Alternatives to Densitization for Hydrocarbon Contaminated Aquifers. Ground Water Monitoring Review (Fall).
- Yaniga, P. and R. Chaves. 1992. Advanced Techniques to Contain and Recover of Refined Petroleum Hydrocarbons from Groundwater. DTG Federal, Venezuela, South America. UPAH 82. Proceedings of the XVII Congress of the Pan American Federation of Engineering Societies.
- Yaniga, P. and D. Dumbie. 1993. Hydrocarbon Contamination of Carbonate Aquifers: Assessment and Abatement. In Proceedings of the Third National Symposium on Aquifer Restoration and Ground Water Monitoring. National Water Well Association.

DISSOLVED HYDROCARBON CONTAMINATION

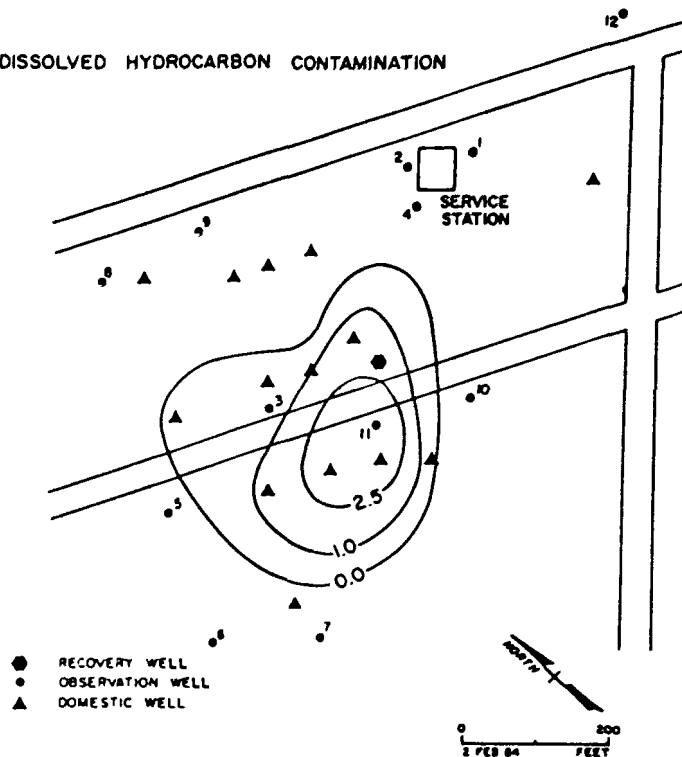


Figure 10. Isocore Map of Hydrocarbon Contamination (ppm) of Domestic Wells, November 2, 1983

Groundwater Extraction System Design for a U.S. EPA Superfund Site

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ABSTRACT

Baird & McGuire, Inc. operated a chemical mixing and batching facility in Holbrook, Massachusetts, producing household and industrial products including floor waxes, wood preservatives and pesticides. Widespread contamination of the bedrock and overburden aquifers by over 200 chemicals including pesticides, volatiles, semi-volatiles and metals has occurred due to improper handling and disposal of products and waste. The town well field, located 1,500 ft from the site, was abandoned in 1982 because of volatile chemicals detected in the water. In 1982, the site was scored on the hazardous ranking system and currently is ranked high on the U.S. EPA NPL.

In 1988, Metcalf & Eddy, Inc. was contracted to design remedial measures for the site including the design of a groundwater extraction system, a recharge system and a groundwater treatment plant. Monitoring wells were installed and two aquifer tests were performed to obtain design information. By utilizing a state-of-the-art electronic data acquisition system developed by the Illinois State Water Survey, a high density of accurate data characterizing aquifer behavior was collected.

The data from the pumping tests were used to construct and calibrate a three-dimensional groundwater flow model of the site. The model was utilized to predict the effects of various extraction well schemes on the flow regime and to locate wells strategically to result in quick and efficient groundwater cleanup. The USGS Modular Groundwater Flow Model (MOD3) was used in this study. Calibration of the model involved replicating aquifer behavior exhibited during the pumping tests and matching assumed steady-state head distributions. Model simulations provided a better understanding of aquifer interconnections, recharge areas and interactions with a river flowing through the site. Ultimately, the model was used to determine the optimal well configuration based on an evaluation of capture radii. The design of the groundwater extraction system was based on modeling results indicating pumping well location, pumping rates and well screen depth and intervals.

INTRODUCTION

This paper describes the approach taken to the design of a groundwater extraction system for a U.S. EPA Superfund Site in Holbrook, Massachusetts. The system is part of a groundwater remediation scheme involving groundwater extraction, treatment and reinfiltration. The groundwater at this site is contaminated with over 200 chemicals including pesticides, volatiles, semi-volatiles and metals. The objective was to design a groundwater extraction system to capture contaminated groundwater in three somewhat distinct aquifers and to promote flushing of the aquifers.

The approach that was used to develop the data necessary for design included three basic steps:

- Exploratory drilling and the installation of monitoring wells to gather information about the potentiometric surface, the bedrock, the overburden geology and groundwater quality
- Pumping tests, utilizing a state-of-the-art electronic data acquisition system, to characterize the flow characteristics of the aquifers, identify hydrologic or impermeable boundaries and determine the degree of hydrologic connection between the aquifers
- Three-dimensional groundwater flow modeling to determine optimal extraction well locations, screened intervals and pumping rates

BACKGROUND

For over 50 yr, Baird & McGuire, Inc. operated a chemical mixing and batching facility producing household and industrial products including floor waxes, wood preservatives and pesticides. In 1982, the town well field, located only a few hundred feet away from the site, was closed due to the detection of volatile chemicals in the water supply. After site investigations, it became obvious that improper handling and disposal of waste products had resulted in contamination of bedrock and overburden aquifers.

The bedrock is a gabbro-diorite formation, the top 20 ft of which are fractured and weathered. The overburden consists of two hydrogeologically distinct units. The lower layer is glacial till consisting of sand, silt, cobbles and boulders. The upper layer is stratified drift consisting of fine to coarse sand with trace amounts of silt. Within the stratified drift, two layers with distinct textural differences were identified. The lower part of the stratified drift is predominantly coarse-grained sand. The upper part consists mostly of silty fine sand.

An RI/FS performed by other engineering consultants indicated that groundwater contamination exists predominantly in the bedrock, till and coarse-grained sand layers. Information from approximately 70 wells installed under the RI/FS was used to determine piezometric surfaces and the direction of groundwater flow. Groundwater quality data from the RI/FS and an additional sampling episode conducted by M&E were used to identify the plume boundaries. From these studies it was determined that contaminated groundwater flows toward the Cochato River that flows through the site. A downward vertical gradient was identified in the western portion of the site, while an upward vertical gradient was identified in the vicinity of the river.

The horizontal extent of the plume with respect to the river and site boundaries is illustrated in Figure 1. The studies indicated that contaminated groundwater migrates horizontally and vertically downward to deeper layers in the source areas located in the western extent of the plume and eventually discharges to the Cochato River. The portion of the plume existing on the other side of the river exists predominantly in the till and bedrock, indicating that some contamination migrates past the river.

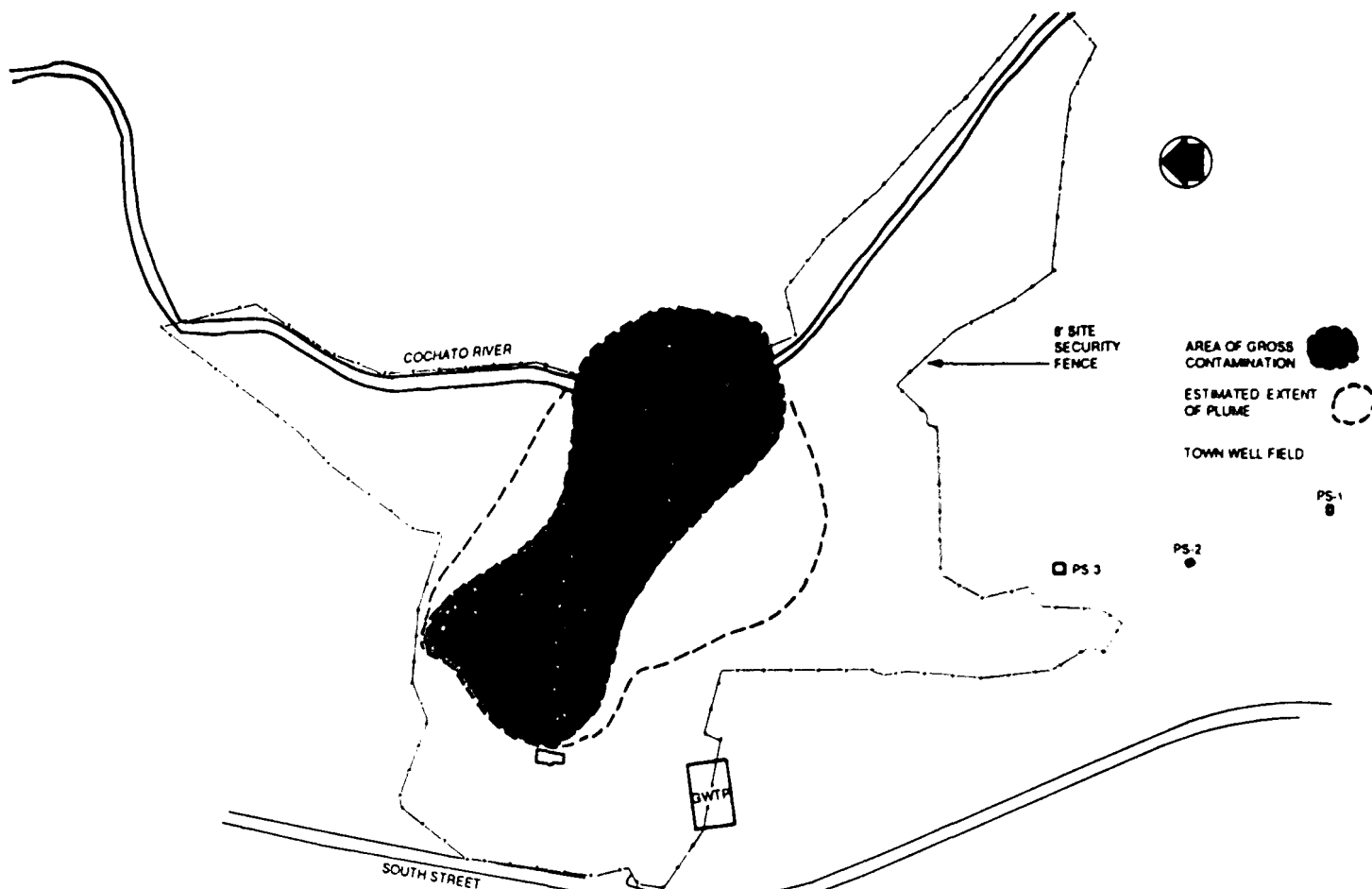


Figure 1
Site Map With Plume Delineation

WELL INSTALLATION

Additional field work beyond that conducted under the RI/FS was needed to fill in data gaps. In particular, information regarding areal and vertical extent of contamination near the river and the source area was lacking. Therefore, the first phase of the field work involved installing additional monitoring wells in stratified drift, till and bedrock in those areas to further define the extent of contamination. These wells also were used to refine the interpretation of the piezometric surface. M&E sampled 50 new and existing wells to determine the present-day plume configuration. The data indicated that the greatest contamination levels exist in the coarse-grained layer of the stratified drift. Till and bedrock were found to be moderately contaminated.

In addition to the wells installed for sampling purposes, 16 observation wells and two extraction wells were installed for use during the pumping test. Information obtained from an exploratory boring in the vicinity of the pumping test location was used to determine screen size and screen location of the pumping wells.

AQUIFER TESTING

The second phase of the field work involved performing two groundwater pumping tests to determine aquifer flow characteristics. The tests were performed in the till and stratified drift aquifers. Originally, a test was to be conducted in the bedrock aquifer as well. However, during well development, it was observed that groundwater yields within the consolidated bedrock was too low to permit aquifer testing.

The pumping tests were designed by performing pretest calculations utilizing data from previous geological site studies. Utilizing transmissivity values obtained from slug tests and grain size analyses, an estimate of the zone of influence of the extraction wells was made to locate

observation wells an adequate distance away from the extraction wells. Observation wells were installed in clusters consisting of stratified drift, till and bedrock wells. The intent was to monitor the drawdown in all layers during the pumping of each overburden layer to characterize the degree of hydraulic connection between layers. The well clusters were installed at right angles to the extraction wells to determine the degree of anisotropy. A sketch of the aquifer test set-up is provided in Figure 2. Based on the estimated low yield of the bedrock pumping well, and the drillers' opinions that the weathered bedrock holds a considerable amount of water, a decision was made to install two additional observation wells in the upper fractured and weathered bedrock zone. These wells were monitored during each test to determine the influence of pumping the till and stratified drift on the weathered bedrock.

The pumping rates and the length of each test were governed to some extent by the eventual fate of the pumped water. The pumped water was expected to be highly contaminated, precluding the possibility of convenient discharge to a surface water body or sewer system. After investigating various discharge alternatives, it was decided to store the water on-site in a holding tank. A 500,000-gal storage tank was constructed approximately 200 ft away from the pumping wells. The structure was a rectangular tank consisting of galvanized steel sides and support frames. The tank was fitted with an HDPE liner and floating cover to prevent the escape of water and volatile chemicals to the environment. The capacity of the tank governed the pumping rate and the length of each test. Based on this, two consecutive pumping tests of the till and stratified drift aquifers consisting of 3-day pumping and 3-day recovery periods were conducted. The pumping rates were 20 gpm and 75 gpm for the till and stratified drift aquifers, respectively.

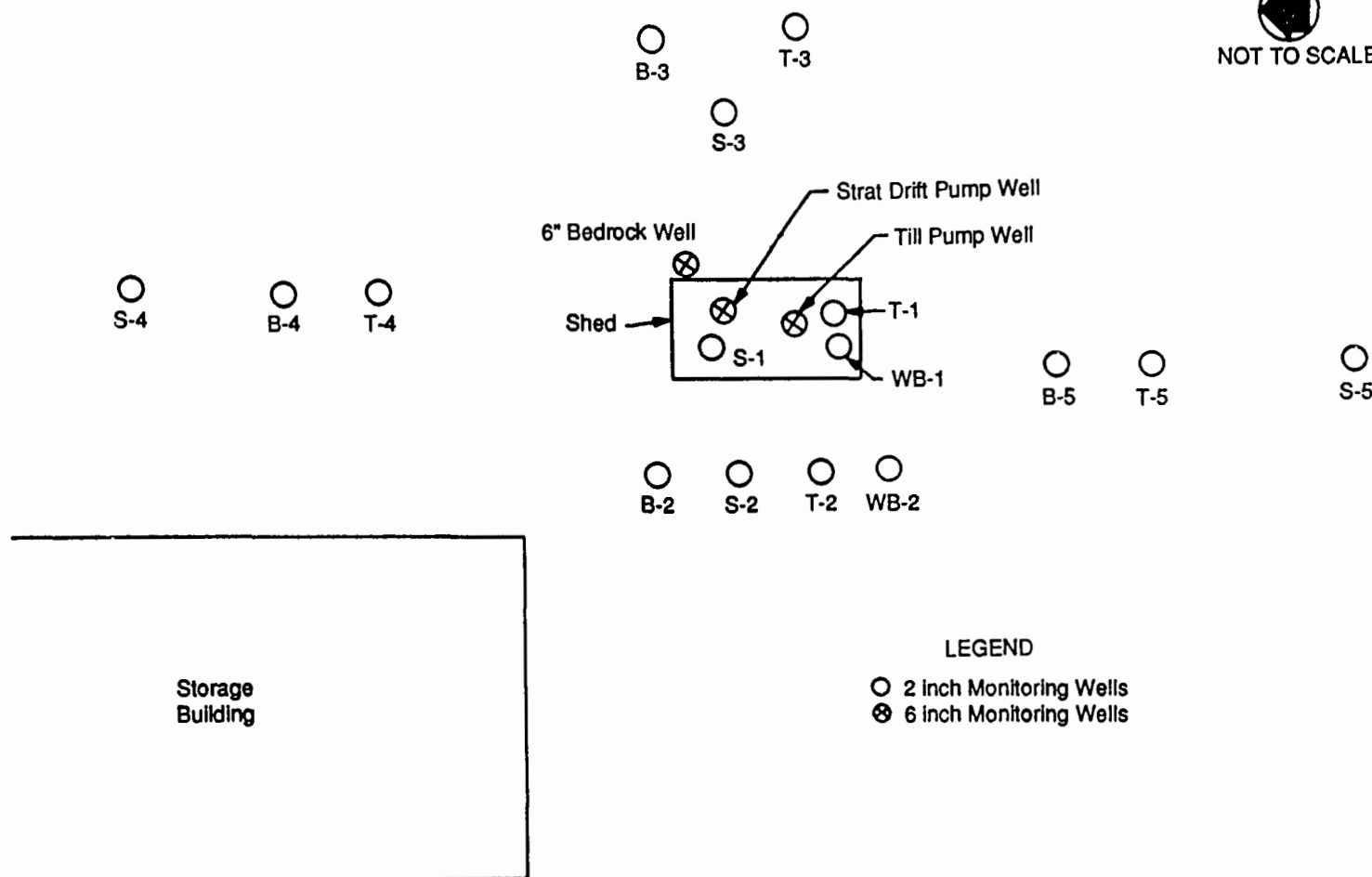


Figure 2
Aquifer Test Area Sketch Map

Thirty-five wells were monitored during the aquifer tests. Fourteen wells located within a 100-ft radius of the extraction wells were monitored by an electronic data acquisition system built by the Illinois State Water Survey. The system utilizes submersible pressure transducers to monitor water pressure. Analog-to-digital and current-to-voltage conversion circuitry allow direct transmittal of water pressure measurements from submerged pressure transducers to a laptop computer. The data are then stored in a floppy disk. The laptop computer allows the data to be viewed as they are being recorded. This added convenience allowed the test operator to evaluate the behavior of each aquifer during each test and was helpful in making decisions regarding operation of the test.

The data acquisition system proved to be an extremely useful tool in this application. By logarithmically logging a high density of accurate data, the response at each aquifer was clearly defined, thus facilitating analysis. The data from the pumping test were plotted and analyzed utilizing various software analysis packages. Time-drawdown, distance drawdown and recovery analysis resulted in somewhat consistent results. Values of transmissivity, storage coefficient and vertical permeability of each layer were computed.

An evaluation of the shapes of the curves (clearly defined by the high density drawdown measurements) indicated that the upper stratified drift behaved as a unconfined aquifer with delayed yield, while the deeper till and bedrock units behaved as semi-unconfined aquifers (unconfined with leakage from higher permeability confining layers). The conclusion was that the stratified drift and till aquifers are highly connected with differences in transmissivity of only a factor of three. The analysis of the drawdown data from weathered bedrock wells indicated that the unit responds similarly to the till unit and has a similar hydraulic

conductivity. The values of transmissivity, storage coefficients and vertical permeabilities as well as the shapes of the time drawdown curves and the results of the evaluations of the relative response of the aquifers were used to construct and calibrate a representative flow model of the site.

GROUNDWATER MODELING

The final step in the extraction system design involved construction and calibration of a representative groundwater flow model and then utilization of the model to predict the effect of various extraction well schemes on the groundwater flow regime. The model used in this study was the three-dimensional modular groundwater flow model (MOD3) written by Michael G. McDonald and Allen W. Harbough of the U.S.G.S.. A three-dimensional model was needed in this study to simulate the hydraulic relationship of the aquifers with each other and with the river flowing through the site. It was apparent at the outset that it would be pertinent to incorporate the effects of these relationships into the design of the extraction system. The model consisted of three layers.

- Silty-fine sand layer—the uppermost layer of the stratified drift.
- Coarse-grained layer—the lower-most layer of the stratified drift.
- Till and weathered bedrock—the lower most overburden unit.

A graphic interpretation of a vertical cross-section through the model is shown in Figure 3. As the figure indicates, neither the silty-fine sand aquifer nor the coarse-grained sand aquifer is continuous throughout the site. Both layers pinch out to the west. Due to the similar response exhibited during the pumping tests, the glacial till and weathered bedrock were modeled as one unit. This layer (layer 3) extends down to compe-

tent bedrock where the hydraulic conductivity is assumed to be negligible.

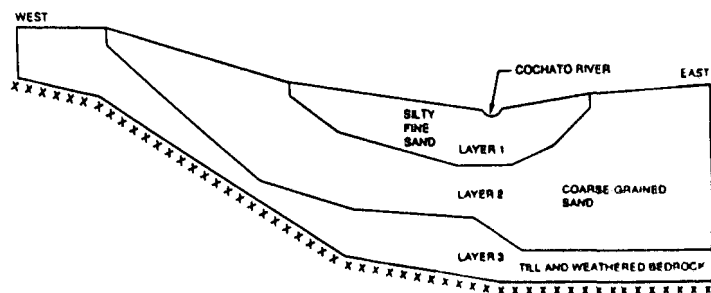


Figure 3
Model Cross-Section

A steady-state calibration of the model was performed by adjusting transmissivity, vertical permeability, river bed conductance, recharge and boundary conditions until the model-computed piezometric head distribution for each layer matched the observed distributions. The distributions were observed to be very similar for each layer except in a few areas where vertical gradients were detected. Due to the lack of seasonal data, the steady-state head distribution was assumed to be the most recent interpretation of head distribution. A mass balance calculation was performed to determine the amount of groundwater flowing into the river and out of constant head boundaries. This value was used in evaluating the effectiveness of each extraction system scheme. The calculation results indicated that most of the water existing in the system eventually flows into the river while a small amount of water flowing in deeper layers migrates past the river. This explained the observed contamination in deeper layers on the opposite side of the river.

Utilizing data from the aquifer tests, a transient calibration was performed to verify the predictive capabilities of the model. In this effort, each aquifer test was simulated by inserting extraction wells and running the model for a 3-day pumping period. Model-computed drawdowns in each layer were compared to those exhibited during each test. Input conditions were adjusted further until a good match was achieved. The parameter that had to be varied the most was the vertical permeability. This was expected due to the relative uncertainty in the calculation of the value. Thirty-two comparisons of computed head and observed head over two tests were made utilizing 17 wells within the model area. The average difference between model computed head and observed head was 0.51 ft. At this point it was assumed that the predictive capabilities of the model were adequate.

The next step in the modeling effort was to utilize the model to predict the effect of various extraction well schemes. The objective was to determine the optimal extraction scheme that would effectively remove the contaminated groundwater by forming a cone of depression that encompassed the contaminant plume. Due to schedule constraints, preliminary design of a groundwater treatment system has already commenced, based on an estimated maximum flow rate of 200 gpm. All model simulations were performed at a rate of 200 gpm or less. The steady-state head distribution utilized as initial conditions for layers 1, 2, and 3, respectively, are illustrated in Figures 4, 5, and 6. The figures illustrate the horizontal extent of each layer. Areas in which the contours are discontinuous represent locations where the deeper layers crop out at the surface.

Various extraction well configurations were modeled with different well locations, screened intervals and pumping rates. System flow rates were varied from 100 gpm to 200 gpm. It was found that the full 200 gpm would be needed to capture the entire contaminant plume.

RESULTS

The final design was reached through an iterative process of varying individual well pumping rate, well depths and well locations and determining the resultant impact on the aquifers. The design includes two wells located in the till and weathered bedrock and four wells located

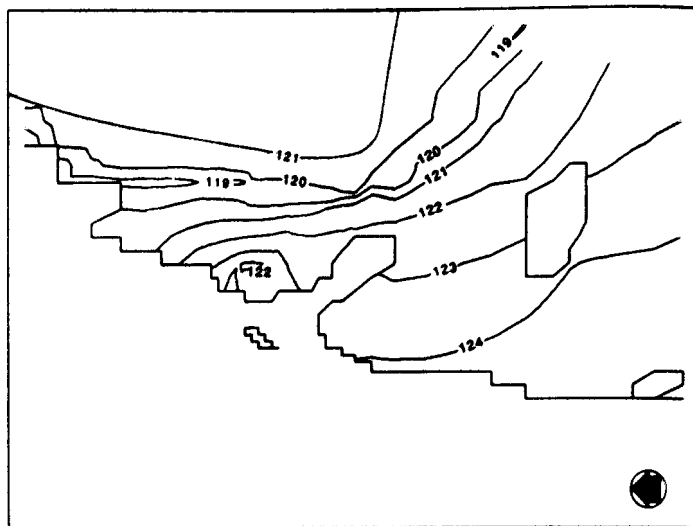


Figure 4
Steady-State Head Distribution—Layer 1

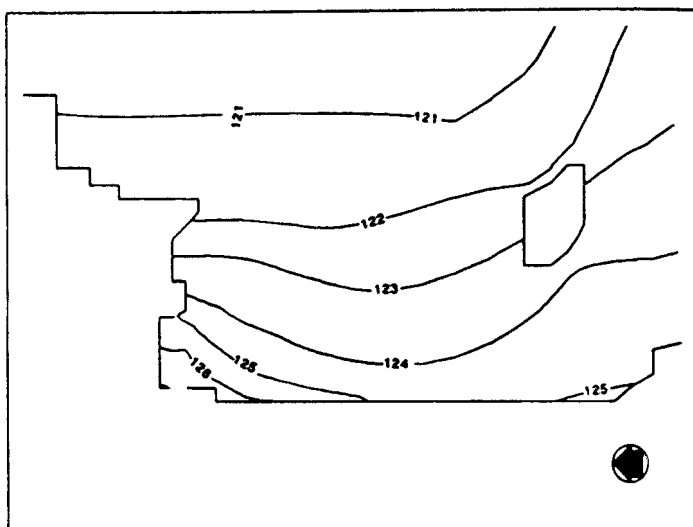


Figure 5
Steady-State Head Distribution—Layer 2

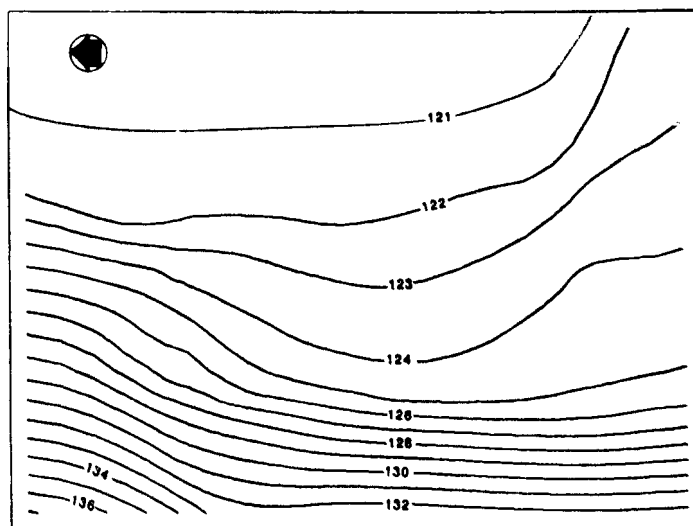


Figure 6
Steady-State Head Distribution—Layer 3

in the coarse-grained sand layer which is the most transmissive. Figures 6, 7, 8 and 9 illustrate the cone of depression created in each layer. The groundwater mound formed in the right side of each figure is created by the basin recharge system. The water will be conveyed to this system after it has been treated in the on-site treatment plant. The figures indicate that the cone of depression will effectively contain and remove the contaminant plume.

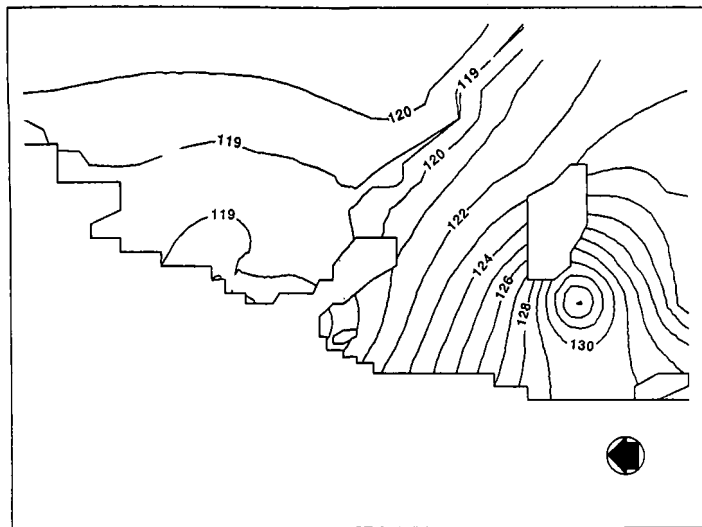


Figure 7
Head Distribution After Long Term Operation of
Extraction And Recharge Systems—Layer 1.

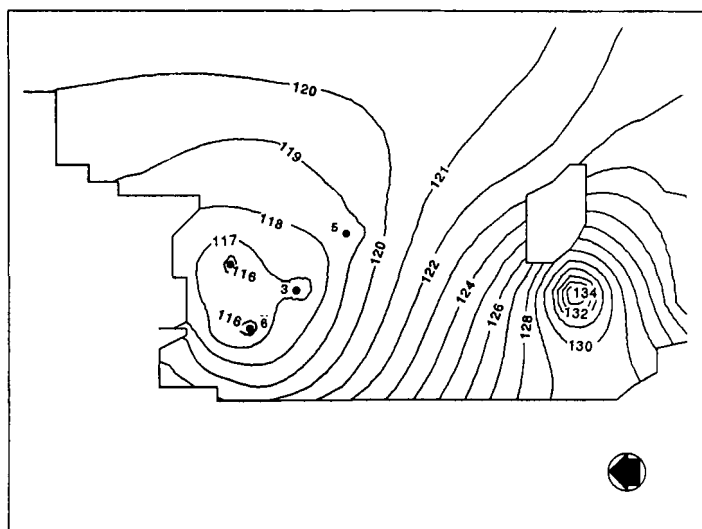


Figure 8
Head Distribution After Long Term Operation of
Extraction and Recharge Systems—Layer 2

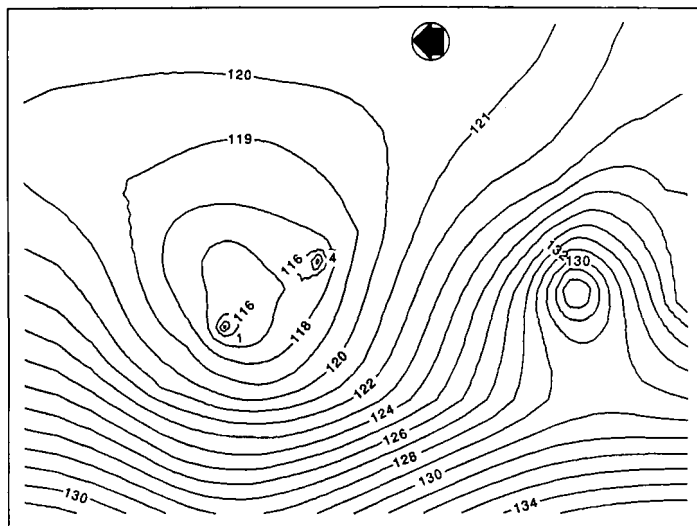


Figure 9
Head Distribution After Long Term Operation of
Extraction and Recharge Systems—Layer 3

Precise predictions of the time it takes to remove all contaminants from groundwater could not be made utilizing a flow model alone. Furthermore, the large array of chemicals existing in the groundwater makes it difficult to estimate retardation effects. However, rough estimates of pore-volume removals indicate that considerable cleanup may occur in less than a decade. Calculations show that more than 10 pore volumes may be removed from the contaminated area in this time, indicating that a significant amount of flushing and removal will occur.

CONCLUSIONS

The design of the extraction system discussed in this paper was based on the results of three-dimensional groundwater flow modeling. Keeping in mind that the representativeness of model predictions is governed by the quality of the field information used to construct the model, the field work performed under this project were tailored to meet the data needs of the model.

The use of an electronic data logger proved to be a cost-effective way of acquiring a high density of accurate drawdown measurements during aquifer tests. In effect, it simplified the evaluation of aquifer behavior and enhanced the representativeness of data used to construct the groundwater model. MOD3 proved to be an effective tool for optimizing extraction well schemes. Although groundwater modeling results often are viewed with some skepticism, it cannot be argued that a well-constructed and representative model can provide valuable insight into the behavior of a complex hydrogeological system. Used correctly, a groundwater model can be a useful design tool.

Evaluation of the Effectiveness of Groundwater Extraction Systems

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ABSTRACT

The most common method for addressing contaminated groundwater is extraction and treatment. To evaluate the effectiveness of this process in achieving concentration goals in the groundwater, data from 19 ongoing and completed groundwater extraction systems were analyzed. This analysis indicated several trends including: containment of groundwater plumes was usually achieved; contaminant concentrations initially decreased significantly followed by a leveling out; after the period of rapid decline, the continued decreases in containment concentration were usually slower than anticipated; and data collected during the remedial investigation were often insufficient to optimize system design.

Factors limiting the achievement of concentration goals fell into four basic categories: hydrogeological factors, such as subsurface heterogeneity, low permeability units and presence of fractures; contaminant-related factors, such as high sorption to soil and presence of non-aqueous phases (dissolution from a separate non-aqueous phase or partitioning of contaminants from the residual non-aqueous phase); continued migration from source and size of the plume itself; and system design factors, such as pumping rate, screened interval and extraction well location.

The findings of this study indicate that groundwater extraction is an effective method for preventing further migration of contaminant plumes and achieving risk reduction by removing a substantial mass of contaminants from the groundwater; however, the findings indicate that in certain situations, it may not always be practicable to achieve health-based cleanup concentrations throughout the groundwater to fulfill the primary goal of returning groundwater to its beneficial uses. Where cleanup to health-based concentrations throughout the groundwater is not practicable, extraction and treatment can be operated to optimize contaminant mass removal and contain the groundwater plume. Conclusions that can be drawn from the study are: plume containment should be considered early during site management planning; certain data not currently collected on a routine basis should be gathered to better estimate restoration time frames and system response; and groundwater remedies should be flexible to allow for modification to the system.

INTRODUCTION

Laboratory researchers and hydrogeologists involved in groundwater contamination cleanup have been encountering several conditions that can limit the rate at which contaminants can be removed from the subsurface. The project described in this paper was initiated to assess the validity and prevalence of these findings in actual experiences with groundwater extraction to date. The purpose of the project was to assess the effectiveness of groundwater extraction systems in achieving specified goals at sites where groundwater extraction systems had been operating for a period of time long enough to generate performance

information.

Several sources of data were reviewed in an effort to identify groundwater extraction systems currently in operation and actions that had been completed and pumping terminated. Information on 112 sites including Superfund, RCRA and industrial sites where groundwater response actions were being implemented by the U.S. EPA, other Federal Agencies, States or responsible parties, was collected and organized in a data base for review. The majority of these sites, however, had not reached a full implementation phase and consequently were not useful for this study. Nineteen cases were identified as good candidates for more in depth evaluation based on the data available on actual performance.

This paper presents the findings of the study and provides examples from the 19 case studies examined in detail that illustrate the various factors that can affect the performance of groundwater extraction systems. Finally, recommendations based on this study are summarized.

BACKGROUND ON CASES

The 19 case studies form a representative sample of the variety of conditions frequently encountered when performing groundwater extraction. Pertinent aspects of the 19 sites is provided in Table 1. Several general characteristics are worth noting.

In all cases, one of the goals of the extraction systems was to prevent further migration of contaminants. Twelve of the cases also specified quantitative concentration or contaminant mass reduction goals as well as containment. The seven remaining cases generally indicated a desire for contaminant mass reduction but did not clearly specify this as a goal. Three of the sites involved treatment at existing well-heads; however, this action was incorporated into the groundwater extraction system, generally not with the goal of reducing contaminant concentrations but with the intent of preventing further migration beyond the wells. The existing wells acted as a barrier system which prevented contaminant migration to other drinking water wells.

The period of operation of the 19 extraction systems at the time available data were reviewed ranged from 5 mo to 6 yrs. In most cases, the systems had been operating longer than the projected time required for cleanup; however, concentration-based goals had not yet been attained and extraction was continuing.

The variety of contaminants encountered in these sites was limited. The primary contaminants in all but two cases were volatile organic compounds (VOCs). This finding is not surprising since VOCs are the most prevalent groundwater contaminants found at Superfund sites and tend to be more mobile than other classes of compounds. Semi-volatiles were also present in two cases. Chromium, pesticides and creosote were detected at one site each.

The 19 case studies represent a broad spectrum of geologies from

Table 1
Summary of Case Study Site Characteristics

<u>Site Name</u>	<u>Date of Initial Extraction</u>	<u>Remedial Objective</u>	<u>Chemicals Present</u>	<u>Geologic Environment</u>	<u>Innovative Technologies</u>
Amphenol Corporation	January 1987	Restoration	Organics	Unconsolidated glacio-fluvial sediments	
Black & Decker, Inc.	May 1988	Restoration	Organics	Glacial till & fractured	Fracture enhancement
Des Moines TCE	December 1987	Restoration	Organics	Unconsolidated glacio-fluvial sediments	
Du Pont Mobile Plant	December 1985	Containment	Organics	Alluvial sand & clay	
Emerson Electric Company	December 1984	Restoration	Organics	Sand	
Fairchild Semiconductor	1982	Containment	Organics	Alluvial sand & gravel with silt & clay layers	Slurry wall
General Mills, Inc.	Late 1985	Restoration	Organics	Peat, glacial deposits, & fractured rock	
GenRad Corporation	Late 1987	Restoration	Low Sorption Organics	Glacial sand, gravel	Intermittent pumping
Harris Corporation	April 1984	Well-head treatment & Restoration	Organics Metals	Sand & shell with a clay layer	Well points
IBM Dayton	March 1978	Was restoration, now containment	Organics	Sand with clay layers	Well points Reinjection
IBM San Jose	May 1982	Restoration	Organics	Alluvial sand & gravel with silt & clay layers	
Nichols Engineering	January 1988	Restoration	Organics	Weathered & fractured shale	
Olin Corporation	1984	Containment	Organics	Unconsolidated glacio-fluvial sediments	
Ponders Corner	September 1984	Well-head Treatment	Low Sorption Organics	Unconsolidated glacio-fluvial	Vapor extraction
Savannah River Plant	September 1985	Restoration	Low Sorption Organics	Coastal plain sand, silt & clay layers	
Site A	August 1988	Restoration	Organics	Limestone & sand	
Utah Power Light	October 1985	Restoration & Containment	Organics	Alluvium & fractured basalt	Intermittent pumping
Verona Well Field	May 1984	Restoration & Containment	Organics	Glacial sand, gravel, & clay	Vapor extraction
Ville Mercier	1983	Containment	High and Low Sorption Organics	Unconsolidated glacial sediments & fractured rock	

various geographic locations. Two of the sites are located in the northwestern United States, seven are located in the southeast, six in the northeast, two in the southwest and two in the midwest. This geographical distribution was considered an important factor in assessing the role that varying hydrogeologies may play in impeding or promoting extraction of contaminants.

GENERAL OBSERVATIONS

Several trends were observed in looking at the overall performance of the systems. As discussed above, a common goal of all the actions was containment of the contaminant plume. In the majority of the cases, this goal appeared to be successfully achieved. Groundwater gradient data indicated an inward gradient toward the center of the plume and little or no movement of contaminants beyond plume boundaries that existed at the initiation of the action.

Contaminant mass removal was usually significant. Removal of thousands of pounds of contaminants (up to 130,000 lbs in one case) was not uncommon. However, the rate of mass removal often declined quickly to low levels. This initial drop in removal rate is thought to be the result of a combination of removing groundwater faster than the contaminants can desorb from the soil, lowering water tables below the most contaminated portions of the subsurface and diluting concentrations by drawing in less contaminated groundwater from surrounding areas. Although concentrations in the groundwater appeared to be reduced significantly, the levels remaining were generally above health-based standards for drinking water, which was the most common concentration goal of the actions.

FACTORS AFFECTING PERFORMANCE—CASE EXAMPLES

The factors affecting the performance of the extraction systems examined in this study fell into the following four primary categories:

- Aquifer properties such as subsurface heterogeneity and presence of low permeability units or fractures
- Contaminant properties such as level of sorption to soil, immiscibility (dissolution from non-aqueous phases or partitioning of other contaminants from residual non-aqueous phase) and density
- Adequacy of source removal and size of the plume itself
- System design such as pumping rate, location of extraction wells and depth/length of screened interval

The following sections illustrate the impact these factors may have on the performance of groundwater extraction systems using examples from the case studies reviewed.

Aquifer Properties

All of the cases reviewed in this study reflected complications resulting from the heterogeneous nature of the subsurface. Well-sorted homogenous hydrogeological systems below a contaminated site tend to be the exception rather than the norm. At a chemical plant site in Alabama, it appeared that the implications of the heterogeneous nature of the subsurface material may not have been accounted for in the design of the extraction system. The water level data from monitoring wells located around the site indicated that plume capture had been achieved. However, a mass balance on the system revealed that about half the contaminant mass was escaping the recovery wells. A possible explanation for this apparent conflict is that contaminants were moving below the screened interval of the extraction wells. This explanation is supported by the fact that the hydraulic conductivity of the subsurface material increased with depth and all the on-site wells were screened in the upper, less permeable portion of the aquifer. In addition, a nearby production well screened at the lower depths continued to operate during this period and may have increased the vertical migration of contaminants.

The impact of low permeability units in the subsurface is illustrated by the Ponder's Corner site in Lakewood, Washington. At this site, the variation of contaminant concentrations with depth was assessed and correlated to the subsurface stratigraphy. This analysis indicated that almost 90% of the primary contaminant, tetrachloroethylene (PCE), present was located in a very low-permeability silt and clay unit. Con-

taminant removal rates are limited not only by the slow rate at which groundwater can be pulled through this unit, but also by the fact that the soil in this zone has a higher organic carbon content and consequently enhances sorption of the PCE to the soil.

Several of the case studies involved sites where fractures played a role in contaminant movement. At the Black and Decker Site in Brockport, New York, the identification of discrete fractures led to the conclusion that recovery of TCE-contaminated groundwater would be very difficult. In order to create interconnections between the discrete fractures, explosives were set off in the contaminated zone.

Contaminant Properties

Another factor that plays a role in virtually all the case studies reviewed is sorption. The amount of contaminants sorbed to the soil often is not accounted for in estimating restoration time-frames or in confirming that final cleanup goals have been attained. At the Savannah River Plant in Aiken, South Carolina, the contaminant mass in the groundwater was estimated based on groundwater concentrations. After 3 yrs of extraction, a comparison was made between the mass removed at the extraction wells and the difference in the estimated mass remaining *in situ* based on the groundwater concentrations before and after extraction. The mass actually removed by the system was 148,000 lbs; however, the groundwater concentration comparison indicated that only 23,000 lbs had been removed. The discrepancy can be attributed to contaminants sorbed to the soil that were dissolving into the groundwater as it was drawn to the extraction wells.

The presence of non-aqueous liquids that either float or sink in the aquifer can substantially increase the restoration time by acting as a continuing source of contaminants to the groundwater. At the IBM Dayton Facility in South Brunswick, New Jersey, the extraction system was operated for 6 yrs, and concentrations appeared to be stabilizing at a level determined to be acceptable to the State. Extraction was then terminated. Continued groundwater monitoring revealed that containment concentrations were increasing. It was concluded that this was the result of contaminants present in a non-aqueous phase more dense than water that had sunk within the aquifer. Because it would be very difficult to locate and completely remove the pockets of contamination, the goal of the extraction system was changed to containment. Extraction was re-initiated at a lower pumping rate and was projected to continue indefinitely.

Problems can result from non-aqueous liquids that are less dense than water, as well. At the Verona Well Field site in Battle Creek, Michigan, a non-aqueous phase liquid layer approximately 1 ft thick was detected floating on the water table. Traditional product recovery techniques involving creation of a drawdown cone into which product would flow and could be recovered were used to reduce this layer to approximately 1 in. At this point, product recovery techniques were no longer effective, but the remaining floating layer was sufficient to provide a source of contaminants to the groundwater at levels above the cleanup goals established for the site. A vapor extraction system was then installed to remove the remaining product.

Adequacy of Source Removal

One of the more obvious factors that can affect the ability of groundwater extraction systems to achieve concentration reductions in the groundwater is the adequacy of measures taken to prevent continued contaminant migration from source areas. Soil cleanup levels often are based on an evaluation of direct contact threats and may not account for the continued migration of contaminants to the groundwater. At an industrial site in Minnesota, concentrated wastes were removed from a disposal pit during the source action. Contaminated soil below the waste was not removed, despite sampling results which indicated that significant levels of contaminants were present in the soil. This factor probably contributed to the difficulty experienced in efforts to reduce groundwater concentrations during extraction at this site.

System Design

Another factor affecting extraction performance is the design of the extraction system. In the case of the Alabama site previously discussed,

the screened interval of the extraction wells may have been too shallow to contain the plume of contaminated groundwater. At an industrial site in Florida, portions of the contaminant plume were not captured by the extraction system since the extraction system did not address contaminants in the upper aquifer. Fortunately, the extraction system included the operation of barrier wells (existing water supply wells with well-head treatment systems) downgradient from the restoration system which were expected to capture the portion of the plume that escaped.

CONCLUSIONS

The results of this project highlight factors and approaches that are prudent to consider in developing and implementing groundwater response actions. These findings do not alter the primary goal of returning groundwater to its beneficial uses in a time-frame that is reasonable given the particular site circumstances. Rather, they argue for the collection of data to allow for the design of an efficient cleanup approach that more accurately estimates the time-frames required for remediation and the ultimate cleanup levels achievable. The conclusions cover three basic aspects of site remediation: consideration of early action, site characterization and remedy specification. In addition, consideration on a more routine basis of various methods to enhance the effectiveness of groundwater extraction appears warranted.

Conclusion 1: Plume Containment Should Be Considered Early

One of the program management principles identified in the revised NCP is the intent of the U.S. EPA to balance the goal of definitively characterizing site risks with the bias for initiating response actions as early as possible. Where groundwater contamination is involved, this bias for action should be reflected by considering, early in the site management planning process, measures that can be implemented to prevent further migration of contaminants if these measures will prevent the situation from getting worse and provide useful information to design the final remedy. Because the data needed to design a containment system often are more limited than that needed to implement full remediation, it will in many cases be valuable to prevent the contaminant plume from spreading while the site characterization to select the remediation system progresses.

The determination of whether or not to implement such a system would be based on existing information, best professional judgment and data defining the approximate plume boundaries, contaminants present and approximate concentrations. The justification for taking the action would be based on a comparison of the benefits of taking an action and the possible benefits of waiting to act until the investigation has been completed.

The advantages of early action include prevention of further contaminant spreading and the generation of useful data on the response of the hydrogeologic system. If it is determined that a containment action should be implemented, the advantages of initiating an action should be maximized by carefully monitoring system response. In particular, groundwater flow should be monitored frequently, immediately before, during and immediately after initiation of the action to obtain information on system response.

Conclusion 2: Data That Will Assist In Assessing Contaminant Movement and Likely Response to Extraction Should Be Collected

In addition to the traditional plume characterization data normally collected, assessments of contaminant movement and extraction effectiveness can be greatly enhanced by collecting more detailed information during construction of monitoring wells. Frequent soil or rock coring and the use of field techniques to assess relative contaminant concentrations in the cores are ways that might be used to gain this information. Analysis of contaminant sorption to soil in the saturated zone can also provide the basis for estimating the time-frame for reducing contaminant concentrations to established levels and identifying the presence of non-aqueous phase liquids. Cores taken from depths where relatively high concentrations of contaminants were identified might be analyzed to assess contaminant partitioning between the solid

and aqueous phases.

Conclusion 3: Flexibility Should Be Provided In The Selected Remedy That Allows For System Modifications Based on Information Gained During Operation

In many cases it may not be possible to determine the ultimate concentration reductions achievable in the groundwater until the groundwater extraction system has been operated and monitored for some period of time. Remedies should provide flexibility that allows for modifications, or should indicate that the initial action is an interim measure and that the ultimate remedy will be evaluated at some specified future date. This iterative process of system operation, evaluation and modification can effectively result in the optimum system design. Three options for describing remedies that account for the uncertainty in system response to extraction are outlined here. The appropriateness of a given option relates to the level of confidence associated with the expected performance of the extraction system with respect to achieving specified concentration goals. The options are listed below in order of decreasing confidence that specified concentration goals are practicable to attain:

1. Select a remedy designed to achieve specified concentrations in the groundwater that reflect achievement of the basic goal of returning groundwater to its beneficial uses. If the achievement of these goals is determined to be impracticable based on data gathered during implementation, the remedial action would be continued or modified to achieve the secondary goal of optimizing contaminant mass removal. The methods used to evaluate when optimum mass removal is achieved and any associated ARAR waivers would be fully described in advance as a contingency remedy.
2. Select an interim remedy that will be monitored carefully for some specified period of time; e.g., 5 yrs, to determine the practicability of returning the groundwater to its beneficial uses. At the end of this defined observation period, the effectiveness of the remedy would be evaluated and the final action determined.
3. Select a remedy designed to optimize mass removal, reducing risks to the extent practicable, over those portions of the aquifer where contaminant concentrations cannot be reduced sufficiently to return the groundwater to its beneficial uses. Any ARARs, such as MCLs or State standards, that would not be achieved in the area of attainment would be waived. Institutional controls would be implemented in perpetuity to prevent access to portions of the groundwater where contaminants remain above health-based levels and containment measures would be continued to prevent migration of contaminants at concentrations exceeding health-based levels to clean groundwater. The decision to use this option must be based on data that clearly indicate the impracticability of returning groundwater to its beneficial uses. A contingency should be included to the effect that if operation of the system indicates that health-based goals can be attained, the remedy should be operated to achieve this goal.

Under all of the options, groundwater monitoring should continue for at least 2 to 3 yrs after active remediation measures have been completed to ensure that contaminant levels do not begin to increase. For cases where contaminants remain above health-based levels, a review after 5 yrs would be required.

If it is determined that the primary goal cannot be met over some portion of the area of attainment, an evaluation of when optimum mass removal has been achieved must be made. This evaluation might be based on reaching a point of diminishing returns; that is, concentration reductions are no longer significant although contaminant mass continues to be removed (concentrations approach an asymptotic level). Alternatively, the evaluation may be based on the concentrations that would be expected to migrate from the site should the extraction system be shut off. Experience to date on this phase of groundwater remediation is limited and more definitive guidance can only be developed with collection of data during actual system operation. When the point of diminishing returns has been reached, however, this should be viewed as a signal that some re-evaluation of the remedy is warranted.

Conclusion 4: Methods to Enhance Extraction Effectiveness and Efficiency Should be Considered

It is clear from many of the case studies that variations on system design and operation can improve the effectiveness and efficiency of extraction. Some of these methods such as infiltration/re-injection and construction of slurry walls are fairly traditional. Others, like vapor extraction in conjunction with groundwater extraction and fracture enhancement, are relatively new and appear promising for certain types of situations. It may be appropriate to use some innovative technologies, such as in-situ bioremediation, in a treatment train where extraction is used to achieve initial concentration reductions followed by the use of the innovative technology to reduce concentrations an additional increment. Finally, some alterations of traditional pumping systems may be worth consideration in the majority of cases. This includes intermittent pumping to allow for containment and water level re-equilibration. Another consideration is how operation of the system,

e.g., location of operating extraction wells, can be progressively modified based on observation of aquifer and plume response.

SUMMARY

Groundwater extraction will continue to be a primary method for addressing contaminated groundwater to reduce plume spread and remove contaminants from the groundwater. An evaluation of several representative cases of groundwater extraction indicates that there are several factors and circumstances that can limit the overall performance of extraction. These factors should be recognized during site investigation through more detailed data collection. Also, remedies should be modified during system operation in response to data collected. In addition, it is valuable to consider the benefits of implementing a containment system prior to full site characterization to prevent contaminant migration as the investigation is completed.

Field Investigation to Characterize Relationship Between Ground Water and Subsurface Gas Contamination At a Municipal Landfill

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ABSTRACT

Under the direction of the U.S. EPA, a remedial investigation was performed at an inactive municipal landfill. Leachate from this municipal landfill had contaminated an upgradient municipal well in an adjacent residential area with organics. Methane and other gases were historically detected in homes in the same area, apparently entering the homes from the subsurface.

Determination of the source/pathway from the landfill to the municipal well was complicated by the fact that the well was upgradient and that rapidly moving inorganic contaminants associated with leachate (i.e., cations, anions) were never detected in the well discharge. Thus, it was suspected that there was a relationship between contaminants in the subsurface gas phase and those detected in groundwater at the municipal well. In order to determine the nature and extent of contamination and to design appropriate remediation, both ground water and subsurface gas contamination needed to be assessed.

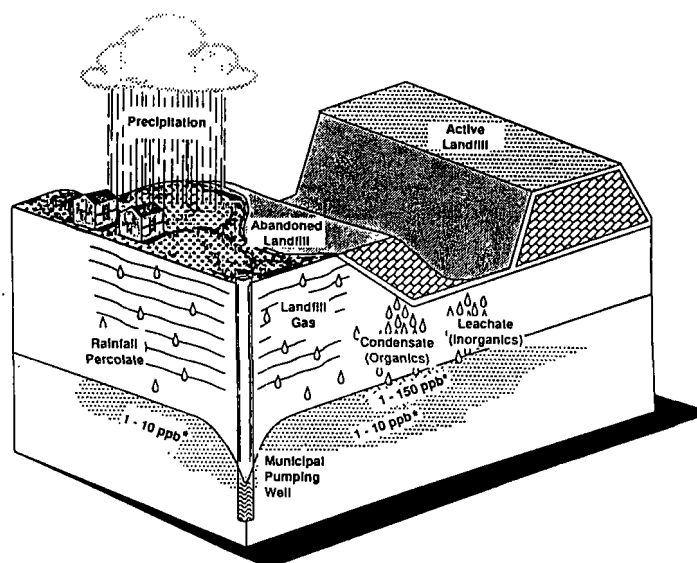
A field investigation and sampling protocol were designed to study the relationship between contaminants in various media including gas, groundwater and soil. Groundwater monitoring wells were installed upgradient and downgradient of the landfill. Soil samples were collected from the vadose zone during the installation of subsurface gas monitoring wells. Gas monitoring wells with multilevel probes were installed in the adjacent neighborhood. Groundwater samples were collected to coincide with seasonal gas sampling events. Samples of landfill leachate and gas emanating from the surface of the landfill also were collected, and an evaluation of the landfill gas migration control (extraction) system was performed.

INTRODUCTION

The landfill site described in this paper is located in New York State, on Long Island, where residents rely almost exclusively on groundwater for drinking water. The regional geology consists of bedrock, overlain by Cretaceous deposits including the Lloyd aquifer, the Raritan clay (a significant aquitard) and the Magothy formation. These Cretaceous deposits lie under Pleistocene glacial deposits over most of the Island. The Lloyd aquifer, Magothy formation and Upper Glacial formation all are used for water supply in communities neighboring the site.

The landfill is located in a former sand and gravel pit which is adjacent to a residential area. The pit was excavated towards the residential area, creating a sand cliff. Refuse was placed in this pit (Fig. 1). Because of poor construction records, it is not clear if a continuous clay barrier was installed between the refuse and the residential area.

Construction and filling of the landfill began in 1974. As refuse was collected, a 20-mil PVC liner was installed until an area of 29 ac was covered. There were several documented leachate spills prior to com-



NOTE:

* - Concentrations Representative Of Total Volatile Organic Priority Pollutants.

Figure 1
Conceptual Block Diagram of Contaminant Transport

pletion of the liner. Approximately 260,000 tons of municipal and construction debris were disposed of each year until the landfill ceased operation in 1981. There also were undocumented reports of illegal dumping and drum disposal in the landfill. Refuse is still received in an active fill area adjacent to the inactive landfill.

During the winters of 1979-1981, small explosions (furnace "puff-backs") occurred in several homes in the residential area. Air monitoring by the local fire department and the department of health revealed that methane levels exceeded the lower explosive limit (LEL) in several homes as well as the subsurface. Other gases, including vinyl chloride, benzene, toluene and tetrachloroethene, also were detected in homes. In 1981, a passive gas venting system was installed around the periphery of the landfill. Soon after, additional vents were installed and blowers were attached to create an active gas extraction system for the landfill. Also in 1981, volatile organic contaminants were detected in the upgradient municipal supply well located in the adjacent neighborhood (Fig. 1). The municipal well was closed because of this contamination.

Current operations at the inactive landfill include a gas extraction system (active system) consisting of stainless steel and PVC active vents

(located around the periphery of the landfill) attached to a manifold blower system. Gases are pumped to a horizontal combustion unit for destruction. There is also a passive gas venting system consisting of PVC vents around the periphery of the landfill and large concrete cisterns (passive vents) throughout the fill. A leachate collection system was installed in 1976, and leachate is collected and aerated at the base of the inactive landfill before being pumped to a POTW. This landfill is not capped, and rainfall entering the fill, generates significant quantities of leachate.

The understanding of contamination prior to initiation of field activities indicated that if the landfill were to be the source of upgradient groundwater contamination at the municipal well, then there would have to have been a transport mechanism that could account for the organic contaminants alone (i.e., without inorganic contaminants). Because of the gas contamination which had occurred in the subsurface surrounding the fill, it was suspected that contamination existing in the gas phase was contributing to contamination detected in the groundwater.

FIELD PROGRAM DESIGN AND IMPLEMENTATION

The sampling program was designed to evaluate the nature and extent of contamination and to evaluate the source/receptor pathway for the contamination detected off-site. Historically, methane and volatile organic vapors (such as vinyl chloride and tetrachloroethene) had been detected off-site. The installation of the gas venting system at the landfill had reduced significantly off-site migration of methane gas, but trace concentrations of volatile organics continued to be detected in subsurface wells designed to monitor the effectiveness of the gas venting system. The quality of groundwater hydraulically upgradient of the landfill had not been characterized except for the historic detection of volatile organics at the municipal well and at monitoring wells directly adjacent to the landfill.

Prior to the start of the field investigation, various contamination sources and pathways were considered for evaluation. These pathways included discharge of leachate to the groundwater (although the lack of inorganic contaminants at the upgradient municipal well limited this hypothesis), gas to soil to groundwater partitioning of organic contaminants in the subsurface, condensation of gas phase contaminants when warm moist air from the landfill encountered cooler ambient soil, and direct gas to groundwater partitioning when rainfall percolated through the vapors in the subsurface surrounding the landfill.

The field investigation set out to first, fill in the data gaps for both the groundwater and the subsurface gas, and second, to assess whether the landfill was the source of upgradient groundwater contamination. The effort to supplement the existing groundwater data included the installation of an extensive groundwater monitoring well network, the sampling of new and existing groundwater wells, and the performance of hydraulic permeability and pump tests. In order to address the subsurface gas data gaps, additional, multi-level gas monitoring wells were installed off-site, and samples of the subsurface gas were collected from the new and existing gas wells. Finally, an assessment of the effectiveness of the landfill gas extraction system was performed, and samples were collected to determine the emission rate of volatile organic compounds (VOC) through the surface of the landfill. The results from the groundwater, subsurface gas and landfill assessment investigations were compared to address whether the landfill was the source of upgradient, groundwater contamination.

Groundwater Investigation

Groundwater monitoring wells were installed upgradient of the landfill between the fill and the contaminated municipal well and at background locations. Additional wells were installed hydraulically downgradient of the landfill to determine if additional contamination existed at downgradient locations and to compare contamination patterns. The monitoring wells were installed in the Upper Glacial formation with several clusters which included wells screened in the Magothy formation.

Two rounds of groundwater samples were collected to coincide with two of the seasonal subsurface gas sampling events. The basic contami-

nation pattern indicated a significant plume of volatile organic contaminants (total VOC concentrations > 500 mg/L) associated with the monitoring wells just upgradient of the landfill. Lower concentrations of these contaminants were detected in wells further upgradient from the landfill, closer to the municipal well. Contamination was not detected when the municipal well was sampled. However, the well had been off line for over 6 yr.

Groundwater contamination was also detected downgradient of the landfill. In comparison, this contamination was similar to that which might result from leachate contamination. Downgradient groundwater contained not only some VOCs, but also various semi-volatile and inorganic compounds. Contamination was detected at much lower concentrations (generally < 10 mg/L for a few individual volatile and semi-volatile organic contaminants). The inorganic compounds were detected at proportions very similar to the leachate collected from the landfill. However, many more organic contaminants were detected in the leachate than in the downgradient groundwater.

The results of earlier pump tests which had been performed on the closed municipal supply well indicated that the zone of capture of this well extended well under the inactive cell of the landfill during both summer (maximum) and winter (minimum) pumping conditions. The pattern of contamination observed during groundwater sampling (highest groundwater contamination closest to the landfill, with decreasing concentrations with distance from the landfill) led to the conclusion that the landfill was the likely source of upgradient contamination. Comparison to observed downgradient concentrations indicated that upgradient contamination probably was not the result of leachate migration. Also, the known historical pattern of contamination indicated that concentrations and types of contaminants did not result from leachate.

Subsurface gas investigation

The focus of the RI into the subsurface, vapor phase contamination was to define the nature, degree and extent of this contamination within the unsaturated zone off-site and to determine whether this was inter-related with the groundwater contamination problem.

In an effort to define the nature, degree and extent of the vapor contamination problem, a complex gas monitoring well network and sampling plan was devised. The goals of this approach were: (1) to determine whether subsurface vapor contamination was related to landfill generated gases in terms of composition and concentration, and (2) to evaluate the potential for landfill generated gases to migrate from the landfill to the vadose zone off-site, by performing a mass balance approach on the landfill and by analyzing the effectiveness of the existing gas migration control system.

At the initiation, and during the course of the study, several conceptual pathways were identified to explain the observed patterns of contamination in off-site gas and groundwater. Several of these pathways included vapor phase contamination from the landfill affecting concentrations of organic contaminants in groundwater. It was recognized that the result of the study would probably indicate that a combination of pathways was acting. The conceptual pathways are outlined as follows:

1. Gas-Water Partitioning:

Relationships for vapor-liquid equilibrium for dilute aqueous solutions are very well defined and are governed by Henry's law, which states:

$$p = Hx$$

where p = partial pressure of a substance at a given temperature (T) and pressure (P)

H = the Henry's law constant at a given T and P,

x = the liquid phase concentration at a given T and P

Therefore, Henry's law defines the distribution of a substance between the vapor and liquid phases for a system in equilibrium. If we assume that gases within the subsurface are in equilibrium with infiltrating rainwater, then Henry's law defines a pathway for the transport of vapor phase contaminants to the groundwater.

2. Gas-Soil-Water Partitioning

Several researchers^{1,2} have studied the sorptive characteristics of soils for volatile organic compounds (VOCs) under conditions

representative of the saturated and unsaturated (or vadose) zones. These studies have shown the soil-vapor partition coefficients to significantly differ such that the soil-vapor partition coefficient (soil concentration to vapor concentration) is orders of magnitudes greater in unsaturated conditions rather than saturated. Thus, gas partitioning to the solid/soil phase, with subsequent partitioning to the liquid phase from infiltrating rainwater could be a significant mechanism.

3. Direct or Indirect Landfill Condensate Discharge

Gases generated within a landfill carry large quantities of water, along with any primary gases or trace contaminants. In fact, gases within a landfill are saturated (relative humidity of 100%) with landfill temperatures ranging from 80 to 140°F. Due to this high moisture content, condensate traps are standard requirements for all landfill gas extraction systems. The condensate formed when these warm, moisture-saturated gases are extracted to cooler surroundings usually contains high concentrations of VOCs, and, in fact, can form a free organic phase.³ Due to a poorly designed manifold system between active wells at this site, it was observed that condensate from extraction vents within the landfill could collect in the headers and then drain into active vents external to the landfill and into native soil. Additionally, it was theorized that indirect discharge could result from condensate forming as moisture laden landfill gas migrated from the warm landfill (80 to 140°F) into the vadose zone off-site where subsurface temperatures dropped to approximately 50°F.

The subsurface gas field investigation was designed to test all the pathways contributing to the contamination, except for the discharge of leachate, and included several different field activities. The activities are described in the following paragraphs.

Monitoring Well Network Installation

To define the nature, degree and extent of off-site, subsurface gas contamination by VOCs, a monitoring well network using multilevel, nested, subsurface gas monitoring wells (denoted landfill gas wells or LFG wells) was installed. The purpose of the wells was to determine the lateral and vertical (with depth) distribution of vapor phase contaminants. Typical well construction for the LFG wells is shown in Figure 2. The wells contained four probes (labeled A through D) set at approximately equidistant intervals. The probes were 0.5-in. O.D. virgin Teflon-TFE tubing with the bottom 5 ft perforated with 0.25-in. holes. Each perforated section (designated as the probe section) was screened in a 15-ft zone of #1 moire gravel and isolated from the other probes by a 2- to 5-ft layer of bentonite/cement slurry. Each well was installed using hollow-stem auger drilling techniques.

The LFG wells were placed both to supplement existing LFG wells and to complement new and existing groundwater wells (Figures 3a and 3b). During installation of the LFG wells, soil samples were collected in specially designed split-spoon sampler liners to evaluate the vapor-soil-water contaminant pathway. The samples were collected in two foot intervals to correspond to the intervals in which the gas monitoring probes would be set. The intervals were generally 20-22, 50-52, 100-102, and 120-122 below grade. The soil samples were collected in decontaminated stainless steel sleeves inserted into 2¹/₂ split spoon samplers. The ends of the samples were covered with air tight plastic caps and Teflon inserts. This method minimized volatilization of soil contaminants.

Sampling of the LFG Wells

A large amount of landfill gas monitoring data had been collected from the site before the initiation of the RI. This included an investigation by U.S. EPA's FIT team and monthly sampling of existing landfill gas wells by the local municipality. However, up to this point most of the gas sampling data lacked the quality to withstand litigation. For this and other technical reasons (including a need to cover a wide range of concentrations, the affects of humidity on sorbent traps and analytical reproducibility) SUMMA canisters were chosen as the method of sampling.

SUMMA canisters are stainless steel canisters with a specially passivated internal surface (passivated by the SUMMA process) that makes

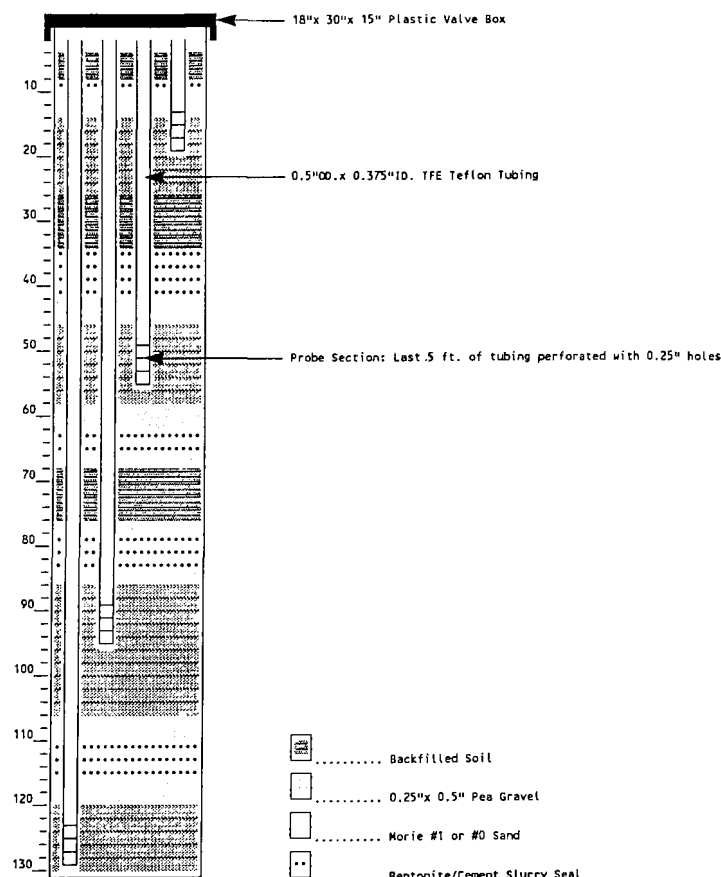


Figure 2
Typical EPA LFG Well Construction

them inert to the adsorption, desorption and degradation of VOCs. Although, the SUMMA technology is relatively new, U.S. EPA-RTP has tested the stability of VOCs within the canisters^{4,5} and has had success using them in ambient air studies. It appears that U.S. EPA may eventually support SUMMA canisters as the recommended method for air and vapor sampling for VOCs, replacing EPA draft methods TO-1 and TO-2.

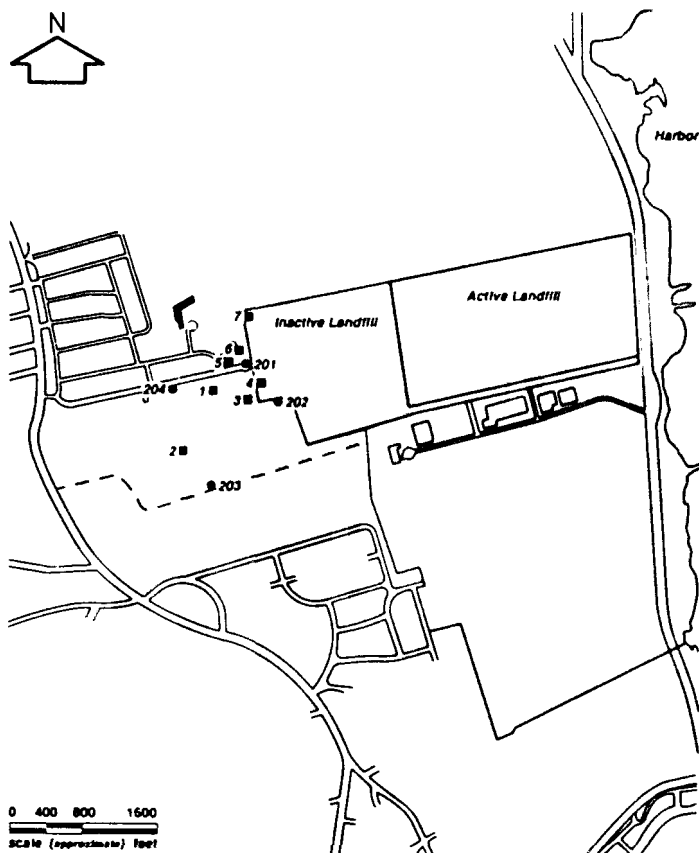
At the time of the field investigation, several methods for the analysis of gas/air samples from SUMMA canisters had been developed,^{6,7} but the U.S. EPA's draft method TO-14 (for the analysis of VOCs from SUMMA canisters) was still under preparation. A modified version of water method 624 (GC/MS), where the gas from the canisters was passed through a sorbent trap and then desorbed to the GC/MS system, was applied and proved to be very successful.

Four rounds of LFG well sampling were performed, one in each season, in an attempt to measure seasonal effects on the concentrations of VOCs within the subsurface off-site. Additionally the LFG well sampling events were performed concurrently with the four rounds of landfill surface emission rate sampling and the two synoptic rounds of groundwater sampling.

Landfill Assessment

In order to assess the potential for landfill-generated gases to migrate from within the landfill to the unsaturated zone off-site, and to provide a basis for selection of remedial alternatives for the FS, an assessment of the effectiveness of the existing landfill gas migration control system (or gas extraction system) was performed. This assessment of the gas extraction system involved the following activities:

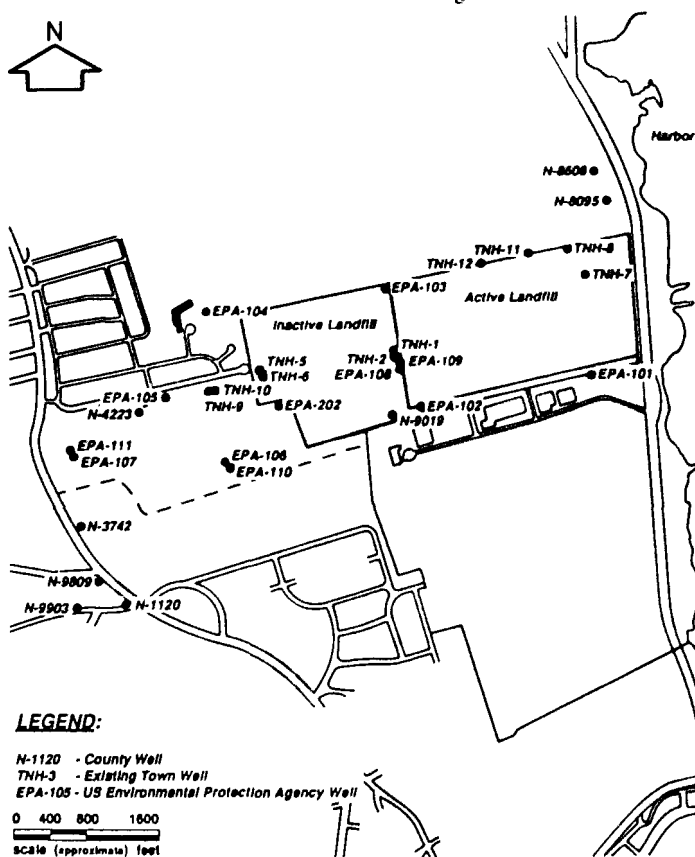
- The installation of multi-level, nested, pressure-probe wells at radial distances from a representative extraction vent. These probes, when monitored under the varying conditions of the vent testing, would provide an estimate of the sphere of influence for the extraction wells



LEGEND:

- - Represents The Seven TNH Off-Site Landfill Gas Monitoring Wells (1-7)
- - Represents The Four EPA On-Site Landfill Gas Monitoring Wells (201-204)

Figure 3a
Location of Landfill Gas Monitoring Wells



LEGEND:

- N-1120 - County Well
- TNH-3 - Existing Town Well
- EPA-105 - US Environmental Protection Agency Well

Figure 3b

Location of Groundwater Monitoring Wells

- and thereby determine the proper well spacing within the refuse;⁴⁹
- The collection of extraction vent gas samples for primary gas (O_2 , CO_2 , N_2 , CH_4) analysis and for VOC analysis and the measurement of well head vacuums, flow rates and methane contents under conditions of varying applied vacuum;
- An examination of the physical condition of the extraction system including the measurement of water and sediment levels in extraction vents;
- Sampling of condensate collected within the extraction system manifold for VOCs.

Also, under the heading of the landfill assessment, but concurrent with the LFG well sampling, samples of the gas venting through the landfill surface were collected using specially designed flux isolation chambers (flux boxes). The flux boxes were adapted versions of those used by Radian and the U.S. EPA⁵⁰. The purpose of these samples was to quantify emission rates from the landfill to the ambient for use in the public health evaluation (PHE) for the RI.

Other studies have suggested that surface flux emission rates along with data from pressure probes and vent tests could be used to perform a mass balance analysis on a landfill⁵¹. This approach was examined during the RI to see if it could be used to determine estimated quantities of gas migrating off-site.

The general approach for performing a landfill gas mass balance analysis on a landfill involves estimating or measuring each stream leaving the landfill and estimating an overall emission rate. Consider a control volume around the landfill, which identifies each of the following four streams exiting this particular landfill:

- Migration out of the landfill into the subsurface off-site
- Gas removed via the active gas extraction vents
- Gas emitted from the passive venting plastic vents and concrete cistern vents
- Gas emitted through the surface (soil cover) of the landfill

By estimating the gas production rate, P , and measuring streams 2, 3 and 4, one can determine the quantity of gas migrating into the subsurface off-site. However, it was determined in the study that because an overall gas production rate and an overall surface emission rate are both gross figures, from measured point samples, and due to the large heterogeneity in trace gas compositions (of VOCs) at any point within or at the surface of the landfill, the mass balance approach lacks the accuracy and precision required for the RI.

RESULTS OF THE LANDFILL GAS INVESTIGATION

Landfill Gas Well Investigation and Sampling

Table 1 contains data on the concentrations of VOCs detected in the LFG wells during three rounds of sampling and compares them with the results from neighboring groundwater wells. Although it is not shown on this table, only three (probes B, C, and D) of the four probes (A, B, C, and D) from the U.S. EPA wells were sampled. The shallowest probe (probe A) showed no observable variation from the barometric pressure, and was assumed to be in good hydraulic connection with the atmosphere. Generally, the medium (C) and deep (D) probes for all the LFG wells consistently exhibited the greatest number of contaminants and the higher concentrations. However, some of the detections from the B probe exhibited the highest concentration for a particular contaminant. Nine VOCs were identified as the major contaminants in the off-site, subsurface gas based upon their frequency of detection and also their presence in the groundwater:

- 1,2-Dichloroethane
- Trichloroethene
- 1,1,1-Trichloroethane
- 1,1-Dichloroethene
- Tetrachloroethene
- Chloroform
- 1,2-Dichloroethene (total cis/trans)
- Vinyl Chloride
- 1,2-Dichloroethane

Except for chloroform, each of these contaminants also was present

The soil samples collected during the installation of the LFG wells indicated the presence in the groundwater of very few VOCs (TCE, toluene and 2-butanone) each estimated at 10 mg/L or less (Table 4). Based upon these results, there does not appear to be a significant degree of partitioning to the soil phase.

Landfill Assessment

Results from the landfill assessment consisted of data and samples collected during the flux box emission rate sampling, vent testing, and condensate sampling events. The analytical results for the flux box and condensate samples are shown in Tables 2a/2b and 5 respectively. The system performance data recorded during the vent testing (for use in the FS Alternatives analysis) are not necessarily pertinent to this paper and therefore are not presented.

The primary purpose of the landfill assessment was to evaluate the effectiveness of the landfill gas extraction system and determine whether gases were migrating from the landfill to the subsurface off-site. At the time of the vent testing program, the landfill gas extraction system had fallen into disrepair. Numerous sections of the extraction manifold piping were blocked by collected condensate (which caused surging) the extraction blowers were operating below design capacity and the entire system was operated 8-12 hrs out of every 24 hr day. Additionally, methane was found in 1 of the LFG wells at concentrations up to 3% of the lower explosive limit (LEL) and in another well at up to 100% of the LEL. Due to the fact that the vent testing could not be performed

Table 1
Correlation Between Detected Landfill Gas and
Groundwater Contamination

COUPLET		OBSERVED CONCENTRATIONS					
GROUND WATER MONITORING WELL	LANDFILL GAS WELL	CONTAMINANT	GROUND WATER (ug/l)		VAPOR PHASE (ppbv) *		
			RND 1	RND 2	RND 1	RND 2	RND 3
EPA 106	EPA 203	1,1-Dichloroethene			25	12	13
		Trichloroethene				9	5
		1,1,1-Trichloroethene			198	90	73
		1,1-Dichloroethene	6 J				6
		Tetrachloroethene	6 J		478	105	121
		Chloroform				1 J	3
		1,2-Dichloroethene (total)				4	
		Vinyl Chloride					
		1,2-Dichloroethene					
EPA 105	EPA 204	1,1-Dichloroethene					
		Trichloroethene					
		1,1,1-Trichloroethene	2 J		79	46	22
		1,1-Dichloroethene					
		Tetrachloroethene	3 J		131	75	63
		Chloroform				4	3
		1,2-Dichloroethene (total)					
		Vinyl Chloride					
		1,2-Dichloroethene					
EPA 104	TNH LFG7	1,1-Dichloroethene		2 J		54	26
		Trichloroethene					
		1,1,1-Trichloroethene	2 J	5 J	152	692	252
		1,1-Dichloroethene				1 J	9
		Tetrachloroethene	1 J	5 J		8	7
		Chloroform					
		1,2-Dichloroethene (total)		9 J			
		Vinyl Chloride					
		1,2-Dichloroethene				30	
TNH 10/9 **	TNH LFG1	1,1-Dichloroethene	52	33		27	26
		Trichloroethene	12	14		5	3
		1,1,1-Trichloroethene	184	34		83	87
		1,1-Dichloroethene	7	9		2	3
		Tetrachloroethene	39	22		101	116
		Chloroform	3		2 J	2	
		1,2-Dichloroethene (total)	65	35		17	
		Vinyl Chloride	11	7			
		1,2-Dichloroethene					
TNH 6	TNH LFG4	1,1-Dichloroethene	117	100			
		Trichloroethene	20	18			
		1,1,1-Trichloroethene	106	91			22
		1,1-Dichloroethene	9	13			1
		Tetrachloroethene	67	46		20	6
		Chloroform					
		1,2-Dichloroethene (total)		230			1
		Vinyl Chloride	19	42		6	
		1,2-Dichloroethene					
EPA 202	EPA 202	1,1-Dichloroethene	4 J	5	385	326	138
		Trichloroethene			119	34	14
		1,1,1-Trichloroethene	14	27	612	310	147
		1,1-Dichloroethene		1 J		31	19
		Tetrachloroethene	10	32	614	292	116
		Chloroform				1 J	3
		1,2-Dichloroethene (total)		2 J	2 J	68	
		Vinyl Chloride					
		1,2-Dichloroethene					

Notes: J - Estimated Value
 * - Reported value is highest detected at any of three probes sampled
 ** - Reported value for IWH 12/9 is geometric mean of concentrations measured for both monitoring wells

to its fullest extent (surging caused inaccurate flow and wellhead vacuum measurements and the applied vacuum could not be varied) and the detection of elevated levels of methane off-site verified the ineffectiveness of the extraction system, in its current condition, the vent testing program was terminated early. Interpretation of the results from this abbreviated testing indicated that landfill gas was migrating from the landfill to the subsurface off-site.

The flux box sampling results were only used for the Public Health

Table 2a
Flux Box Analytical Results (Round 2)

Sample Location	F0401	F0402	F0403	F0404	F0405	F0406	F0408	F0407	F0409	F0408	F0409	F0405	F0407	F0410	Blank	Con Vert	PL Vert
Sample Number	Spt1	Spt1	Spt6	Spt4	Spt6	Spt3	DSD	Spt6	DSD	Spt1	Spt1	Spt1	Spt1	Spt1	Spt1	Spt1	Spt1
Chloromethane	7 U	3 U	7 U	6 U	6 U	15 U	10 W	180 U	U	7 U	6 U	7 U	4 U	4 U	7 U	7 U	8 U
Bromomethane	4 U	4 U	4 U	3 U	3 U	4 U	7 U	6 U	100 U	4 U	3 U	4 U	4 U	4 U	4 U	4 U	4 U
Vinyl Chloride	4 U	5 U	6 U	4 U	5 U	106 E	103	2080 E	6 U	5 U	6 U	6 U	6 U	6 U	5 U	6 U	6 U
Chloroethane	5 U	5 U	6 U	5 U	5 U	5 U	7 U	150 U	6 U	6 U	5 U	6 U	6 U	6 U	6 U	6 U	6 U
Methylene Chloride								5770 E							25	2 U	
Aceetone	Fep	Fep	Fep	Fep	Fep	Fep	Fep	3160 E	Fep	Fep	Fep	Fep	Fep	Fep	Fep	Fep	Fep
Carbon Dioxide	2 U	2 U	2 U	2 U	2 U	2 U	2 U	62 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
1,1-Dichloroethene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	26 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
1,1-Dichloropropane	2 U	2 U	2 U	2 U	2 U	2 U	2 U	1470 E	4 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Trans-1,2-Dichloroethene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	1500 E	4 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Chlorobenzene	1 U	1 U	1 U	1 U	1 U	1 U	1 U	2 U	407 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
1,2-Dichlorobenzene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	400 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
2-Butanone	Fep	Fep	Fep	Fep	Fep	Fep	Fep	2500 E	Fep	Fep	Fep	Fep	Fep	Fep	Fep	Fep	Fep
1,1,1-Trichloroethane	1 U	1 U	1 U	1 U	1 U	1 U	1 U	3 U	833 E	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
Carbon Tetrachloride	1 U	1 U	1 U	1 U	1 U	1 U	1 U	2 U	210 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
Vinyl Acetate	2 U	2 U	2 U	2 U	2 U	2 U	2 U	3 U	540 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Bromodichloromethane	1 U	1 U	1 U	1 U	1 U	1 U	1 U	2 U	397 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
1,2-Dichloropropane	2 U	2 U	2 U	2 U	2 U	2 U	2 U	140 E	429 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Trans-1,2-Dichloropropene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	437 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Trichloroethene	1 U	1 U	1 U	1 U	1 U	2 U	2 U	480 E	178 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
Dibromochloromethane	1 U	1 U	1 U	1 U	1 U	1 U	1 U	2 U	720 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
1,1,2-Trichloroethane	1 U	1 U	1 U	1 U	1 U	1 U	1 U	2 U	354 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
Benzene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	4 U	127 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Cis-1,3-Dichloropropene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	437 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
2-Chloroethylvinylether	2 U	2 U	2 U	2 U	2 U	2 U	2 U	3 U	452 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Bromobenzene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	1 U	182 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
4-Ethoxy-2-Pentanone	2 U	2 U	2 U	2 U	2 U	2 U	2 U	3 U	481 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Hexanone	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	481 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Tetachloroethene	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	3070 E	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
1,1,2,2-Tetrachloroethane	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	79 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U	1 U
Toluene	2 U	2 U	2 U	2 U	2 U	Fep	Fep	3 U	440 U	2 U	2 U	2 U	2 U	2 U	Fep	Fep	Fep
Chlorobenzene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	479 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Ethylbenzene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	479 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Styrene	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	462 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U	2 U
Triethylamine	2 U	2 U	2 U	2 U	2 U	2 U	2 U	3 U	725 U	2 U	2 U	2 U	2 U	2 U	71	2 U	2 U

(i) a replication comparison was analysed by (a) first (intercept) of the value of the

- indicates that the analyte was found in the blank
- indicates that the concentration of the analyte exceeded the calibration of the FS but

Table 2b
Flux Box Emission Rates (Round 2)

Compound	00	01	02	03	04	05	06	07	08	09	10
Vinyl Chloride						5.70 E-03	1.30 E-03				
Methylene Chloride							1.30 E-03				
Acetone							1.30 E-03				
1,1-Dichloroethane							2.01 E-04				
1,1-Dichloroethane						6.00 E-04	1.10 E-03				
trans 1,2-Dichloroethane						2.01 E-03	1.30 E-03				
Chloroform										1.01 E-02	
2-Butanone							1.30 E-03				
1,1,1-Trichloroethane						3.21 E-02	1.10 E-03				
1,2-Dichloropropane							1.30 E-03				
1,1,1-Trichloroethane						2.10 E-02	1.30 E-03				
1,1,1-Trichloroethane						2.10 E-02	1.30 E-03	1.30 E-03			
Chlorobenzene						1.30 E-02				3.21 E-02	
Chlorobenzene						6.00 E-04				1.30 E-02	
toluene (Field)										6.10 E-02	

1. Emission rate is 0.00 L/d

Flux rate is reported in kilograms per square meter per day

Emission rates are based upon standard conditions of 24°C temperature and 1.013 bar

Evaluation (PHE). Due to the high variability in on-site gas concentrations and emission rates, and the generally poor precision of overall surface emission rates and gas production rates, the mass balance analysis was not useful and was therefore not performed.

Interrelationship Between Groundwater and Gas Concentrations

Comparing the observed subsurface vapor concentrations with the observed groundwater concentrations shown in Table 1, we first concluded, does not appear to be a direct relationship between the vapor phase and groundwater concentrations of VOCs. However, if the data are compared using the Henry's Law relationship,¹² one sees that

much of the data are comparable, i.e., the calculated equilibrium water concentrations are close to the observed groundwater concentrations. Table 6 presents an example of this calculation.

Two notable exceptions to the close correlation are ground water wells TNH-6 and TNH 10/9 (wells 10 and 9 are a nested pair of wells at the same general location). These wells exhibited much higher concentrations than predicted according to the vapor phase concentrations. The explanation of the anomalies at these two wells may be several-fold. For instance, the ground water and vapor phase concentrations of VOCs near TNH 9 and 10 had been greater prior to the installation of the gas migration control system and when the public supply well was in operation (and drawing water from beneath the landfill). Since that time, the concentration of VOCs in the water from these two wells has been decreasing with time. The current groundwater concentrations may then be a result of residual contamination.

However, this trend noted above does not explain the results from TNH-6, which has remained relatively constant over time. In this instance, two explanations have been proposed. First, TNH LFG-4 usually does not measure representative subsurface gas concentrations due to the well's close proximity to two gas extraction vents (as a result, when the gas system is on, ambient air is drawn into the LFG monitoring well, thereby diluting the subsurface vapor concentrations). Second, it has been postulated that the consistently high concentrations at this well may be a result of the indirect discharge of concentrated condensate due to the change in temperature between the landfill and the surrounding soils.

CONCLUSIONS AND RECOMMENDATIONS

The results of the field investigation into the various sources of contamination from a municipal landfill not only provided a basis for completing the RI and FS, but also verified the applicability of and the

Table 3
Volatile Organic Analysis from On-Site Gas Vents

Compound	Active Vents				Passive Vents			
	Vent		Vent		Vent		Concrete	
	No. 103 (B0747)	No. 116 (B0742)	No. 116 (dup) (B0739)	No. 122 (B0732)	No. 2 (B0744)	Concrete Cistern (B0804)	Concrete Cistern (dup) (B0794)	Blower Inlet (B0734)
Vinyl chloride	51.5	19.9	27.5	5.34	642	343	348	71.0
Chloroform	1.58U	1.58U	1.30U	1.58U	1.58U	1.58U	1.58U	1.58U
Methylene chloride	1.46U	1.46U	1.87	1.46U	1.46U	3.29	2.95	13.7
1,1-dichloroethane	9.88	0.92U	0.76U	0.92U	20.7	7.64	7.78	12.9
1,1-dichloroethane	8.50	8.69	8.76	0.8U	325	13.3	12.6	32.0
1,2-dichloroethane	35.6	1.94	1.65	0.98U	5.14	1.87	1.75	8.63
Trans 1,2-dichloroethane	22.5	2.55	2.55	0.89U	9.28	19.0	19.4	24.5
Bromodichloromethane	1.55U	1.55U	1.27U	1.55U	1.55U	1.95U	1.55U	1.55U
Trichloroethane	16.9	2.20	1.86	1.27	38.2	6.48	6.00	21.5
1,1,2,2-tetrachloroethane	70.8	12.70	1.32U	29.4	1.6U	1.6U	1.6U	68.6
1,1,1-trichloroethane	1.31U	1.31U	1.08U	1.31U	13.6	1.31U	1.31U	3.29
Tetrachloroethane	67.2	5.69	5.98	1.78	53.6	18.2	17.4	59.8
Carbon tetrachloride	2.08U	2.08U	1.71U	2.08U	2.08U	2.08U	2.08U	2.08U
1,1,2-trichloroethane	4.58	1.52U	1.25U	1.52U	1.52U	1.52U	1.52U	4.09
Benzene	143	86.3	77.3	3.66	127	58.1	49.6	151
Chlorobenzene	151	123	113	3.06U	153	3.06U	60.8	160

NOTES:

U = Undetected at the detection limit shown.

All concentrations in parts per billion on a volume per volume basis.

Table 4
Analytical Results from Soil Samples Collected
During Installation of EPA LFG 201 to EPA LFG 204

Well No.	Sampling Interval Below Grade (ft)	Results	% Moisture Content
EPA LFG 201	20 to 24	No volatile organic compounds detected	15
	50 to 54	No volatile organic compounds detected	8
	100 to 104	No volatile organic compounds detected	14
	126 to 130	No volatile organic compounds detected	12
EPA LFG 202	29 to 34	Toluene detected at a concentration of 2J	13
	60 to 65	Toluene detected at a concentration of 5J	13
	90 to 95	No volatile organic compounds detected	15
	120 to 125	Tetrachloroethene detected at a concentration of 2J Toluene detected at a concentration of 2J	10
EPA LFG 203	10.5 to 15.5	No volatile organic compounds detected	9
	29.5 to 34.5	No volatile organic compounds detected	6
	92 to 97	No volatile organic compounds detected	10
	110 to 115	No volatile organic compounds detected	12
EPA LFG 204	15 to 20	No volatile organic compounds detected	15
	50 to 55	No volatile organic compounds detected	2
	90 to 95	No volatile organic compounds detected	2
	124 to 129	2-Butanone detected at a concentration of 10J	1

Notes:

All concentrations are reported in ug/kg.
J = Estimated concentration.

Table 5
Results of Condensate Sampling

Sample #	1	2	3	4	5	6	7				
	Field Blank			Trip Blank		BT 264					
Sample I.D.	BR 821	BT 257	BT 258	BT 259	BT 260	BT 261	BT 262	BT 263	Dup	BT 265	BT 266
<hr/>											
Compound											
Chloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bromomethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Vinyl chloride	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Methylene Chloride	ND	ND	ND	ND	ND	2 J	ND	ND	ND	ND	ND
Acetone	15,000	2,900 J	ND	ND	560	ND	630	2,100 J	2,900	11,000	12,000
Carbon Disulfide	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-Dichloroethene (total)	ND	ND	24	ND	21 J	ND	47	64 J	49	ND	ND
Chloroform	ND	ND	ND	ND	ND	4 J	ND	ND	ND	ND	ND
1,2-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2-Butanone	4,600 J	1,600 J	FQA	FQA	87 J	FQA	200 J	ND	79 J	3,400 J	3,200 J
1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	160 J	ND	ND	ND
Carbon Tetrachloride	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Vinyl Acetate	FQA	ND	ND	ND	FQA	ND	FQA	ND	FQA	FQA	FQA
Bromodichloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-Dichloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
cis-1,3-Dichloropropene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Trichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibromochloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzene	ND	ND	5	ND	ND	ND	20 J	ND	ND	ND	ND
trans-1,3-Dichloropropene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bromoform	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4-Methyl-2-pentanone	ND	ND	35	ND	ND	ND	61	ND	ND	ND	ND
2-Hexanone	ND	ND	11 J	ND	ND	ND	ND	ND	ND	ND	ND
Tetrachloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Toluene	ND	ND	12	ND	17 J	ND	45	ND	ND	ND	ND
Chlorobenzene	ND	ND	5	ND	ND	ND	ND	ND	16 J	ND	ND
Ethylbenzene	ND	ND	13	ND	ND	ND	44	ND	ND	ND	ND
Styrene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Xylene (total)	ND	ND	16	ND	ND	ND	54	ND	ND	ND	ND

ND Not Detected.
FQA Failed Quality Assurance.
J Estimated Value.

success in using several new and innovative monitoring and sampling techniques.

As for the RI, the following conclusions could be made based upon the results of the investigation and upon historical data:

- Landfill generated gases containing trace constituents of VOCs have historically migrated and continue to migrate from the landfill into subsurface soils off-site
- The large degree of heterogeneity in landfill gas concentrations both on- and off-site make it difficult to positively prove, by a "fingerprint" comparison of relative VOC constituent concentrations, that off-site vapor contaminants originated from the landfill
- The presence of the same nine VOCs in samples of landfill gas, off-site subsurface gas and groundwater, plus the absence of leachate characteristics indicates that somehow VOC contaminants (possibly vapor borne) are being transferred to the groundwater upgradient of the landfill. Probable mechanisms for this interphase transport are from the combined action of indirect condensate discharge (through vapor condensation via a temperature change) and by vapor-to-liquid partitioning of VOCs to infiltrating rainwater
- Except for several anomalies and despite the large heterogeneity in both on- and off-site gas concentrations, comparison of groundwater and gas data generally support the vapor/infiltrating rainwater partitioning mechanism.

BT 264 is a duplicate sample of BT 263
BT 266 is a duplicate sample of BT 265
All concentrations are in (ug/l)

Table 6
Calculation of Equilibrium Water Concentrations

CONTAMINANT	Henry's Law		Round 1		Calculated		GAS CONCENTRATION		CALCULATED	
	Constant (12)		Equilib		Equilib		Round 2		EQUILIBRIUM WATER CONC	
	mol/L	18407	water conc		18407		176.7	176.7	EPA 252	EPA 252
	mol/L	(pphm)	(ppm)		(pphm)		(pphm)	(pphm)	(pphm)	(pphm)
1,1-Dichloroethane	0.107	490	20	54	27	326	7.15	5.07	12.00	
Trichloroethane	0.163	1100	45	5.7	5.7	34		0.17	5.78	
1,1,1-Trichloroethane	0.328	109	2	497	47	310	12.12	1.45	5.43	
1,1-Dichloroethane	0.348	355	3	1	2	31	0.91	0.02	0.26	
Tetrachloroethane	0.794	3370	62	62	101	292	1.51	2.45	7.00	
Chloroform	0.061			0	2	1	0.06	0.16	0.00	
Trans-1,2-Dichloroethane	0.101	6760	150		17	60		0.30	5.17	
Vinyl Chloride	0.634	20500	87							

Regarding sampling and monitoring techniques the following were successful applications of innovative technologies:

- Split-spoon liners were successfully employed to collect undisturbed soil samples for chemical analysis
- SUMMA canisters were demonstrated to be a viable technique for the collection of subsurface gas and landfill gas samples
- Nested probe design landfill gas monitoring wells were successfully used to monitor the migration of subsurface gas from a landfill

Further areas of research in the field of subsurface and landfill gas migration should include numerical modeling of migration in order to better predict the impact of subsurface gas sources, such as landfills, on surrounding areas.

REFERENCES

- Chion, C.T., Sharp, T.D. "Soil Sorption of Organic Vapors and Effects of Humidity on Sorptive Mechanism and Capacity," *Environ. Sci. Tech.*, 19 (12), pp. 1196-1200, 1985.
- Peterson, M.S., Lion, L.W., and Shoemaker, C.A. "Influence of Vapor-Phase Sorption and Diffusion on the Fate of Trichloroethylene in an Unsaturated Aquifer System," *Environ. Sci. Tech.*, 22, (5), pp. 571-577, 1988.
- Shuster, K.A., "Environmental Issues: Condensate," *Proc. of the GRCDA 7th International Landfill Gas Symposium*, pp. 139-142, GRCDA, Silver Spring, MD.
- Oliver, K.D., Pleil, J.D., and McClenny, W.A. "Sample Integrity of Trace Level Volatile Organic Compounds in Ambient Air Stored in SUMMA Polished Canisters," *Atmos. Environ* 20:p. 1403, 1986.
- Holdren, M.W. and Smith, D.L. "Stability of Volatile Organic compounds while stored in SUMMA Polished canisters," *Final Report, U.S. EPA Contract No. 68-02-4127*, Research Triangle Park, N.C., Battelle Columbus Laboratories, Columbus, OH, Jan., 1986.
- McClenny, W.A., Pleil, J.D., Holdren, J.W., and Smith, R.N. "Automated Cryogenic Preconcentration and Gas Chromatographic Determination of Volatile Organic Compounds," *Analytical Chemistry*, 56 (14), 1984.
- Dayton, D.P., and Rice, J., "Development and Evaluation of a Prototype Analytical System for Measuring Air Toxics," *Final Report*, Radian Corp. for the U.S. EPA, EMSL, Research Triangle Park, N.C., Nov. 1987.
- Lofy, R.J. "Study of Zones of Vacuum Influence Surrounding Landfill Gas Extraction Wells," *Argonne National Laboratory Rpt. No. ANL/CNSV-TM-113*, Argonne National Lab., Argonne, Ill., March 1982.
- Kunz, C.O. and Lu, A.H. "Methane Production Rate Studies and Gas Flow Modeling for the Fresh Kills Landfill," *Interim Report, N.Y. State Energy Research and Development Authority Rpt. No. 80-21*, N.Y. ERDA, Albany, N.Y., Nov. 1980.
- Klenbusch, M.R. "Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber," *U.S. EPA Rpt. No. EPA/600/8-86/008*, U.S. EPA, EMSL, Las Vegas, Nevada, Feb. 1986.
- Lytwyszyn, G.R., et al., "Landfill Methane Recovery Part II: Gas Characterization," *Final Report, Argonne National Laboratory Rpt. No. ANL/CNSV-TM-118*, Argonne National Lab., Argonne, Ill., Dec. 1982.
- Gossett, J.M. Measurement of Henry's Law Constants for C1 and C2 Chlorinated Hydrocarbons, *Environ. Sci. and Tech.*, 21, No. 2, 1987.

Use of Hydraulic Controls in an Aquifer Impacted By Tidal Forces

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ABSTRACT

The Wyckoff Company facility on Bainbridge Island occupies approximately 40 ac at the mouth of Eagle Harbor adjacent to Puget Sound in the state of Washington. The facility, which currently is used for log peeling, storage and shipping, had been used as a wood preserving and treating plant since the early 1900s. Contamination of soils and groundwater exist in the operations area comprising approximately 15 ac of the facility. Groundwater contamination exists in immiscible and miscible phases.

In 1987-1988, the U.S. EPA and Tetra Tech evaluated alternatives for dealing with identified contamination as part of an expedited response action. As part of that evaluation, a hydraulic barrier well system along the perimeter of the site was identified as the preferred means of addressing seepage of product and contaminated groundwater into Puget Sound.

The site is particularly complex because of the multi-phase nature of contaminants and very large tidal influences. Four pump tests, including monitoring of tidal responses, were performed to develop a better understanding of the site. Additional analysis based upon the results of the pump tests suggested that the hydraulic barrier well system would not be a viable option for the site. The proposed option is hydraulic control in the form of pumping from the central portion of the site where the majority of the contaminants occur and more modest pumping in shoreline areas where product is known to leave the site.

INTRODUCTION

The Wyckoff Company facility on Bainbridge Island occupies approximately 40 ac at the mouth of Eagle Harbor, adjacent to Puget Sound (Fig 1). The average ground surface elevation is approximately 10 ft above mean sea level (MSL). The ground surface is composed primarily of permeable fill, with some paved surfaces over operational areas of the site. The facility borders approximately 0.8 mi of shoreline along its eastern and northern edges. A bluff at the southern boundary of the facility ascends toward the island interior to an elevation exceeding 200 ft.¹²

The area of concern at the facility has been identified as the operations area which occupies approximately 15 ac in the northern portion of the facility. This 15 ac area of concern is referred to as the Wyckoff site.

Operations at the Wyckoff site included aromatic oil and creosote unloading and storage, chemical storage, wastewater treatment, untreated pole and pile storage, log rafting, log peeling, wood preserving, treated wood storage and shipping. The site currently is used for log peeling, storage and shipping.

The site had been used for wood-treating since about 1910⁵. The original wood-treating operation was constructed on a small peninsula

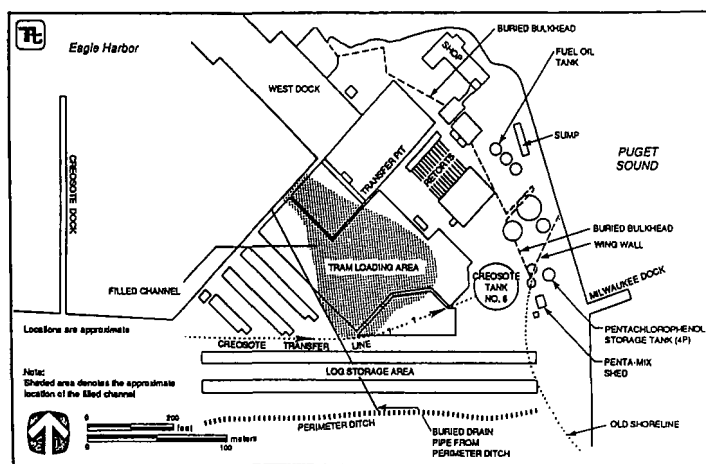


Figure 1
Site Map of the Wyckoff Bainbridge Island Facility¹²

formed by longshore currents in Puget Sound that pass across the mouth of Eagle Harbor. The area of the harbor between the peninsula and the shoreline of Bainbridge Island formed a cove which, before it was filled in the 1920s, was used as a untreated and treated log storage and shipping area.

Prior to 1929, the eastern and northern shoreline of the peninsula (facing Puget Sound) were protected from tides and wave erosion by a bulkhead located inshore of the present bulkhead. The site has undergone at least two major changes, once in the 1920s and again in the 1940s.⁶ A significant amount of fill has been added to the site, extending the shoreline into Eagle Harbor and Puget Sound.

Contamination at the site includes soil contamination, buried sludges and groundwater contamination. Chemicals of concern include Polycyclic Aromatic Hydrocarbons (PAH) and chlorinated phenols. Groundwater contamination exists in three phases at the site. A floating product phase exists with total PAH concentrations ranging from 6.9 to 36%. Groundwater at the site also shows soluble PAH concentrations ranging from less than 80 to 166,000 ug/L. Finally, sinking product identified in several wells at the site has shown total PAH concentrations ranging from 0.5 to 50%¹². Petroleum products seepage into Puget Sound from this site has been observed for at least 25 yr¹².

Expedited Response Action

In 1987-1988, the U.S. EPA and Tetra Tech conducted an evaluation of alternatives for dealing with identified contamination at the site as part of an expedited response action. As part of that evaluation, a

hydraulic barrier consisting of six wells spaced along the perimeter of the site was identified as the preferred means of addressing the seepage of product and contaminated groundwater into Puget Sound. The U.S. EPA and Wyckoff Company signed an Administrative Order on Consent in 1988 to perform this response action.

Prior to implementation, the practicality and effectiveness of a hydraulic barrier well system was re-evaluated. Among the major concerns were the estimated material properties for the site and the large tidal effects. The tidal water level fluctuation in Puget Sound can exceed 15 ft.

These concerns were initially addressed by numerical modeling and sensitivity analysis by Wyckoff's consultant, Hydrotechnique. The preliminary analyses indicated that the existing data were not sufficient to provide reasonable assurance of the effectiveness of a hydraulic barrier well system. Accordingly, four pump tests and additional analyses of a hydraulic barrier well system were performed. The better estimates of material properties derived from the pumping test and the results of the additional analyses indicated that the hydraulic barrier was not a viable option for the Eagle Harbor site.

This paper includes a discussion of the analysis of the four pump tests that were run at the site, analysis of the hydraulic barrier wells based upon the results of the pump tests and a discussion of proposed strategy for the site.

PUMP TESTS

The major factors complicating the performance and analysis of the pump tests were the large tidal effects and proximity of the ocean. The fluctuation in water levels due to tidal responses in the near-shore areas can actually be larger than the drawdowns that can be achieved by reasonable pumping rates in testing wells. The distances from the areas of interest to the shoreline are also comparatively small and the tests were therefore susceptible to irregular boundary conditions.

Methods

Four pumping tests were performed to estimate properties. Each test consisted of pumping out of one 8 in diameter pumping well and observing drawdowns in the pumping well and two to four 2-in diameter observation wells. The wells were 39 ft deep with screening from approximately 5 to 35 ft. Test durations ranged from 5 to 24 hr.

Tidal corrections were applied to both pre-test pumping and the long-term pumping tests at each of the four test locations. Water levels of the ocean and in available wells were monitored for a period of approximately 24 hr prior to pumping. Tidal correction factors based upon attenuation of the amplitude of water level fluctuation and phase

lags were determined from these data. The corrected data for each well were obtained by subtracting the estimated tidal influence from the uncorrected data for each well. Comparison of the estimated tidal influence at the well with the actual recorded water level in test well PW-2, shown in Figure 2, indicates good agreement.

Analysis of Pumping Test Data

Estimation of hydrologic properties for each test was performed on the basis of an unconfined model. Selection of the unconfined model was based upon comparison of data to unconfined, confined and leaky aquifer solutions. An analytic solution for analysis of pumping test data from an unconfined aquifer developed by Neuman¹⁹ was used for the analysis. The major assumptions include:

- The fluid is isothermal and single phase with constant viscosity and density
- The aquifer is homogeneous and its principal directions of hydraulic conductivity are oriented horizontally and vertically
- The aquifer overlies an impermeable horizontal layer and is of infinite lateral extent
- The well fully penetrates the aquifer and is of infinitesimal radius (i.e. no wellbore storage effects)
- No skin effects
- The initial drawdown in the aquifer is zero and a constant flow of rate Q is imposed at the wellbore at time $t = 0$

An inverse fitting technique was used to analyze the data from the four Eagle Harbor pumping tests. The governing equation was evaluated numerically with standard numerical integration schemes²⁰.

Analysis of the long-term pumping test data suggests that flow in the areas of the four tests occurs under unconfined conditions. This conclusion is consistent with observed geohydrologic conditions at the site. An example of drawdown versus time for an observation well associated with pumping well PW-1 located in the central portion of the site is shown in Figure 3. The horizontal hydraulic conductivities for the four tests ranged from 4×10^{-5} m/sec to 2×10^{-4} m/sec, respectively. Vertical hydraulic conductivities ranged from 5×10^{-5} m/sec to 2×10^{-4} m/sec. The storativities estimated ranged from 2×10^{-3} to 8×10^{-3} . The specific yields for the four tests range from approximately 0.1 to 0.3. Some uncertainty is associated with the specific yields because they were derived from the later portions of the various tests where the ocean boundary condition may be significant.

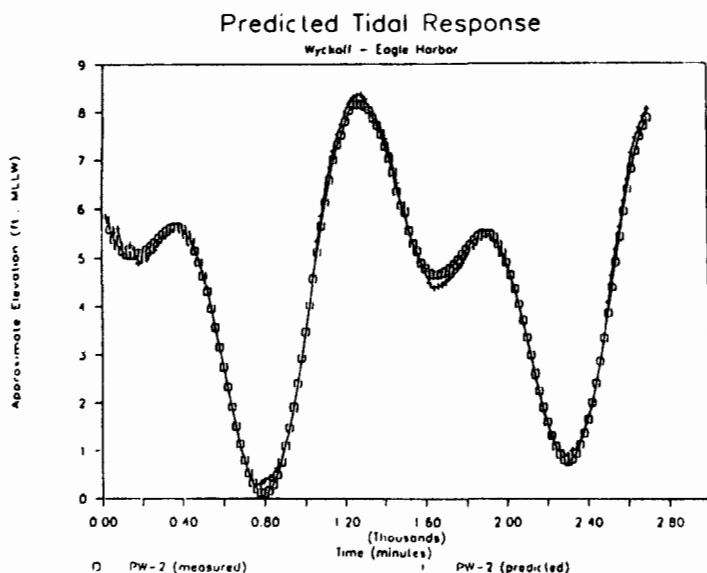


Figure 2
Observed and Predicted Water Level versus Time Data for
Eagle Harbor and Well PW-2¹¹

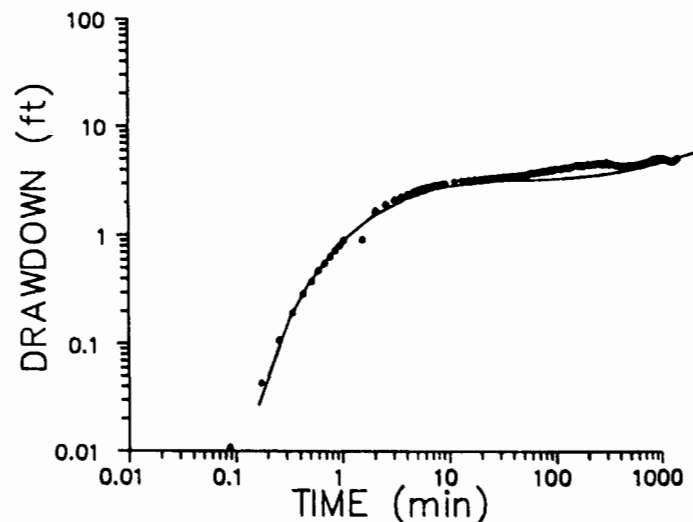


Figure 3
Drawdown versus Time for Observation Well OBI-1, Pumping Test 1
(Tidal Corrections Applied)²

ANALYSIS OF HYDRAULIC BARRIER WELL SYSTEM

The preliminary sensitivity analyses of the hydraulic barrier well system performed before the pumping tests, involved a numerical model

with pumping wells and time-varying boundary conditions. A simpler approximate model was used in the analyses described here. The numerical model was not used because the preliminary analyses suggested that the hydraulic barrier would not be viable for the types of material properties derived from the pumping tests; the numerical modeling suggested that the approximate model provided reasonable accuracy and the results of the approximate model would not be used for design of a hydraulic barrier well system.

The analytical model used for the analysis is based on combining two sub-models, namely a pumping well model and an ocean tide model. The pumping well model is used to analyze distributions of groundwater levels due to pumping. The ocean tide model is used to analyze distributions of groundwater levels resulting from response to the ocean tides. Because the governing equation and boundary conditions for groundwater flow in an unconfined aquifer can be approximated as linear⁹, the distributions of groundwater level at the site can be approximated by combining of groundwater levels predicted by the pumping well and ocean tide models.

To illustrate the performance of a hydraulic barrier well system, a pumping well located in the areas of Milwaukee Dock, shown in Figure 4, was considered where shoreline seeps are visible during the outgoing tide. The distances from the pumping well to the eastern, western and northern shorelines are approximately 30.5 m, 244 m and 213 m respectively. Because the eastern shore is much closer to the pumping well than the northern and western shores and the tidal response drops off exponentially with distance, the influences of the northern and western boundaries were ignored.

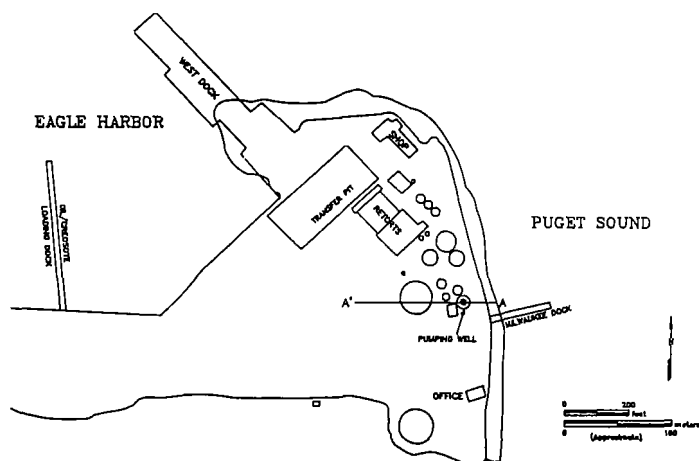


Figure 4

Location of Cross-section A'A for Hydraulic Barrier Well System Analysis.

Note that subsequent figures illustrating the models and results are presented with A on the left and A' on the right (i.e., AA' as opposed to A'A)³.

Pumping Well Model

In order to predict drawdowns in such a system, the method of images¹ was adopted. An imaginary infinite system, shown in Figure 5, was used. The system includes one real pumping well and one imaginary injection well. The distributions of water levels resulting from pumping and injection can be predicted by the unconfined aquifer solution presented by Neuman⁹. Tidal effects were considered by a tidal response model. The material properties used in the analysis were those derived from pumping tests.

Ocean Tide Model

In general, in an unconfined aquifer, fluctuation in groundwater levels in response to the ocean tide decreases with distance inland from the shoreline. Analysis of tidal influence on groundwater flow in the areas near the shoreline was approximated by solving a one-dimensional flow in a semi-infinite domain with a sinusoidal approximation of the ocean tide. The governing equation for the one-dimensional problem can be expressed as:

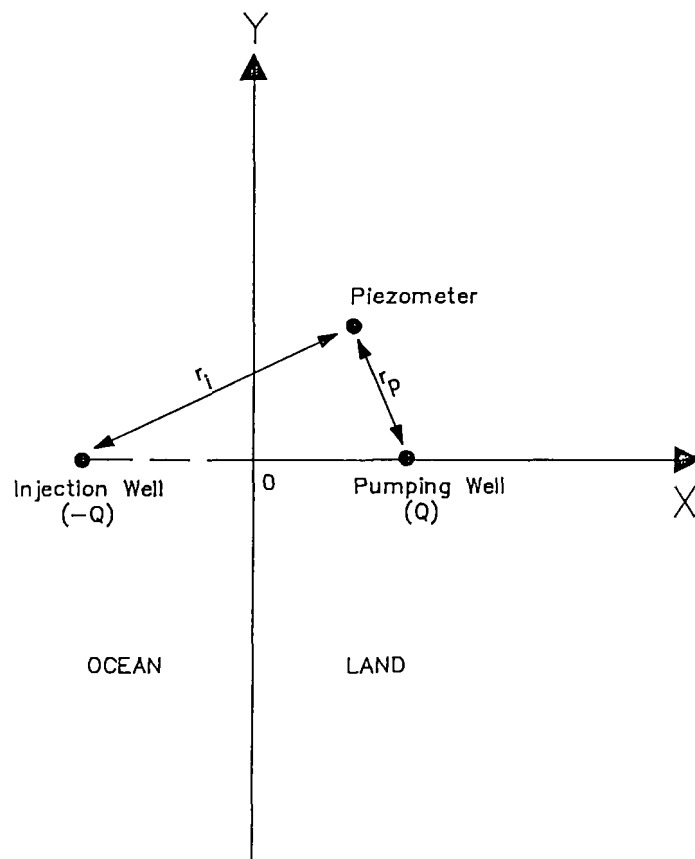


Figure 5
Schematic Representation of the Method of Images for the Pumping Well Model²

$$\frac{\partial^2 H}{\partial x^2} = \frac{S}{T} \frac{\partial H}{\partial t} \quad (1)$$

where

- H = water level with reference to the mean sea level
- x = distance inland from shoreline
- T = transmissivity; (K=b)
- S = effective storage coefficient
- t = time

To solve the above equation, it is assumed that the initial water level of the aquifer is zero (mean sea level) and that boundary conditions include $H = H_0 \sin 2\pi t/t_0$ at $x = 0$ (shoreline) and $H = 0$ at $x = \infty$, where t_0 is the tidal period. The steady periodic condition at the site was expressed as:^{4,13}

$$H = H_0 \exp [-x (\pi S/t_0 T)^{1/2}] \sin [2\pi t/t_0 - x(\pi S/t_0 T)^{1/2}] \quad (2)$$

In Equation 2, H_0 represents the amplitude of the ocean tide for the major tidal period, t_0 and T/S represents the average hydraulic diffusivity of the aquifer. To application of Equation 3 to the Wyckoff site, the value of T derived from the long-term pumping tests was used. S is derived by solving Equation 2 for S with field observations of tidal response to a 12 hr tide. Through this calibration process, it was found that the effective storativity S is on the order of 0.02.

The solution for the ocean tide is one-dimensional and for a confined aquifer situation. It was selected for simplicity. The approximation with the large storativity is stated by Todd¹³ to be reasonably good for an unconfined situation and the overall solution derived from combining the pumping and tidal influences to corresponded reasonably well with the results of the numerical model used in the preliminary sensitivity studies for the hydraulic barrier well system. The large storativity which was derived from calibration with field data can be viewed in a sense as a lumping of storativity and specific yield.

Figure 6 shows the range of groundwater fluctuation versus distance from shoreline predicted by Equation 2 with $T = 1.83 \times 10^{-3} \text{ m}^2/\text{sec}$, $S = 0.02$, $t_0 = 12 \text{ hr}$ and $H_0 = 1.68 \text{ m}$. Groundwater fluctuations shown in Figure 6 are reasonably consistent with those observed at the site, indicating that the model and the parameters used are appropriate for the site.

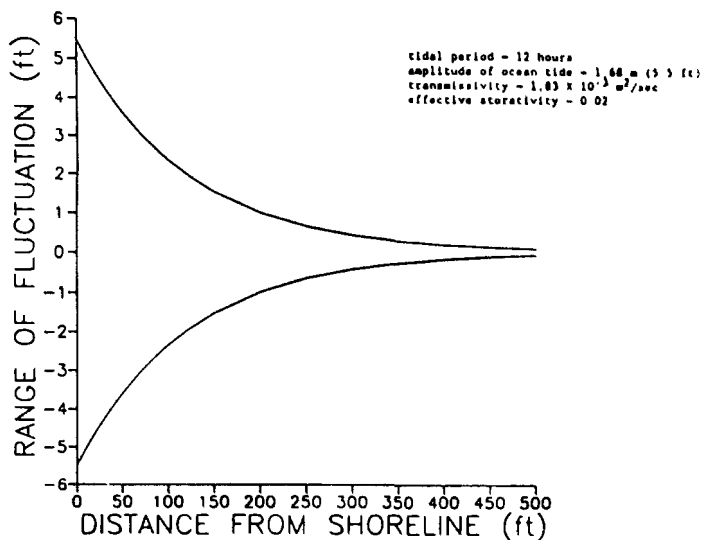
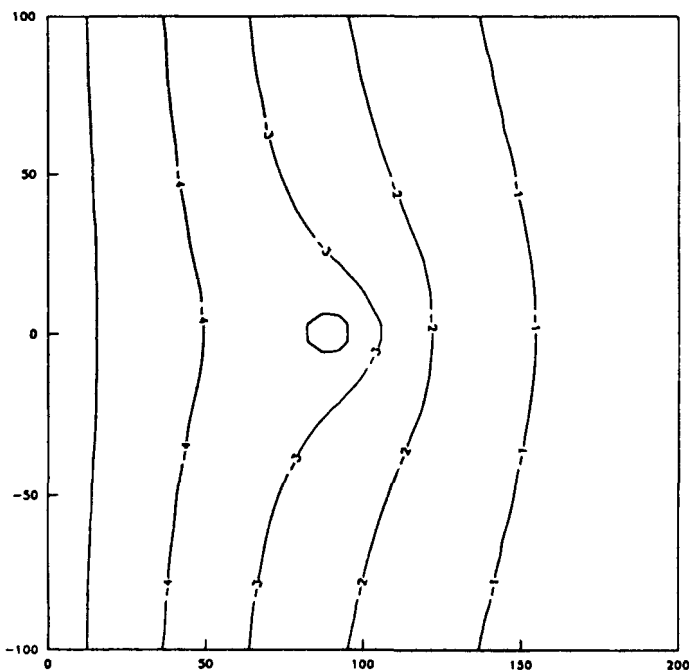


Figure 6
Range of Groundwater Level Response to Ocean Tides³

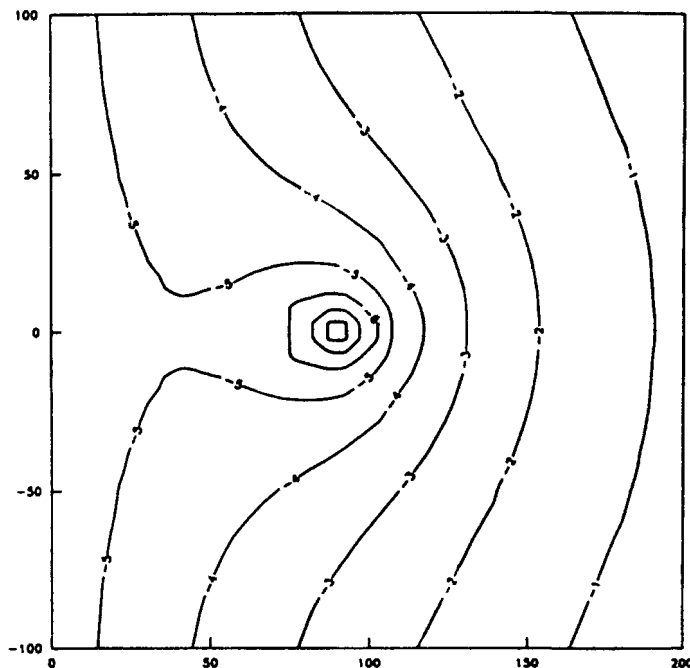


pumping rate - 40 gpm
 $K_r = 2 \times 10^{-4} \text{ m/sec}$
 $K_v = 2 \times 10^{-6} \text{ m/sec}$
 storativity - 2×10^{-3}
 specific yield - 0.1
 $b = 9.15 \text{ m (30 ft)}$
 pumping period - 6 hours
 tidal period - 12 hours
 amplitude of ocean tide - 1.68 m
 transmissivity - $1.83 \times 10^{-3} \text{ m}^2/\text{sec}$
 effective storativity - 0.02

Figure 7
Contour of Groundwater Levels at Low Tide Predicted by
Combination of Pumping Well and Ocean Tide Models
(Pumping of 40 gpm from a well, Case 1)³

Superposition of Models

Evaluation of a hydraulic barrier well system was made by combining of the pumping well and ocean tide models presented in the previous sections. For a scheduled pumping of 40 and 100 gpm from a well in the areas of Milwaukee Dock, distributions of groundwater level for low tide in these areas are shown in Figures 7 and 8, respectively. Figure 7 shows that the pumping rate of 40 gpm would not be sufficient to create a hydraulic barrier to movement of groundwater flow from the site to Puget Sound during the low tide period. At 100 gpm (Fig 8), the gradient between the well and the ocean is nearly reversed. The drawdowns illustrated in Figure 7 were in reasonable agreement with drawdowns observed during the pumping tests.



pumping rate - 100 gpm
 $K_r = 2 \times 10^{-4} \text{ m/sec}$
 $K_v = 2 \times 10^{-6} \text{ m/sec}$
 storativity - 2×10^{-3}
 specific yield - 0.1
 $b = 9.15 \text{ m (30 ft)}$
 pumping period - 6 hours
 tidal period - 12 hours
 amplitude of ocean tide - 1.68 m
 transmissivity - $1.83 \times 10^{-3} \text{ m}^2/\text{sec}$
 effective storativity - 0.02

Figure 8
Contour of Groundwater Levels at Low Tide Predicted by
Combination of Pumping Well and Ocean Tide Models
(Pumping of 100gpm from a well, Case 2)³

Evaluation of these results indicated that the well spacing required to form a continuous hydraulic barrier is approximately 15 m and 30 m. For the present purposes, a well spacing of 23 m is adopted. Because the perimeter 30 m inland from the shoreline of the site is on the order of 550 m, the number of wells required for the barrier system is approximately 24 wells, resulting in a very large total pumping rate of approximately 1,200 gpm (average over the full tidal cycle).

After reviewing this analysis and considering other potential problems discussed in the following section, the hydraulic barrier approach was abandoned in favor of the hydraulic control approach discussed below.

HYDRAULIC CONTROL STRATEGY

The major complexities at the Eagle Harbor Site are the very large tidal influences, multi-phase nature of the contaminants, existence of

multi-phase contaminants off-shore and nature of the expedited response action. As in the case of the hydraulic barrier well system, these factors suggest that immediate cessation of seepage off-shore or containment probably can not be practically achieved by implementation of reasonable physical barriers.

Because of their complex nature and lack of data, direct analyses of movement of contaminants at the site were not performed. Accurate estimates of movement of the floating, sinking and soluble phases in the heterogeneous, variably saturated media at the site would require a multi-phase numerical model. The lack of data such as relative conductivity and capillary pressure curves and 'retardation' data for various contaminants suggests that such an undertaking would not be justified.

It is known, however, that product, especially floating product, is significantly more abundant in the central portion of the site and that contaminated groundwater occurs in most portions of the site, but with higher concentrations in the central area and in the area of the old sump. There are three considerations: stopping off-shore seepage, removal of contaminants from the central portion of the site and prevention of movement of contaminants from the central area to the near-shore areas of the site.

It is likely that the central area is ultimately the major contributor to off-shore seepage. The central area likely remains significantly more contaminated than the near-shore areas not only because of the initial locations of spills, but also because net movement seaward associated with the regional gradient is far smaller than the cyclic landward-seaward movements of groundwater associated with the tides. Near-shore activities directed at immediate containment and stoppage of off-shore seeps will not address the overall problem and in the case of a very high pumping rate hydraulic barrier well system could potentially worsen the problem by accelerating the movement of contaminants from the central to near-shore portions of the site.

Given the logistic as well as technical problems associated with the hydraulic barrier, attention was directed at more modest near-shore pumping and direct control of the contaminated central portions of the site. The strategy that is described below is being developed in cooperation with Wyckoff's consultants (Hydrotechnique and Fahrenthold and Associates), the U.S. EPA, the Washington State Department of Ecology and the U.S. EPA's consultant (CH2M Hill).

There are two basic objectives. In the central portion of the site, the objective is control, in the sense of removal of contaminants and minimization of migration to near-shore areas. In the near-shore areas, the objective is to intercept product and soluble contaminants that are leaving the site because of the regional gradient and tidal influences. It would appear that the central portion of the site is more important to the long term solution, but that timeliness dictates that a large, immediate effort be directed at the near-shore areas.

There is general concern about movement of immiscible phases from more contaminated to less contaminated areas both horizontally and vertically. Movement of oil from a contaminated area through a clean area can result in residual saturation of oil in the originally clean area that will be very difficult to remove. The large drawdowns associated with very high pumping rates have the potential to pull a floating layer of product down through or laterally across a comparatively clean medium.

This finding suggests that contaminants should be attacked at their sources, but that initial pumping rates should be modest and caution should be exercised in near-shore areas. Given the uncertainties associated with movement, particularly of immiscible phases, a phased startup of pumping in the central portion and near-shore portions of the site is proposed. The first phase will include relatively low pumping rates from each of three wells located in the central portion of the site. Well startup will be staggered so that product thicknesses and concentrations of soluble contaminants in pumping and observation wells can be monitored. This monitoring will provide a better understanding of the movement of contaminants.

Because of the importance attached to stopping off-shore seepage, it is proposed that pumping in the near-shore areas be started as soon as the information derived from pumping the central portion suggests

that such pumping may be safely initiated. The proximity of the ocean will result in smaller drawdowns in the near-shore areas and in efficiency because most of the water ultimately will originate from the ocean. This has a negative impact on the area from which contaminants may be drawn but, on the positive side, lessens the possibility of drawing contaminants from the central portion of the site.

As in the case of the wells in the central portion of the site, the startup of wells in the near-shore area will be staggered and start at a comparatively low pumping rate. Given the importance attached to off-shore seepage and the expected small drawdowns, however, it is expected that pumping in the near-shore areas may be increased more rapidly than in the central portion of the site. Subject to findings during startup, the total pumping rates in the near-shore areas may exceed those in the central portion of the site. The near-shore extraction system will include four wells whose locations are based primarily upon areas where off-shore seepage is known to occur. The first well is northeast of the transfer pit. The second well is east of the retorts, and the third well is in the area of the Milwaukee Dock. An additional well is being added next to a recently installed monitoring well near the Milwaukee Dock where the most visible seeps are observed. The area is also farthest from the central area contamination and will be started first.

It is expected that the early phases of operation of the near-shore wells will provide a better understanding of movement of contaminants in this area of high tidal influence. This information will allow for final adjustment of pumping rates in these areas.

CONCLUSIONS

The large tidal effects and multi-phase nature of the contaminants at the Eagle Harbor site make it difficult to develop a definitive remediation strategy. Preliminary analyses suggest that direct containment by a hydraulic barrier well system is not a viable option for the site. The proposed source control and more modest pumping in the near-shore areas is believed to be a practical alternative. There is little question that such source control will, as a minimum, have a positive impact on conditions at the site. Monitoring early phases of pumping will help to provide the additional information that is necessary to more fully evaluate the system. Final analyses on the design of the system are presently underway.

REFERENCES

1. Bear, J., *Dynamics of Fluids in Porous Media*, Elsevier Publishing Co., New York, NY, 1972.
2. Berkeley Hydrotechnique, Inc., "Final Pump Test Report for Eagle Harbor Site—Analyses," Jan. 24, 1989.
3. Berkeley Hydrotechnique, Inc., "Groundwater Extraction System for the Wyckoff Eagle Harbor Site," Draft, June, 1989.
4. Carslaw, H.S. and Jaeger J.C., *Conduction of Heat in Solids, 2nd Edition*, Oxford University Press, 1959.
5. Entrix, Inc., "Data Report for the RCRA 3013 Investigation," Prepared for the Wyckoff Company, Eagle Harbor, 1986.
6. Joy, J., Memorandum: Eagle Harbor Facilities Tour and Historical Review. Washington Department of Ecology, Sept. 4, 1984.
7. Neuman, S.P., "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table," *Water Resources Res.*, 8, pp. 1031-1045, 1972.
8. Neuman, S.P., Supplementary Comments on "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table," *Water Resources Res.*, 9(4), 1102, 1973.
9. Neuman, S.P., "Analysis of Pumping Test Data from Anisotropic Unconfined Aquifers Considering Delayed Gravity Response," *Water Resources Res.*, 11, pp. 329-342, 1975.
10. Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T., *Numerical Recipes, the Art of Scientific Computing*, Cambridge University Press, Cambridge, 1986.
11. Struck, R.G. and Adams, M.A., "Final Pump Test Report Wyckoff Company Eagle Harbor Site - Data," Jan 24, 1989.
12. Tetra Tech, 'Assessment of Expedited Response Actions, Wyckoff Company-Bainbridge Island,' Feb 2, 1988.
13. Todd, D.K., *Groundwater Hydrology*, John Wiley & Sons, New York, NY, 1959.
14. U.S. EPA, Consent Order No. 1088-02-17-106, in the matter of Wyckoff Company, Eagle Harbor Facility, July 29, 1988.

A Review Of ULTROX®

Ultraviolet Oxidation Technology

As Applied To Industrial Groundwater, Wastewater And SUPERFUND Sites

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INTRODUCTION

Ultraviolet oxidation technology has had limited exposure to the various engineering disciplines despite having been commercialized almost 9 yr ago with the installation of an ULTROX® system at IBM in Boulder, Colorado. The application of this technology is steadily expanding, however, as it offers a means of solving many of the problems created by the toxic, water soluble organic chemicals that are found in groundwater, wastewaters, leachate and drinking water supplies.

More conventional or better known unit processes and operations such as liquid/solids separation, reverse osmosis, air stripping, biotreatment or granular activated carbon can remove many toxic organics from water. However, these methods may solve the one problem only to create a problem in another medium. Air stripping removes VOCs from water only to discharge them into the ambient air; reverse osmosis generates a reject stream of concentrated contaminants that must be dealt with; granular activated carbon requires either regeneration or burial; and liquid/solids separation obviously creates sludges requiring disposal.

Therefore, it is significant that UV/oxidation, when used in tandem with some of the above mentioned process, or as a stand alone treatment process, can effectively destroy or render non-toxic many of the organic chemicals found on the priority pollutant list.

Chemical oxidation without ultraviolet enhancement has been used in water treatment for a number of years. Potassium permanganate, chlorine and chlorine dioxide also have been used to treat solutions containing organics such as phenol, and hydrogen peroxide with a catalyst such as Fenton's Reagent has been used to oxidize phenol.

There is a need for more powerful oxidizing methods which do not produce hazardous by-products. This paper describes the experience of Ultrax International in applying ultraviolet/oxidation for the destruction of organic chemicals in wastewaters, drinking waters, leachates and groundwaters. The oxidants used in these applications are ozone (O_3) and hydrogen peroxide (H_2O_2). Ultrax International was issued a process patent in 1988 covering the application of UV light, ozone and hydrogen peroxide to a broad range of organic compounds. Excerpts from the company's patent application are shown in Table 1.

DESCRIPTION OF THE UV-OXIDATION PROCESS

Ultraviolet light, when combined with O_3 and/or H_2O_2 produces a highly oxidative environment significantly more destructive than that created with O_3 or H_2O_2 by themselves or in combination. UV light significantly enhances ozone or H_2O_2 reactivity by:

- Transformation of O_3 or H_2O_2 to highly reactive (OH) radicals
- Excitation of the target organic solute to a higher energy level
- Initial attack of the target organic by UV light

Table 1
Oxidation Results for Several Systems Treaty
Methylene Chloride and Methanol

TIME (MIN.)	CONTROL	UV	UV/ H_2O_2	O_3/H_2O_2	UV/ O_3	UV/ O_3/H_2O_2
0	100	100	100	100	100	100
15	100	59	46	32	36	19
25	100	42	17	21	16	7.6

OXIDATION OF METHANOL

TIME (MIN.)	CONTROL	UV	UV/ H_2O_2	UV/ O_3	UV/ O_3/H_2O_2
0	75	75	75	75	75
30	75	75	75	31	1.2

CONCENTRATIONS = mg/l

The importance of the conversion of the ozone or H_2O_2 to (OH) can be more easily understood after studying the relative oxidation power of different chemicals.

Species	Oxidation Potential Volts	Relative Oxidation Power*
Fluorine	3.06	2.25
Hydroxyl Radical	2.80	2.05
Atomic Oxygen	2.42	1.78
Ozone	2.07	1.52
Chlorine Dioxide	1.96	1.44
Hydrogen Peroxide	1.77	1.30
Perhydroxyl Radicals	1.70	1.25
Hypochlorous Acid	1.49	1.10
Chlorine	1.36	1.00

* Based on chlorine as reference (=1.00)

The design of the equipment in the ULTROX® system is based on the use of components which are highly reliable and require very little maintenance. These systems operate either in a continuous flow or batch mode. They utilize high efficiency UV lamps with a long life and a micro-processor to control and automate the process.

The ULTROX® UV-oxidation system consists of a UV-oxidation reactor and an oxidation source—an ozone generator with an air preparation system and/or a hydrogen peroxide feed system. Reactor volumes range from 75 to 5,000 gal treating up to 250 gpm.

The reactor is fabricated from stainless steel. The UV lamps are enclosed within quartz tubes for easy replacement and are mounted vertically within the reactor. Depending upon the size of the reactor and the type of water to be treated, the reactor can have four to eight stages. Lamps are installed either in all stages or in designated stages, depending upon the type of treatment specified.

When ozone is used as the oxidant, it is introduced at the base of the stage. The ozone is dispersed through porous stainless steel diffusers. The number of diffusers needed will depend upon the type of organics being oxidized and the degree of removal required. If hydrogen peroxide is substituted for ozone, it is directly metered into the influent line to the reactor.

Within the reactor, the water flows from stage to stage in a sinusoidal path using gravity flow. When the reactor uses ozone, the residual ozone in the off-gas is decomposed back to oxygen by the use of a fixed-bed catalytic unit operating at 150°F (66°C). The off-gas is then vented to the atmosphere with less than 0.1 ppmw O₃ (OSHA Standards).

APPLICATION OF UV-OXIDATION TO VARIOUS WATERS

The UV-oxidation equipment developed in the past few years can be used for a wide variety of waters. Table 2 shows compounds found in groundwaters and wastewaters that have been successfully treated with UV/oxidation.

Table 2

Common Industrial Effluents and Groundwater Contaminants

Amines	Methylene Chloride
Aniline	PCB's
Benzene	Pentachlorophenols
BIS (2-Chloroethylether)	Perchloroethylene
Chlorinated Solvents	Pesticides
Chlorobenzene	Phenol
Complex Cyanides	Polynitrophenols
Creosote	Polynuclear Aromatics (PAHs)
Dichloroethylene	RDX
Dioxins	1,1,TCA Tetrahydrofuran
Dioxanes	Trichloroethylene
Freon 113	TNT
Hydrazine Compounds	Toluene
Isopropanol	Triglycol diethyl ether
Methyl Ethyl Ketone	Polynitrophenols
Methyl Isobutyl Ketone	Vinyl Chloride

Table 3
Direct Operating & Maintenance Costs
for UV/Oxidation at Industrial Installations

TYPE OF WATER	CONTAMINANTS	CONTAMINANT CONCENTRATION	DISCHARGE TO	VOLUME TREATED PER DAY	DIRECT O&M COST RANGE
Wood Treating Wastewater	Pentachlorophenol and phenol	150 ppm	POTW 1000/gal	30,000	\$1.25-\$1.35/
Wood Treating Groundwater	Pentachlorophenol and phenol	5 ppm	POTW	86,400	\$0.90-\$1.00/1000 gal
Fume Scrubber Water	Hydrazine, Monomethylhydrazine, Unsymmetrical-dimethylhydrazine	5,000 ppm	Bioreatment Plant On-Site	600-1500	\$0.086/gal
Contaminated Groundwater	TCE, trans DCE, MeCl ₂	5 ppm	Surface Water	300,000	\$0.47/1000 gal
Contaminated Groundwater	TCE, TCA, DCA, PCE, MeCl ₂ , VCl	600 ppb	POTW	72,000	\$0.33/1000 gal
Contaminated Groundwater	THF	1ppm	Ground	216,000	\$0.39/1000 gal
Wastewater	Phenol	90 ppm	POTW	4,300	\$6.48/1000 gal
Drinking Water	PCE	15 ppb	Distribution System	4,300,000	\$0.15/1000 gal
Waste Water	Cyanides	5.0 ppm	POTW	75,000	\$2.25/1000

Table 3 reports direct O&M costs encountered at commercial projects treating industrial wastewater, groundwater and drinking water. Contaminants in these waters include phenols, chlorinated solvents, hydrazine, dimethylnitrosamine, tetrahydrofuran and formaldehyde. Commercial systems have been designed, built and installed to treat flows varying from 1,200 to 1,360,000 g pd.

Standard equipment designs are used in all of these installations. Reactor size varies from 300 to 4,800 gal. Ozone generators range from 21 to 150 lb/day. In several cases, hydrogen peroxide is used in place of or with ozone.

Before designing a treatment plant treatability studies are carried out in the laboratory using glassware equipment to determine the feasibility of treating the water with UV/O₃ or UV/H₂O₂.

If the results are encouraging, the next step in the study involves the installation of a skid-mounted, pilot plant on-site. Sufficient design and economic data normally are collected within 2 to 4 wks. Specifications for the full-scale system are then prepared. Standard reactors, ozone generators and hydrogen peroxide feed systems are utilized.

Full-scale systems, in most cases, are automated using microprocessor control. The system usually requires periodic monitoring (once per shift or once per day). The systems are designed to operate in a batch or continuous mode depending upon treatment requirements.

In a number of cases, UV-oxidation is used as part of a treatment train. For example, at wood treating sites prior to the UV-oxidation treatment, the wastewater or groundwater requires breaking of oil/water emulsions and removal of suspended matter as well as adjustment of pH.

CASE STUDY—LORENTZ BARREL AND DRUM SITE

The U.S. EPA has established a formal program to accelerate the development, demonstration and use of new or innovative technologies to be used in site cleanups. This program, called the Superfund Innovative Technology Evaluation (SITE) Program, has four goals:

- To identify and, where possible, remove impediments to the development and commercial use of alternative technologies
- To conduct a demonstration program of the more promising innovative technologies for the purpose of establishing reliable performance and cost information for site characterization and cleanup decision-making
- To develop procedures and policies that encourage selection of available alternative treatment remedies at Superfund sites
- To structure a development program that nurtures emerging technologies

Each year, the U.S. EPA solicits proposals to demonstrate innovative technologies. To identify the best available technologies, an extensive solicitation is necessary. A screening and selection process follows, based on four factors:

- The technology's capability to treat Superfund wastes
- The technology's performance and cost expectations
- The technology's readiness and applicability to full-scale demonstrations
- The developer's capability and approach to testing

Ultrox was selected in the third year to the SITE program to demonstrate its UV/oxidation technology. The Lorentz Barrel and Drum Superfund site in San Jose, California, was selected for the demonstration project.

The Lorentz site was used for drum recycling for nearly 40 yr. Over this period of time, the site received drums from over 800 private companies, military bases, research laboratories and county agencies in California and Nevada. Drums arrived at the site containing residual aqueous wastes, organic solvents, acids, metal oxides and oils.

Since 1968, there have been several regulatory actions at the Lorentz site. In 1987, the Lorentz facility ceased operation and the U.S. EPA assumed lead agency responsibility for site remediation. Investigations revealed that the groundwater beneath the site was contaminated with a number of chlorinated solvents, chlordane, toxaphene and PCBs.

An ULTROX® P-150 pilot plant was moved to the site on Feb. 21, 1989. Thirteen tests were conducted between Feb. 24 and Mar. 9, 1989, on extracted groundwater from the site. During the treatability bench

studies, TCE, TCA and DCA were chosen to monitor the progress of the pilot.

The final report has not yet been issued by the U.S. EPA. However, based on the preliminary results, the UV/oxidation process was successful in the reduction of all of the VOCs present in the groundwater at the Lorentz site to below drinking water standards.

The bicarbonate level of the groundwater was extremely high (1200 mg/L). Because of this, treatment costs are higher than what would be experienced in more normal groundwater applications. Based on the conditions tested at the site, treatment costs were estimated to be:

Flow Rate:	100 gpm
Influent Concentration:	250-1000 μ /L VOCs, pesticides, PCBs
Effluent Concentration:	< 10 μ /L
Treatment Costs:	\$/1000 gal
Ozone (@ \$0.06/kwh)	\$ 0.370
H ₂ O ₂ (@ \$0.75/lb)	0.156
UV (incl. power and annual lamp replacement)	0.836
O&M Cost	1.36
Capital Amortization (16%/year)	0.75
Total Treatment Cost:	\$ 2.11/1000 gal

CASE STUDY—AUTOMOTIVE PARTS MANUFACTURER, MICHIGAN

Water tested beneath a Michigan automotive parts manufacturer revealed significant VOC contamination. TCE levels of 5,000 to 10,000 μ /L were recorded as well as trace levels of other chlorinated solvents. The Michigan Department of Natural Resources required that the manufacturer pump and treat the groundwater.

The manufacturer investigated air stripping with GAC off-gas treatment, aqueous phase GAC and UV/oxidation as possible treatment alternatives. Bench-scale studies were conducted at a GAC supplier and at Ultrox's laboratory. While all treatment techniques could provide the required removal levels, UV/oxidation was the most economical. A pilot-scale treatment system was delivered to the site. Testing over a 2 wk period confirmed the data obtained in the laboratory. A full-scale treatment system was ordered and installed in April, 1989. The system is currently operating and achieving the following results, which exceed Michigan requirements:

Flow Rate:	210 gpm
Influent Concentration:	5500 μ /L TCE
Effluent Concentration:	1 μ /L TCE
Treatment Costs:	\$/1000 gal
Ozone (@ \$0.06/kwh)	\$ 0.119
H ₂ O ₂ (@ \$0.75/lb)	0.188
UV (incl. power and annual lamp replacement)	0.133
O&M Cost	0.44
Capital Amortization (16%/year)	0.29
Total Treatment Cost:	\$ 0.73/1000 gal

OPERATING AND MAINTENANCE CONSIDERATION

When selecting a treatment process, a number of factors obviously must be considered. Does the process destroy toxics on-site? Does it solve an immediate problem but create a new problem or a long-term

risk to the environment, e.g., air stripping without emission control equipment?

Ultraviolet/oxidation certainly destroys toxics on-site and does not create residual problems. However, one must be aware of the limitations on UV/oxidation systems. Table 4 is a comparison of features of two different UV/oxidation methods. Table 5 contains an economic comparison of UV/oxidation systems.

Table 4
Performance Comparison Between UV/O₃/H₂O₂ and High Pressured UV with H₂O₂

	Capital Cost	O&M Costs	Life Cycle Costs	On-Line Time
UV/O ₃ /H ₂ O ₂	Higher	Low	Lower	High
UV/H ₂ O ₂	Lower	High	Higher	Varies
	Turn-Down Ratio	Lamp Temperature	Emissions	Lamp Replacement
UV/O ₃ /H ₂ O ₂	Good	Low	Low	Once/year
UV/H ₂ O ₂	Poor	High	Low	3-4 times/year

Table 5
Economic Comparison of UV-Oxidation of TCE in Groundwater

Treatment Conditions	UV/O ₃ /H ₂ O ₂	High Press-UV/H ₂ O ₂
Flow Rate	200 gpm	200 gpm
Infl. TCE Conc.	10,000 ppb	10,000 ppb
Eff. TCE Conc.	1 ppb	1 ppb
H ₂ O ₂ Dose	20 mg/L	50 mg/L
O ₃ Dose	20 mg/L	—
UV Energy	432 KWH/day	6,000 KWH/day
O ₃ Energy	720 KWH/day	—
Treatment Costs	\$/1000 Gallons	
UV Power*	\$0.11	\$1.46
O ₃ Power*	0.18	—
H ₂ O ₂ **	0.09	0.31
Maintenance***	0.12	0.13
Capital Amortization at 16%/yr****	0.38	0.21
Operating Labor	N/A	N/A
	\$0.88	\$2.11
YEARLY COST	\$92,506.00	\$221,800.00

* Electrical Energy = \$0.07/KWH

** H₂O₂ (100%) Cost = \$0.75/lb.

*** Includes lamp replacements, once a year for UV/O₃/H₂O₂ and 3 to 4 a year for high pressure lamp

**** 10 year depreciation/10% interest

CONCLUSIONS

Over the last 15 yr, UV/oxidation has progressed from research and development to commercial operation. During these years, Ultrox has advanced its design through applied bench testing, pilot studies and full-scale systems that remove contaminants from a wide variety of wastewaters and groundwaters.

UV/oxidation technology is not suitable for every organic contamination problem. It can, however, effectively address a wide range of contamination problems. This form of on-site chemical oxidation can offer real advantages over conventional treatment techniques and should be considered when evaluating water treatment alternatives.

Hydrological and Geochemical Controls Limiting Contaminant Transport in Groundwater at Weldon Spring, Missouri

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ABSTRACT

The Weldon Spring site, considered for inclusion on the NPL, presents a combination of unique geologic features which precludes the application of conventional contaminant migrating transport modeling to determine the fate of contaminants from four on-site raffinate pits. A contaminant transport model provides a numerical solution to a continuum of contaminant dispersion along a groundwater flow path with the option of a linear retardation term. This approach, however, is not suitable for the modeling of the discontinuous geochemical and hydrological events along a flow path which occur at Weldon Spring.

Contamination at this site, located near St. Louis, Missouri, stems from TNT production during the 1940s and uranium refining operations in the 1950s and 1960s. Although significant sources of uranium and related radionuclides, nitrate and sulfate, heavy metals and nitroaromatic compounds have been identified on-site, off-site receptors show only low levels of uranium, nitrate and nitroaromatics. This paper discusses the transport of uranium and nitrate from the raffinate pits and does not address nitroaromatics.

The off-site contamination by nitrate and uranium has resulted from a series of discontinuous events. Seepage from the raffinate pits, chemical retardation at the raffinate pit/overburden interface, groundwater flow through porous media and subsurface conduits, recharge from losing streams and spring discharge all contribute to transport.

To better understand the sequential effects of these factors, a sound conceptual model identifying the discrete segments of the flow paths and the dominant processes controlling contaminant transport, followed by an analytical solution when appropriate, proved to be a practical and useful approach.

INTRODUCTION

The Weldon Spring site is located approximately 30 mi west of St. Louis in western St. Charles County, Missouri. The site includes the four raffinate pits constructed to contain wastes from uranium refining and the Weldon Spring Chemical Plant. Together these are encompass 217 ac. The U.S. Department of the Army produced TNT from 1941 to 1944 at Weldon Spring, and the U.S. Atomic Energy Commission operated a uranium feed material plant between 1957 and 1966.

Weldon Spring is located on the drainage divide between the Mississippi and Missouri River basins (Fig. 1). Nearby streams include Schote Creek, a tributary of Dardenne Creek north of the site and the southeast drainage, which is an unnamed tributary of the Missouri River south of the site. Three lakes, known as Lakes 34, 35 and 36, have been constructed on the drainages in the August Busch Wildlife Area to the north of the site.

Several springs and seeps, some of which flow only after a rain, are also present in the vicinity. Burgermeister Spring, a major perennial spring located immediately upstream of Lake 34, is hydraulically connected to both groundwater

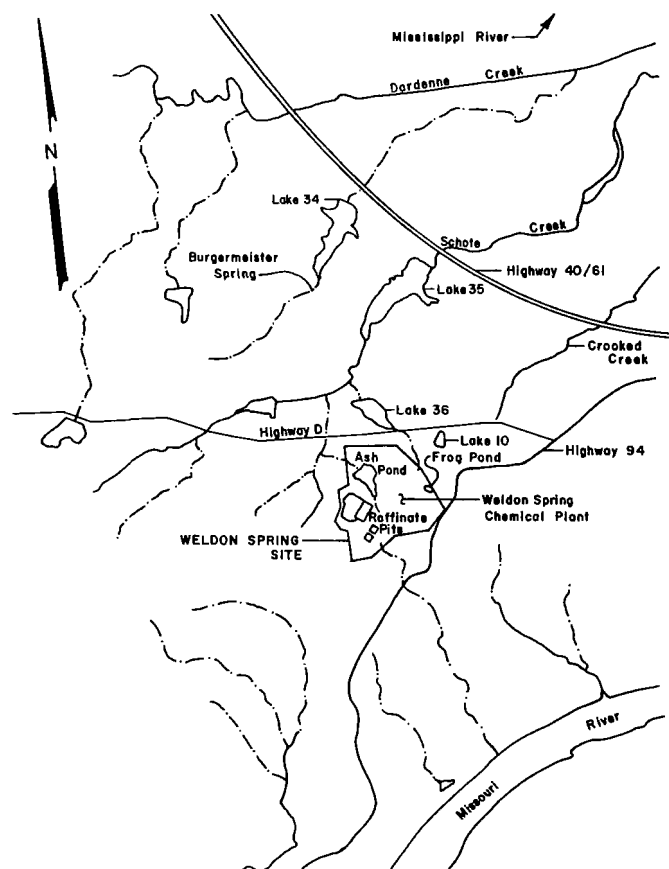


Fig. 1
Weldon Spring Site and Vicinity
(from MK-F and JEG, 1989)

and surface water discharge from the site. This spring has been affected by uranium and nitrate transport.

TNT production at Weldon Spring introduced nitric and sulfuric acids, metals and nitroaromatic compounds to the site soils and water. This contamination generally was confined to areas near the TNT processing plants, wastewater discharge lines, lagoons, the wastewater sludge incineration areas. The wastewater, commonly called red water, was stored in lagoons constructed within surface drainages, and historical records suggest that the lagoons frequently overflowed into ditches and streams. The major component of the wastewater was sodium sulfite, used in the purification of TNT. A surface water impoundment, called the Frog Pond, was constructed as a settling basin for TNT wastewater discharge (Fig. 1).

Uranium metal production from processed uranium ore, or yellowcake, at Weldon Spring involved the use of nitric, sulfuric and hydrofluoric acids; magnesium; sodium carbonate and hydroxide; and other chemicals. The raffinate pits were constructed of local soils to contain neutralized acidic wastes (Fig. 1). Decant water from the pits was discharged off-site into the southeast drainage. Ash Pond, north of the raffinate pits, was constructed to contain ash from an on-site coal-fired steam generating plant and from incineration of materials contaminated with uranium (Fig. 1).

The groundwater and surface water transport pathways from on-site sources to off-site receptors are controlled by geochemical processes within a complex hydrogeologic regime. Two primary mechanisms contribute to the transport of contaminants to the groundwater: leaching and seepage from the surface and subsurface sources through the unsaturated zone into the groundwater, and infiltration of contaminated surface water from streams off-site.

Analysis of the site's geohydrology, contaminant distribution in surface and groundwater and the geochemical processes immobilizing contaminants has shown that the Weldon Spring site does not meet the requirements for conventional contaminant modeling. The examples given in this paper focus on the flow path from the raffinate pits and Ash Pond, the major sources of contamination, north-westward to the streams and ultimately to Burgermeister Spring.

Many of the data referenced in this paper were developed during the site characterization and Remedial Investigation conducted by Morrison-Knudsen and Jacobs Engineering Group for the U.S. Department of Energy.¹ During these studies, site geology, hydrology and geochemistry were interpreted based on borehole logs, hydrologic measurements and water chemistry analysis from geotechnical or monitoring wells drilled to various depths in the overburden and bedrock.

Data presented here were selected from an extensive project data base to illustrate the transport of nitrate and uranium from the raffinate pits. Dye tracing studies to identify the conduit flowing from the site were conducted by the Missouri Department of Natural Resources.² Local hydrologic information was derived primarily from U.S. Geological Survey investigations.³

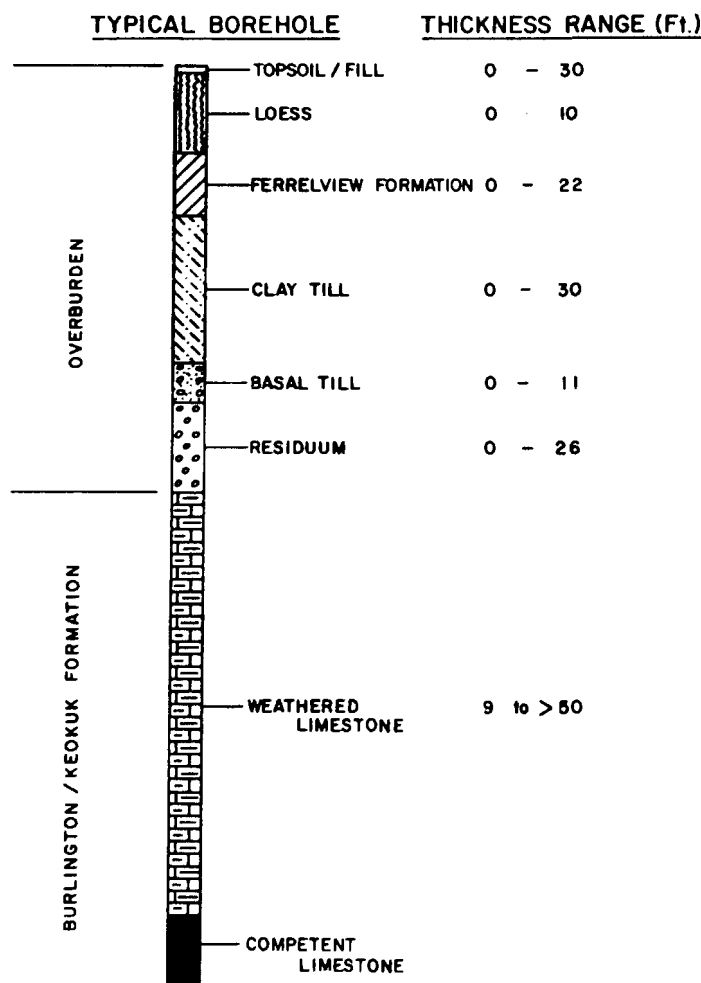


Fig. 2
Representative Stratigraphy of the Weldon Spring Site
(from MK-F and JEG, 1989)

GEOLOGY

The geology beneath the site is characterized by 15 to 60 ft of clayey overburden overlying an argillaceous cherty limestone bedrock of the Burlington/Keokuk Formation (Fig. 2). The overburden has been divided into six recognizable units based on physical characteristics. These are, in ascending order: residuum, basal till, clay till, Ferrelview Formation, loess and topsoil/fill. The overburden generally is thickest over bedrock lows. Much of the original upper overburden stratigraphy and the original surface drainage system across the site were obliterated by cut and fill operations during construction of the uranium feed material plant.

The Mississippian Burlington/Keokuk bedrock has been divided into two units distinguished by the degree of fracturing and weathering exhibited in the rock. The upper weathered unit ranges in thickness from 9 to greater than 50 ft. The competent unit extends to about 130 ft to another unit of limestone.

The bedrock surface exhibits a high on the eastern portion of the site and a low on the north/northwest portion of the site (Fig. 3). The upper unit is highly weathered at the top, exhibiting solution features ranging from pinpoint vugs to small cavities which generally are filled with clay. No large-scale closed depressions characteristic of sink hole development have been identified on the surface of the bedrock. Linear depressions developed on the bedrock surface are interpreted to be preglacial drainages. The formation of these features appears to have been controlled by northeasterly and northwesterly trending joint sets.

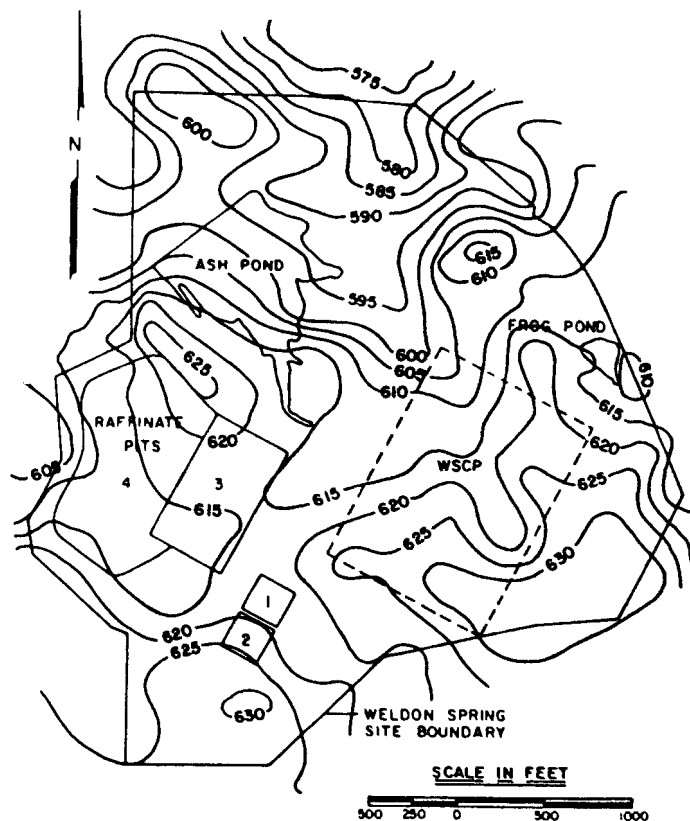


Fig. 3
Contour Map of Top of Limestone Bedrock
at the Weldon Spring Site
(from MK-F and JEG, 1989)

HYDROLOGY

The Weldon Spring site is divided into three general drainage systems. Ash Pond and the raffinate pits drain to the northwest, Frog Pond and related streams drain in the northeast portion of the site and the southeast drainage flows from the site to the Missouri River. Surface run-off from Ash Pond and the outside embankment of the raffinate pits flows off-site via an NPDES-permitted stormwater discharge point into a tribu-

tary of Schote Creek and into Lake 36. Surface water leaving the southeastern portion of the site flows through the southeast drainage toward the Missouri River.

Most local streams are intermittent and are characterized by losing and gaining stream reaches. These streams have highly variable flows and derive most of their water from direct run-off. They lose water by seepage through the stream bed and gain by inflow from springs, creating a dynamic connection between surface water and groundwater. Lost discharge resurges at springs downgradient in the same drainage or in adjacent drainages. Both wet-weather springs and perennial springs are present.

With respect to contaminant transport, the aquifer of importance below the site occurs within the upper zone of the Burlington/Keokuk Formation. Depth to water ranges from approximately 35 to 65 ft. The potentiometric surface shows groundwater flowing in a northerly direction from the site, forming a trough toward Burgermeister Spring (Fig. 4). An east-northeasterly trending divide exists across the site, which roughly corresponds to the regional surface water divide (Fig. 5). The groundwater divide passes beneath Raffinate Pits 1 and 2, within approximately 330 to 660 ft of the site's southern border. Groundwater to the north of the divide flows toward the Mississippi River; south of the divide, groundwater flows to the Missouri River.

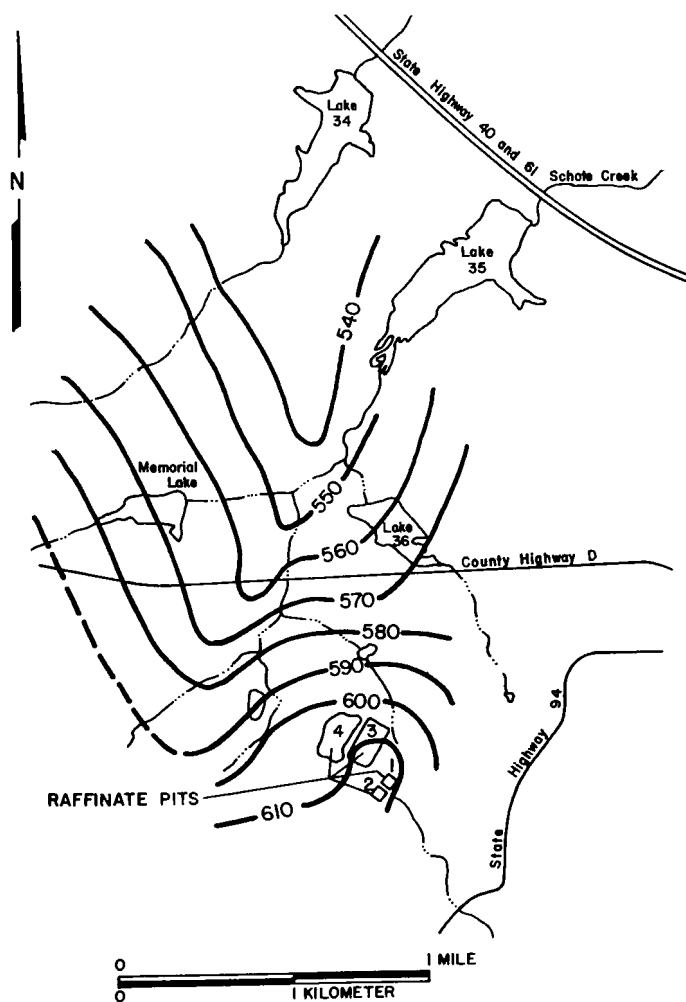


Fig. 4
Potentiometric Surface of Upper Bedrock Aquifer in the
Vicinity of the Weldon Spring Site
(from Kleeschulte and Emmett, 1987)

Results from packer tests, insitu (slug) tests and pump tests show that the hydraulic conductivity of the limestone below the site is highly variable. Hydraulic conductivities, as determined by the tests, range from approximately 10^{-3} to 10^{-8} cm/sec, with a general tendency for values to decrease with depth. Both spatial and vertical variability can be

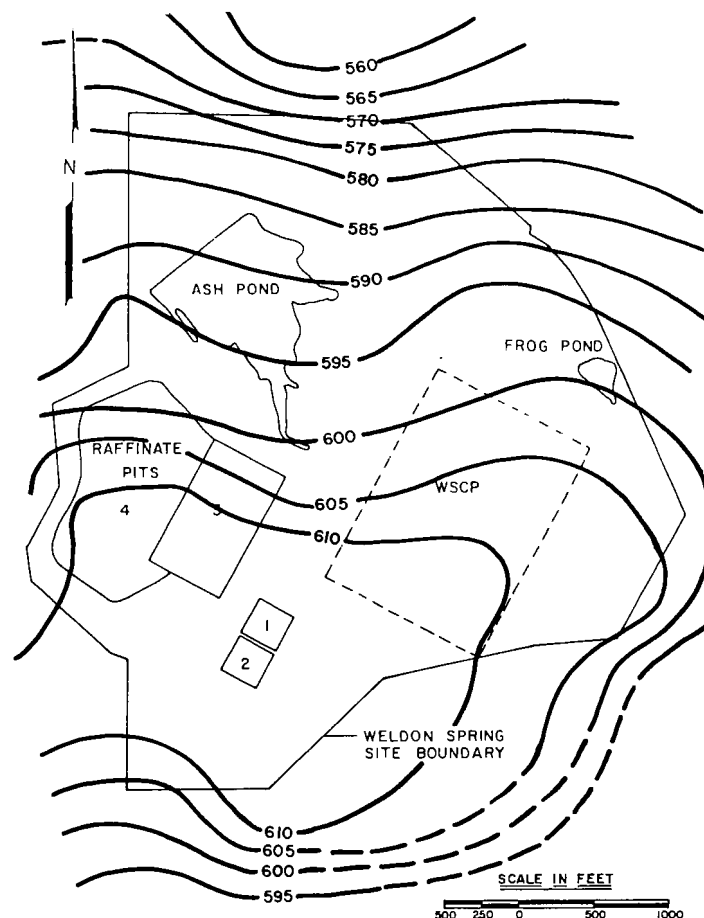


Fig. 5
Potentiometric Surface of Shallow Bedrock Aquifer
Weldon Spring Site from MK-F and JEG, 1989

attributed to the degree of weathering and fracturing, type of fractures and interconnection of the fractures in the limestone.

Groundwater movement in the limestone aquifer beneath the site is believed to occur predominantly by diffuse flow along horizontal bedding planes and, to a lesser extent, through vertical fractures. Due to its higher degree of weathering and fracturing, and generally higher hydraulic conductivities, the upper 10 to 20 ft of saturated bedrock may provide a preferred zone for groundwater transport. As the intensity of weathering and fracturing decreases with depth, the aquifer becomes less homogeneous, flow paths are more widely spaced and the influence of vertical fractures is more limited. Based on hydraulic measurements and water quality data, flow to lower zones and deeper aquifers is believed to be insignificant.

Groundwater flow off-site occurs by diffuse flow as well as through free-flow conduits. Although specific conduits, such as that from Ash Pond to Burgermeister Spring, have been identified, no evidence has been found for conduit flow immediately beneath the site. Dye tracing tests show that surface flow from the site is lost to the subsurface immediately west of the site and reemerges at Burgermeister Spring approximately 48 to 72 hr later, depending on precipitation conditions.² The straight-line subsurface distance is approximately 6,500 ft. Comparison of daily flow hydrographs of Burgermeister Spring and corresponding rainfall indicates that the discharge from the spring responds quickly to rainfall (Fig. 6).

CONTAMINANT DISTRIBUTION

Water within the four raffinate pits is a source of several elements. Elements not present at high concentrations in the raffinate water appear to be elevated above background concentrations in on-site groundwater. This contamination is assumed to be due to the proximity of contaminated soils. Nitrate and uranium, however, are the principal elements

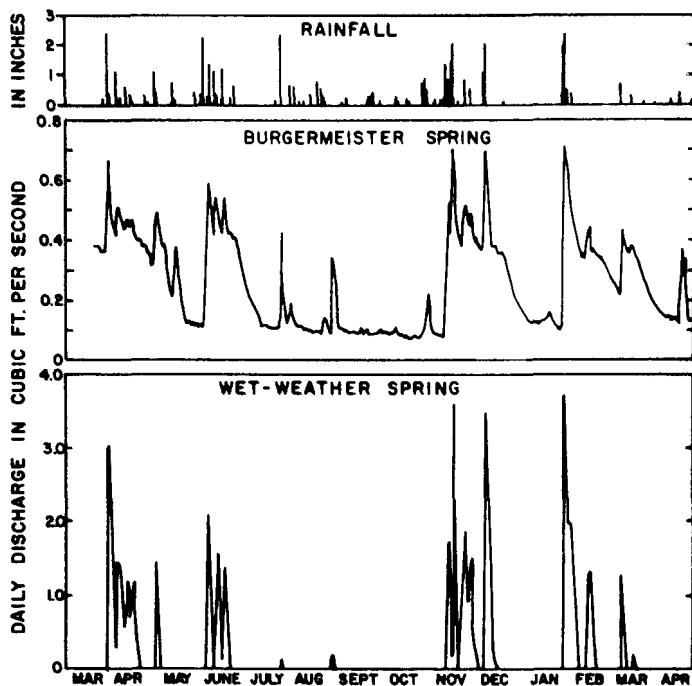


Fig. 6

Hydrographs of Burgermeister Spring and Nearby Wet-Weather Spring and Rainfall, March 1985 to April 1986 from Kleeschulte and Emmett, 1987

which appear in off-site receptors at concentrations above background (Table 1).

Table 1
Mean Values of Elements in Raffinate Pits, Groundwater, Ash Pond, and Burgermeister Spring

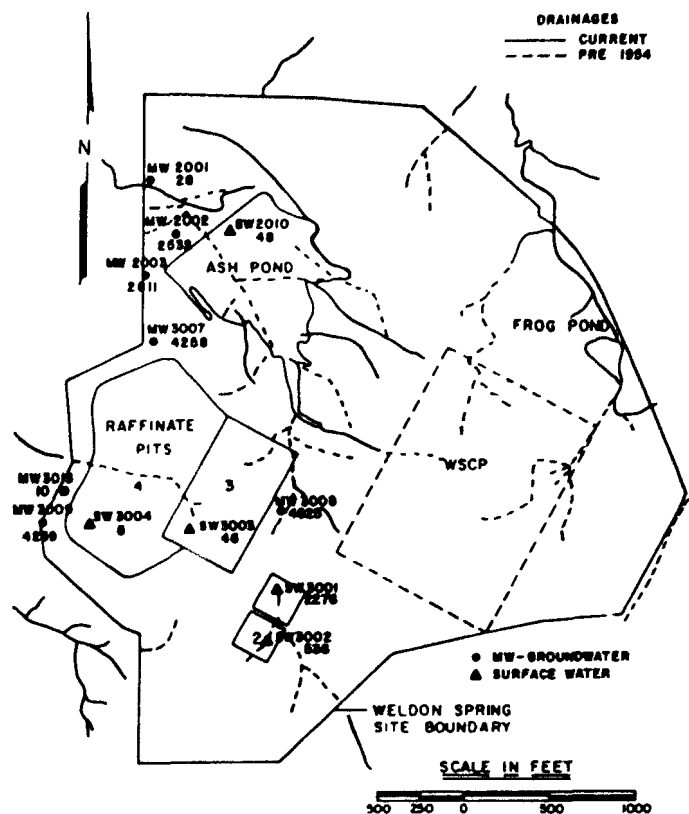
	As	Br	Ca	Cl	Cd	Co	Cu	Fe	Mn	Ni	Pb	Li
Pit 1 ¹	0.6	30	53	90	0.4	488	15	<1	18	36	2	75
Pit 2 ¹	9.4	—	82	72	4	0.2	250	5	<1	20	4	82
Pit 3 ¹	0.5	30	72	130	1	<0.1	095	22	<1	35	14	1060
Pit 4 ¹	9.2	10	11	100	<1	0.3	17	7	<1	5	7	675
Ash Pond ²	0.2	400	—	30	<5	<5	40	4	47	<50	15	0.3
MW2001 ³	7	200	<10	140	<5	<5	015	31	94	23	35	4
MW2002 ³	6.6	427	<10	464	<5	<5	622	20	80	17	32	2.3
MW2003 ³	7.5	1602	<10	709	<5	<5	640	2.3	—	<50	10	0.4
MW2013 ³	7.4	342	<10	32	<5	<5	160	2.1	79	<50	12	1
MW2002 ³	0.6	<100	<10	307	<5	<5	247	26	70	<50	45	2.8
MW2002 ³	7.5	244	<10	200	<5	<5	234	23	51	<50	11	—
MW2001 ³	7.0	309	<10	156	<5	<5	60	4.5	34	<50	4	0.4
Burgermeister Spring ³	6.8	130	—	90	<5	<5	54	22	25	<50	<25	0.25
	Pb	Mn	Ni	Se	Si	SO ₄	Na	NO ₃	U	V	Zn	
Pit 1 ¹	24	18	<0.1	3000	<1	2276	<10	466	395	260	36	3200
Pit 2 ¹	36	21	<0.1	7100	<1	534	<10	150	300	677	104	2000
Pit 3 ¹	306	22	<0.1	3000	<1	46	46	1235	160	437	225	610
Pit 4 ¹	56	7	<0.1	670	<1	5	<10	190	11	117	1950	79
Ash Pond ²	14	54	<0.2	—	<40	40	<5	27	<1	45	2025	50
MW2001 ³	194	46	0.2	117	70	4250	<5	310	<1	397	5	56
MW2002 ³	243	44	0.2	42	62	4825	<5	794	<1	53	10	53
MW2003 ³	30	11	<0.2	<13	43	405	7	13	<1	43	40	<50
MW2013 ³	56	47	<0.2	22	60	10	<5	34	<1	672	6.3	38
MW2002 ³	151	82	<0.2	50	72	2511	<5	195	<1	196	3.6	51
MW2002 ³	82	10	<0.2	37	39	2537	<5	125	<1	104	4.7	34
MW2001 ³	34	8	<0.2	<13	20	10	<5	9	<1	9	2.3	10
Burgermeister Spring ³	12	36	<0.2	—	<40	56	<5	21	<1	45	120	<50

¹ Data for raffinate pits 1, 2, 3 and 4 from Kleeschulte and Emmett, 1987. Dissolved constituents from filtered samples.

² Data from Ash Pond and Frog Pond from MC-Ferguson and Jacobs Engineering Group, 1989. Dissolved and suspended constituents from unfiltered samples.

³ Data for monitoring wells adjacent to raffinate pits from MC-Ferguson and Jacobs Engineering Group, 1989. Dissolved constituents from filtered samples.

The groundwater distribution patterns of uranium and nitrate, shown in Figures 7 and 8, illustrate the processes of geochemical retardation and dispersion. Nitrate is typical of those elements whose concentrations are controlled primarily by dispersion. Uranium concentrations, on the other hand, are more affected by geochemical retardation processes.



Groundwater monitoring wells MW-3007, MW-3008, MW-3009 and MW-3013, listed in Table 1, were installed adjacent to the raffinate pits. Comparison of uranium concentrations in the raffinate pit water to concentrations in the groundwater adjacent to the pits shows a significant retardation between the base of the raffinate pits and the groundwater. This retardation is attributed primarily to the geochemical process of precipitation as uraninite. The concentration of nitrate at thousands of mg/L in the groundwater downgradient of the pits, however, suggests minimal geochemical retardation. The concentrations of nitrate and uranium measured in three downgradient monitoring wells situated along the flow path, MW-2003, MW-2002 and MW-2001, are attributed to hydrodynamic dispersion.

Within the raffinate pits, uranium concentrations average approximately 829 ug/L, decreasing to an average of 6 ug/L in MW-3007 and to background levels (less than 7 ug/L) in MW-2003, MW-2002 and MW-2001 (Fig. 7). Geochemical thermodynamic calculations performed using PHREEQE⁴ suggest that this decrease in uranium concentrations between the raffinate pits and groundwater is caused by precipitation of uraninite. Precipitation is encouraged by chemically reducing conditions within the overburden and limestone formations, caused by the presence of organic carbon and sulfide minerals in the soils and rock.

Highly soluble iron concentrations, up to several hundred ug/L, within the groundwater confirm that this medium is also characterized by the presence of chemically reducing conditions. These reducing conditions allow the precipitation of arsenic, molybdenum and vanadium in a fashion similar to the natural processes occurring during the formation of uranium roll front deposits.⁵ The retardation of radium is attributed to adsorption and coprecipitation.

The pattern of nitrate concentrations in the groundwater illustrates the dispersion of elements along the groundwater flow path, since nitrate is not significantly affected by geochemical retardation processes. Although the reaction from nitrate to nitrite is thermodynamically favored at the redox potentials of the groundwater, slow kinetics of this reaction limit the significance of this process.

Within monitoring wells MW-3007, MW-2003, MW-2002 and MW-2001, mean nitrate concentrations are 4,259 mg/L, 2,811 mg/L, 2,532 mg/L, and 28 mg/L, respectively. The spacing between these four wells is roughly equidistant. The decrease in nitrate levels from greater than 4,000 mg/L to approximately 2,500 mg/L over a distance of approximately 600 ft between MW-3007 and MW-2002 is typical of hydrodynamic dispersion. The decrease from approximately 2,500 mg/L to 28 mg/L in MW-2001 over approximately 300 ft suggests that a significant inflow of water with low nitrate concentrations is causing a dilution of nearly 1 to 100. This contribution of water appears to be from the subsurface conduit which extends from Ash Pond. This conduit carries a large flow of groundwater recharged from the groundwater divide as well as surface water lost to the subsurface outside of Ash Pond. The surface water from Ash Pond contains a mean nitrate value of 48 mg/L. Nitrate concentrations in the discharge from Burgermeister Spring range from 11 mg/L to 203 mg/L, with a mean value of 68 mg/L.

The contribution of surface water from Ash Pond to the groundwater is illustrated by the uranium concentrations in the groundwater, surface water from Ash Pond and Burgermeister Spring. The uranium concentration in the groundwater near Ash Pond is within background concentrations. The surface water from Ash Pond contains greater than 2,000 ug/L of uranium. However, uranium concentrations in Burgermeister Spring range from 31 ug/L to 240 ug/L, with a mean value of 125 ug/L. This decrease in uranium concentrations between Ash Pond runoff and Burgermeister Spring is due to a combination of dispersion into the groundwater system and removal by precipitation due to the changes in chemistry between the surface water and the groundwater.

The comparison between the mass flux of nitrate and uranium discharging from Burgermeister Spring illustrates the differences between the transport patterns of nitrate and uranium (Fig. 9). The mass flux of nitrate is inversely proportional to the discharge, whereas the mass flux of uranium is directly proportional to the discharge. The inverse relationship between mass flux of nitrate and discharge suggests a dilution of nitrate concentration by the increase in discharge, which

is primarily from surface run-off lost to the subsurface. The direct relationship between mass flux of uranium and discharge supports the idea that the major source of uranium is the surface run-off lost to the subsurface. The concentration of uranium remains relatively constant, and the increase in mass flux is attributable to an increase in discharge.

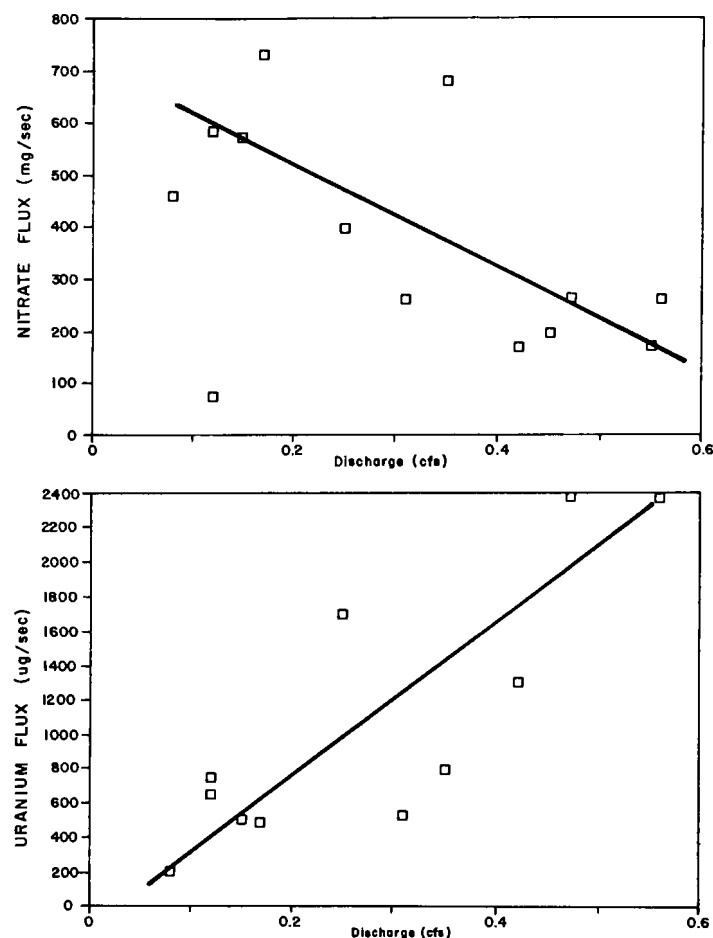


Fig. 9
Contaminant Flux vs. Discharge of Burgermeister Spring, 1987, 1988 (from KM-G and JEG, 1989)

CONCLUSIONS

Waters discharging from Burgermeister Spring are contaminated with nitrate and uranium. Nitrate concentrations are reduced by a factor of 50 between the groundwater at the site boundary and Burgermeister Spring. Concentrations of uranium in the surface water leaving Ash Pond are reduced by a factor of 15 before resurging at Burgermeister Spring.

The mechanisms of contaminant transport between the raffinate pits and Burgermeister Spring comprise a series of discontinuous geochemical and hydrologic events. These events are:

- Seepage from the raffinate pits
- Chemical retardation of uranium and most of the other contaminants, with the exception of nitrate and other anions, to levels near background within a few hundred feet of the raffinate pits
- Dispersion of nitrate and low levels of other contaminants in the area between the raffinate pits and Ash Pond
- Mixing of nitrate-contaminated groundwater with infiltration of surface run-off, from Ash Pond which is lost to the subsurface
- Chemical precipitation of uranium from Ash Pond waters as the surface water mixes with the groundwater system
- Conduit flow of groundwater to Burgermeister Spring

This sequence of discontinuous events acting on contaminant transport between the on-site sources of nitrate and uranium and the major off-site receptor illustrates that conventional contaminant transport modeling would not appropriately describe the existing contaminant distribution.

REFERENCES

1. MK-Ferguson Company and Jacobs Engineering Group, *Draft Remedial Investigation Report for the Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri*, U.S. Department of Energy, Oak Ridge Operations Office, 1989.
2. Dean, T.J., *Groundwater Tracing Project-Weldon Spring Area, Interim Report, Part 1*, Missouri Department of Natural Resources, 1984.
3. Kleeschulte, M.J. and Emmett, L.F., *Hydrology and Water Quality at the Weldon Spring Radioactive Waste-Disposal Sites, St. Charles County, Missouri*, Water Resources Investigation Report 87-4169, U.S. Geological Survey, 1987.
4. Parkhurst, D.L., D.C. Thorstenson and Plummer, L.N., *PHREEQE—A Computer Program for Geochemical Calculations*, Water Resources Investigation Report 80-96, U.S. Geological Survey, 1980.
5. Harshman, E.R., Distribution of Elements in Some Roll-Type Uranium Deposits, *Proc of a Symposium on Formation of Uranium Ore Deposits*, pp. 169-183, Athens, GA, 1974.

Bioremediation Cleans Up the Groundwater Supply Of a Small Mid-Atlantic Community

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ABSTRACT

A community maintenance facility experienced a loss of 1000 gal of gasoline from an underground storage tank. The loss caused an economic impact far beyond the cost of the lost fuel. Like many older communities, the location of added-on service facilities grew from an as-needed perspective. As a result, the fuel storage facility was located near the community well field. The loss of fuel resulted in adsorbed, dissolved, vapor and phase-separated organics in the same carbonate aquifer from which the community drew its 1,000,000 gal of water a day.

An immediate response program, coupled with a comprehensive short-range aquifer restoration program, eliminated the dependence on imported water and restored the wells within the impacted aquifer to service. The elements of on-site/in situ treatment included:

- Volatilization of adsorbed phase organics above the vadose zone with a soil vent system
- Phase-separated organic recovery from the aquifer proper using a Scavenger™ two pump system
- Air stripping for removal of dissolved phase organics in the groundwater
- Enhanced Natural Degradation END™ via native microorganism stimulation to remove residual adsorbed phase organics in the vadose and water saturated zone.

INTRODUCTION

A small community in Northeastern Pennsylvania was the first to use Comprehensive Site Remediation (CSR™) to save its drinking water supply wells from hydrocarbon contamination. Using CSR™, soil and groundwater pollutants decreased to U.S. EPA-acceptable risk levels following implementation of this technology, which eliminated 99%+ of the total contamination.

The contamination occurred in late January, 1985, in Catasauqua, Pennsylvania, a borough 20 mi north of Allentown. Approximately, 1,000 gal of regular leaded gasoline leaked from a 20-yr-old underground storage tank at the borough's Public Water Works, 50 ft from one of the supply wells. Analytical data indicated contamination of municipal well #1.

After discovering the leak, borough officials closed all three wells and all water pumps and purchased water from a neighboring community. Quick resolution of the contamination problem was essential; many residents were without water and the borough could not afford to buy water indefinitely. The normal combined yield of the wells was approximately 1,000,000 gal/day.

SITE DESCRIPTION

The site is approximately 300 ft east of and uphill from, the southern flowing Catasauqua Creek. The site area is underlain by impure lime-

stone and dolomite of the Epler Formation. This formation is locally a highly fractured and solution-channeled limestone that produces large quantities of water from the joint sets and solution channels. Two of the observation wells (OW 1 and OW 5) encounter competent bedrock at approximately 25 to 30 ft below surface grade. Calcareous silty sandy clays and calcareous argillaceous silty and gravelly sands overlay the bedrock.

The shallow groundwater system, as monitored in the installed observation wells, is under water table conditions. Depth to groundwater in the immediate spill area varies from 15 ft to 28 ft below grade.

The water table gradient at this site is relatively flat. This flat lying gradient limited the rate of groundwater contaminant migration from the spill site under non-pumping conditions. The natural gradient measured from the installed wells at the site is approximately 0.1 ft/100 ft towards Catasauqua Creek (west of the loss area).

INVESTIGATION

To define the direction of groundwater flow and confirm the presence of gasoline in the groundwater system, the project team constructed five observation wells around the loss area. Interceptor wells also monitored contamination at the water supply wells. The project team constructed the wells to penetrate the upper 10 to 15 ft of the aquifer. This is the zone typically impacted by free/phase-separated, dissolved product and adsorbed phase organics.

The annular space of all wells was gravel-packed with 1/8-in by 1/4-in gravel as a filter medium. After gravel packing, they developed the wells by air lifting to remove solids.

The project team then surveyed well elevations and tied them into a USGS topographic map. They collected water level data from all five observation wells and the Municipal Well #1. The direction of the groundwater gradient was west, toward Catasauqua Creek with a slope of approximately 0.01 ft/100 ft.

The retention capacity of soils for gasoline is dependent on soil type. The finer grained the soil, the greater the capacity to retain hydrocarbons. In order to reach the water table as a dissolved or free floating phase at Catasauqua, the gasoline needed to overcome the formation's retention absorption capacity.

After installing the observation wells, which showed an initial (stabilizing) absence of free floating product on the water table, GTI conducted a detailed soil analysis. The analysis defined elevated soil concentrations in the tank pit area (>30,000 mg/kg). The team conducted limited excavation of this area, as the elevated concentrations of materials remaining in the soil could leach as dissolved components to the groundwater system and the water supply wells. Depth to groundwater (less than 20 ft) and the physical configuration of the site limited the effectiveness of this excavation to less than 10% of the total loss.

After tank removal, the team found a concrete pad (approximately 12 in thick) in the bottom of the tank pit. The pad had prevented direct infiltration of gasoline downward from the entire tank pit base. After removal of the concrete slab, staining and odors in the formation showed gasoline infiltration was primarily in the northwest area of the tank pit. Based on these data, excavation of contaminated soil continued in this area of the tank pit.

During excavation, samples were collected and analyzed for total gasoline. Gasoline concentrations in the soil ranged from 0.26 gal/ft³ to less than 0.09 gal/ft³ with an average of 0.14 gal/ft³. As a field guide to excavate accessible soils, project geologists selected the most contaminated material by field scanning with an HNu P101 photoionizer. Depth and anthropogenic features limited access to this soil.

Laboratory analysis of excavated samples determined it was not possible to recover more gasoline by soil excavation. The results indicated that excavation of more than 15 yd³ of soil recovered only about 0.15% of the estimated 7,000 lb loss. This calculated recovery value was based on the average concentration of 3.7 gal/yd³. As a result of these findings and calculations, no further excavation was necessary.

After GTI geologists defined the plume, they also installed a 6-in recovery well and began pumping the contaminated water. In initiating the CSR™ program, the technicians equipped the recovery well with a two-pump oil/water Scavenger™. The Scavenger had a two-fold purpose: (1) containment of the plume, and (2) recovery of phase-separated product. In addition, a small-scale aeration apparatus was utilized. The system stripped groundwater of dissolved constituents and allowed it to be discharged into a local surface stream. Recognizing that pump and treat alone could address less than 15% of the contamination at this site, scientists gathered samples for alternative cleanup feasibility strategies.

The project team examined the traditional cleanup processes including massive excavation, pumping, treatment, removal, storage and replacement of contaminated soil and determined none of them to be practical them not feasible. The contaminated plume extended under the water works and outlying buildings. Successful excavation would require demolition of these buildings, which was not feasible. Also, the high costs of such an approach, with the long-term liability of storing contaminated soils, was a major concern for borough leaders.

A bioremediation feasibility study helped to determine the safety and cost-effectiveness of using in situ biodegradation as an alternative to long-term conventional pump-and-treat techniques. The CSR™ program design and implementation focused on reducing soil-adsorbed and dissolved phase hydrocarbons. Scientists accomplished the soil by using both standard pump-and-treat technology with the END™

process for in situ treatment. The focus on the adsorbed-phase organics became paramount because residual adsorbed phase organics accounted for more than 80% of the residual aquifer impacts at concentrations in the tens of thousands of mg/kg.

Microbiologists, after designing and piloting the nutrient mix program, began adding hydrogen peroxide and nutrients to the contaminated water to enhance the natural degradation process. Hydrogen peroxide acted as an oxygen source to overcome certain oxygen transfer limitations through the silty sand soil residue.

RESIDUAL CONTAMINATION CLEANUP

Losses of hydrocarbons to the subsurface can lead to a four-fold problem, dependent on the type and quantity of loss and the nature of the underlying geologic/hydrogeologic system.

Small losses can lead to the development of an adsorbed phase only with possible generation of vapors. Larger losses create an adsorbed problem followed by the development of a dissolved phase within the aquifer. Each type of loss can generate a vapor phase problem. In certain environments, losing significant volumes decreases the ability of the soil to adsorb hydrocarbons and the groundwater system to dissolve hydrocarbon, creating a free-product phase. In this case, all phases contribute to the evolution of vapors. With this background knowledge, one must be aware of the various phases and knowledgeable about their potential environmental impact.

In most losses, the largest volume of contaminants is in the adsorbed phase. Smaller amounts normally are present in the vapor phase.

The free-product phase can represent varying amounts from 0 to 40% or slightly more in certain coarse-grained aquifers. The dissolved phase usually amounts to less than 10% of the overall problem. In this case, 12% of the hydrocarbons were recovered as phase-separated organics, less than 1% as vapor and approximately 2 to 3% as dissolved organics.

The CSR™ process incorporates the natural elements of hydrogeology and soil microbiology to construct an in situ bioreactor. The program involves a comprehensive scientific approach which:

- Uses native groundwater samples containing the indigenous complement of bacteria for evaluation of beneficial hydrocarbon-consuming species
- Samples impacted water for analysis of the type and concentration of organic contaminants present
- Samples impacted soil for analyses of contamination to define vertical and areal impact of fugitive organics
- Defines the specific hydrogeology or rates pre-existing data for the application of such information into the construction of an in situ bioreaction cell, of circulating hydration
- Rates the response of the native microorganisms to nutrient stimulation and enhanced degradation of organic compounds
- Optimizes the nutrient additives to create a formulation of enrich-

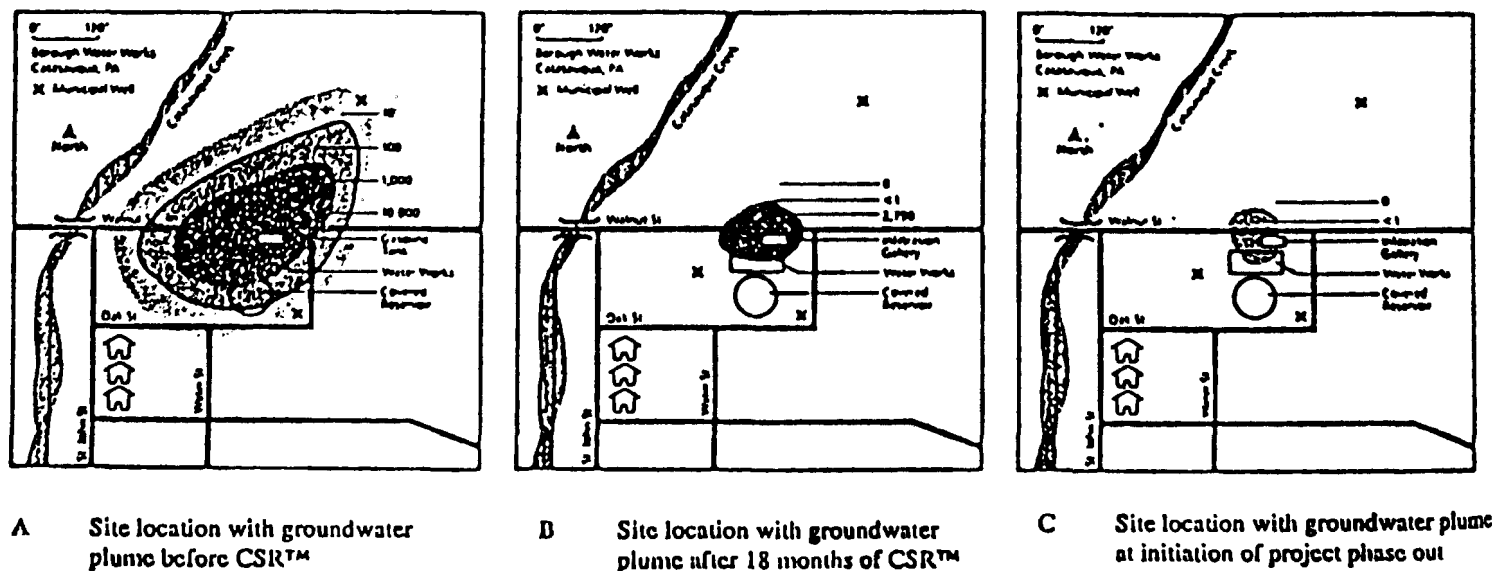


Figure 1
Contaminated Plume

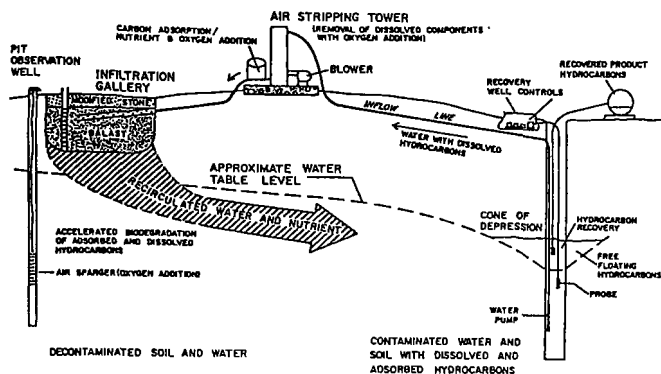


Figure 2
Cross Section of Typical CSR™

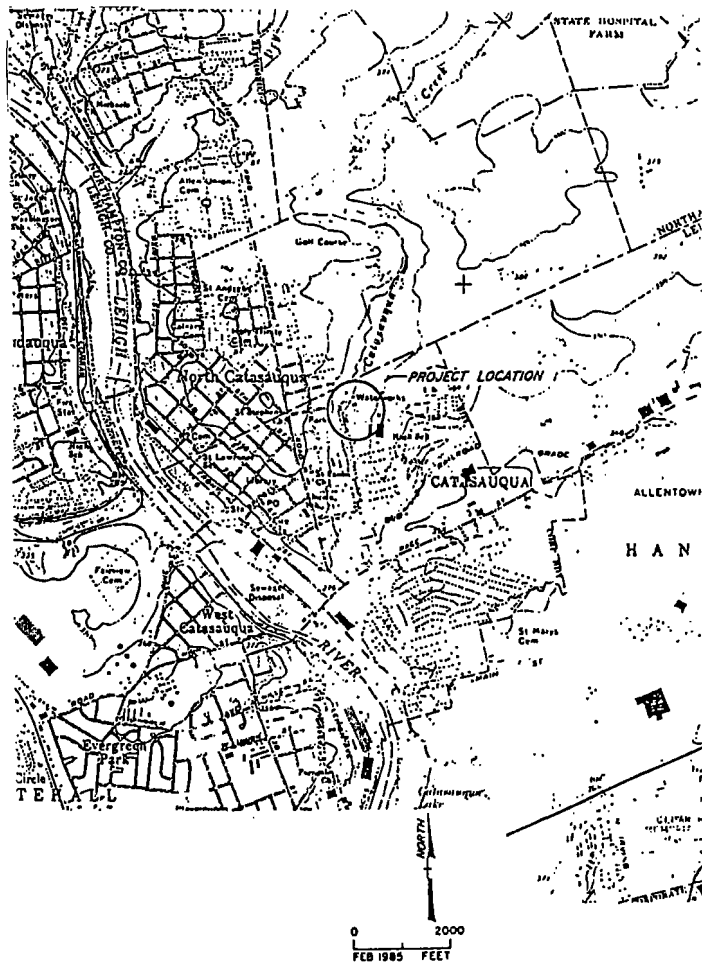


Figure 3
Project Location Borough Water Works Catasauqua, PA

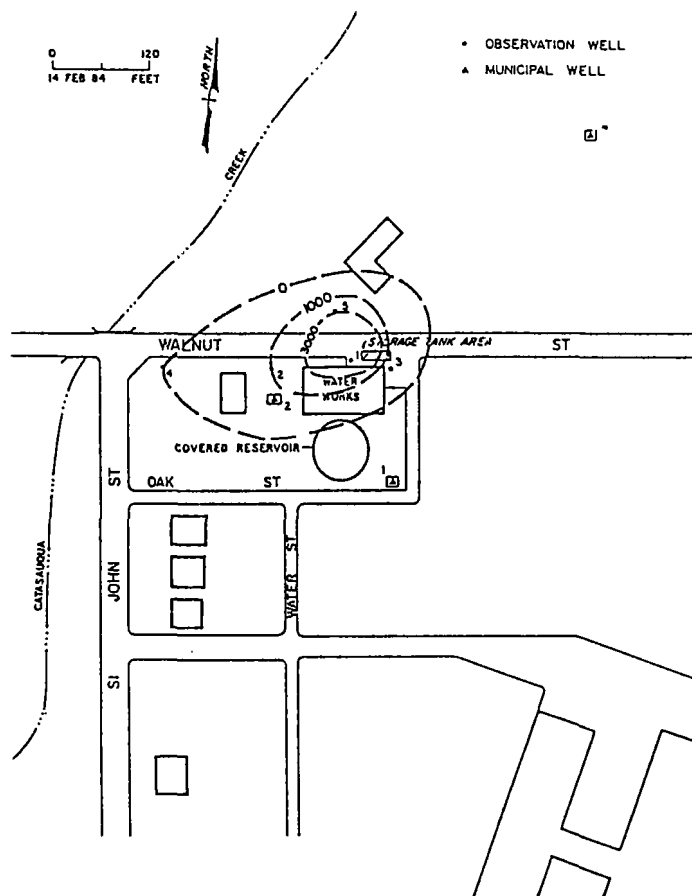


Figure 4
Dissolved Hydrocarbons (ppb) Borough Water Works Catasauqua, PA

nical or food grade constituents necessary for increased growth of bacterial proliferation to those native microbes. This program rapidly accelerates this natural process (by increasing cell numbers and metabolism rates) whereby the aerobic species of bacteria biochemically oxidize organic compounds to CO_2 and water. Bacterial consumption of these compounds as energy and carbon sources reduces their concentrations in the environment. Simultaneously, the dissolved phase concentration of then organics decreases as a result of bacterial consumption as does the amount of contamination in the adsorbed phase.

The primary target of bioremediation is the adsorbed phase of contamination. Reduction of contaminants from the adsorbed phase mitigates not only the dissolved phase but also reduces the amount of volatile organic vapors.

In a bioremediation system, a carefully balanced pump/injection cell supplies oxygen- and nutrient-enriched water over and through the area of concern. This external supply system reaches the adsorbed phase target. By supplying a properly balanced amount of inorganic nutrients and oxygen-rich water to the bacteria in the presence of the organic contaminants, a bloom of beneficial hydrocarbon-consuming bacteria occurs.

The natural consortium of hydrocarbon-consuming bacteria incorporates some of the carbon compounds into cell mass via reproduction; other carbon is oxidized to CO_2 . The bacteria, once formed, further use the organic constituents as an energy source, removing the contaminant concentrations from the subsurface environment. The by-products of aerobic degradation are more bacterial cells, CO_2 and H_2O .

Construction of a system capable of bringing all these factors into balance and accomplishing a steady-state bioreaction is very complicated. The sciences of hydrogeology, engineering and microbiology work together to formulate a comprehensive plan of action to accomplish this technology. Site-specific conditions which need careful analysis and examination include: geology, hydrogeology, chemistry—both organic and inorganic, biochemistry and microbiology.

ment added to the circulating loop of hydration to initiate and sustain a bioreaction

- Designs an applicable program for site-specific installation of equipment which will initiate an accelerated in situ bioremediation of impacted soil and groundwater

BOIREMEDIATION PROCESS

For several years, Groundwater Technology, Inc. has used hydrocarbon bioremediation as part of an overall CSR™ program. Bioremediation is a program utilizing a naturally occurring process for the oxidation of organic contaminants by indigenous bacteria. Naturally existing bacteria flourish within the groundwater and soil of the subsurface environment. The bioremediation enhancement process provides tech-

FIELD APPLICATIONS and RESULTS

Feasibility studies revealed a rich and plentiful microbial population in the groundwater at Catasauqua. Of the normal soil saprophytes present, there was a small percentage present capable of degrading petroleum hydrocarbons. Although the microbial consortium decreased, its fate was favorable for biostimulation based on laboratory studies of nutrient enrichment. Microbiologists expected that an effective nutrient formulation could bring about a rapid bloom of hydrocarbon-utilizing bacteria.

The recommended nutrient mixture was the following:

Amount (parts)	Constituent
400 pts	Groundwater
2 pts.	NH ₄ Cl
1.5 pts.	Na ₂ HPO ₄
0.5 pts.	NaH ₂ PO ₄

The inorganic chemistry and geochemistry of this site were not totally favorable to biostimulation but the overall feasibility for END™ with design, changes was good. Microbiologists recommended the process highly, based on the laboratory data.

Due to the nature of the geology and the resistance to infiltration exhibited via the native soils, GTI decided to consider chemical oxygen supply by hydrogen peroxide additions. This enhanced oxygen source could offset certain permeability limitations. GTI determined, in bench-scale studies, that a period of acclimation by the bacteria would precede effective use of H₂O₂.

The bacterial tolerance of hydrogen peroxide was very low in non-acclimated populations. In unadapted samples, the lethal concentration of hydrogen peroxide was only 30 to 50 mg/L. Samples of groundwater, enriched by nutrients and allowed to acclimate bloom in the presence of oxygen for 10 days before hydrogen peroxide additions, were more tolerant to the peroxide additive. Sub-lethal effects only began when hydrogen peroxide concentrations reached 500 mg/L and lethal effects occurred above 1000 mg/L (0.01%). Total sterility occurred at concentrations above 35,000 mg/L (3.5%).

These studies indicated that direct injection of concentrated hydrogen peroxide is lethal to bacteria, but that dilution would use of hydrogen peroxide as a soluble oxygen source.

The saturation for oxygen at ambient groundwater temperatures is approximately 100 mg/L; exceeding that level is wasteful. The system should maintain a balance between tolerance levels and usable concentration. If anything interrupts the constant supply of oxygen, the microbial cells are stressed. The bacterial consumption of hydrocarbons is most effective if the oxygen source is constant and consistently regulated to supply safe, usable concentrations. In designing the system, it was extremely important to deliver the proper concentration of hydrogen peroxide directly to the groundwater. The design of the delivery system included certain restrictions for safety and liability of handling concentrates. The peroxide was diluted to avoid shock or lethal injury

to the microbes within the zone of contamination.

The preliminary study empirically determined that hydrogen peroxide additions are necessary to the groundwater below the zone of contamination. If the zone of adsorbed contamination is as much as 20 ft below the water table, joint injection of the hydrogen peroxide must be 10 ft below that or 30 ft below the water level.

At the infiltration gallery influent, the scientists calculated that the chemical concentrations were in a usable range as the hydrogen peroxide-enriched water reaches the contaminated zone. Microbiologists took care to not overdose the system by using a diluted hydrogen peroxide solution in the beginning followed by steady, gradual increases in hydrogen peroxide concentration. Microbiologists expected consumption of all the hydrogen peroxide. It was not the intention of the operators to exceed the requirement to prove delivery of the hydrogen peroxide. Tracer studies by other chemical methods proved that hydrogen peroxide was derived. Operators took care in the startup phase of the nutrient additions not to sub-lethally or lethally shock the system.

After the first 3 mo of cleanup, Catasauqua began limited use of its drinking water supply. Groundwater Technology, Inc. stopped adding nutrients temporarily in March, 1987. At that time, the water table stabilized at a historic high level, limiting GTI's effectiveness to treat the zone of impact. Soon thereafter, before a low water table, GTI microbiologists began to add nutrients again. The additional nutrients caused a bloom of the naturally occurring bacteria to occur as the water table was sinking. This finding verified remediation at lower zone levels in the aquifer where low concentrations of contaminants remain adsorbed to soil.

An examination of dissolved hydrocarbons showed nearly complete remediation of soil and groundwater. Project phase-out of biodegradation began in the spring because of the excellent rate of degradation. The project achieved more than 99% + reduction to 1 mg/L total hydrocarbons in the recovery well. The town's water supply returned to normal.

CONCLUSION

Through a review of the collective data, the applied multi-disciplined/multifaceted, comprehensive site remediation CSR™ employing Enhanced Natural Degradation (END™) was most effective in reducing or eliminating contaminant load and restoring aquifer use.

Key elements to the success of the program included:

- Recognition of the adsorbed phase of organics at 2 to 3 orders of magnitude greater concentration than dissolved as the long-term source of impacts
- Development of a closed loop in situ reactor CSR™ system that addressed impacts at the source in a contained manner
- Use of hydrogen peroxide as an oxygen enhancer to accelerate biologic degradation of the organics bound in the silty sand vadose zone

Integration of Borehole Geophysics and Aquifer Testing to Define a Fractured Bedrock Hydrogeologic System

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ABSTRACT

Volatile Organic Compounds were detected in a manufacturing facility production well constructed in a fractured bedrock aquifer of Triassic age. In order to design a remedial alternative for the contaminated aquifer, interval packer tests and long-term pumping tests were planned. A borehole geophysical logging program was designed and implemented to characterize the structural and lithostratigraphic properties of the aquifer. The information provided by the geophysical logs and nine interval packer test results were used in the design of a long-term pump test. The geophysical data and pump test information were integrated to define the hydrogeologic system and to design a remedial alternative for the recovery of groundwater beneath the site.

The borehole geophysical logging program was designed to obtain required hydrogeologic information within a specific budget. Information needs included fracture location and formation geometry as well as other lithostratigraphic parameters necessary to characterize groundwater flow at the site. Natural gamma ray, single point resistance, spontaneous potential, compressional wave acoustic and caliper logs were recorded in eight groundwater monitoring wells. Digital geophysical logs in excess of 600 ft were obtained.

Geophysical logs were interpreted and cross-sections prepared illustrating spatial variability of lithostratigraphic units at the site. Fracture zones were identified based on caliper and acoustic logs for each well. The geophysical information developed was used to identify potential water yielding zones within wells. Using the geophysical data, interval packer tests were designed to provide information on both individual zone yield and cumulative yield for the wells. The packer tests also provided a comparison of the water quality of each testing zone.

A long-term pumping test was designed for an interval packer tested well incorporating eight additional site observation wells. The test design was based on the interpreted hydrogeologic information obtained from the geophysical logs and interval packer tests. The long-term pumping test results were incorporated with geophysical logging and interval packer test data to further define the site groundwater flow system.

The interpretation of the geophysical logs for the monitoring wells provided a better understanding of the subsurface hydrogeologic conditions than previously possible using only lithologic drilling logs. Using geophysical logs, it was possible to better define discrete lithostratigraphic units and structural features and to design an effective packer test and pump testing program. Integration of three major components of the investigation, specifically, geophysical logging, interval packer testing and long-term pumping tests, made characterization of the hydrogeologic system possible. Investigation results are being used to guide selection and implementation of a site remediation program.

INTRODUCTION

Volatile Organic Compounds (VOCs) were detected at a manufacturing

site production well in Southeastern Pennsylvania during a routine water sampling program conducted by the state regulatory agency. Investigations were conducted to confirm the existence and determine the extent of VOCs in soils and groundwater at the facility. Investigation results indicated the locations of potential source areas and the lateral extent of on-site groundwater contaminants. Unfortunately, the existing facility data base did not provide adequate information to design an appropriate, cost-effective site remedial action. A borehole geophysical logging program was completed to expand the existing data base by characterizing subsurface geology. The information provided by the borehole geophysical logs was used to design interval packer tests and long-term pumping tests to define the site groundwater flow regime.

The site is located within the borough of a small suburban town which uses surface water resources for its water supply. Well records indicate that no water supply wells are used within a 0.5-mi radius of the site. Few industrial water supply wells are located between 0.5 mi and 1 mi of the site. Because of site conditions and limited groundwater use, public health risk from site contamination was considered limited. The site is underlain by a Triassic age (240 to 205 million years old) sedimentary formation subdivided into three members: Upper, Middle and Lower. The Middle Member, which directly underlies the site, is approximately 2,300 ft thick. It is composed of fine-grained arkosic sandstone interbedded with red siltstone and shale.¹

These rocks were deposited as coalescing alluvial fans deriving their sediment from nearby crystalline highlands.¹ This depositional environment typically forms rocks that exhibit abrupt vertical and lateral changes in both lithology type and texture. Mineral constituents of the fine-grained sandstone include from 50 to 70% quartz, 30 to 50% feldspar and 1 to 3% iron minerals.¹ Much of the feldspar, originally present in the matrix, has undergone retrograde metamorphism altering to sericite and other clay weathering products.¹

Continued deposition of overlying deposits caused downwarping of the formation units resulting in a simple homoclinal formation dip of 12° North. During downwarping and subsequent loading/unloading events, the formation was subject to fracturing and faulting. Figure 1 illustrates fracture sets developed in formation outcrops perpendicular as well as parallel to bedding. The frequency and interconnection of fractures were considered to be potential factors in groundwater movement beneath the site.

The primary objective of the investigation was to define the hydrogeologic system to the extent necessary to design an effective groundwater recovery system for the identified contaminant plume. Critical to this task was an adequate definition of subsurface geology and its influence on groundwater occurrence and movement. At the initiation of this investigation, site-specific information concerning the subsurface lithologies, condition of the rock matrix, or fracture frequency was not available. The effect of a pumping recovery well on the groundwater



Fig. 1
Well Developed Vertical Fracture Sets and
Weathered Bedding Planes in Outcrop
The Pen in Photograph Center is 5 in. Long

system was unknown. Additionally, the vertical extent of aquifer contamination due to VOCs was not known. This paper summarizes the integration of several technologies including borehole geophysics and pump tests required to characterize the site, to the degree necessary, for the selection of a remedial approach.

TECHNICAL APPROACH

The results of previous environmental consultant investigations indicated elevated concentrations of VOCs to 7.5 $\mu\text{g/L}$ in groundwater beneath the site. The vertical extent of this contamination had not been defined, and the deep production well repeatedly contained elevated VOC concentrations.

Prior to this investigation, a simplified site groundwater flow model was used. This model was developed using limited information gathered during investigations designed for source area and groundwater plume definition. Three types of geologic information pertaining to the site existed: (1) general geologic agency information,¹ (2) geologic information obtained during the drilling of site monitoring wells and (3) structural and fracture trace information gathered from outcrop study and fracture trace analysis. The above information, although useful, did not provide an adequate interpretation of site hydrogeology.

The presence of dominant fracture sets, perpendicular and parallel to bedding planes, and the environment of deposition make the groundwater flow beneath the site complex and not easily predictable. Prior to this investigation it was assumed that some component of groundwater flow occurred in fractures and bedding planes as well as through primary matrix pores. The degree to which fractures, bedding planes and lithologic changes controlled groundwater flow beneath the site was unknown. Specifically, the effect of aquifer anisotropy on groundwater flow to a pumping well was unclear.

The following tasks were designed to meet the informational needs of the investigation:

- Examination of cuttings collected during groundwater monitoring well installation
- Conducting a borehole geophysical investigation including natural gamma ray, spontaneous potential, single point resistance, caliper and compressional wave acoustic logs in nine site wells which range in depth from 38 to 600 ft
- Design and performance of interval packer tests on a 290 ft deep production well
- Design and performance of a 3-day pumping test of the production well
- Performance of short-term pumping tests on shallow monitoring wells to estimate the variability in transmissivities over the site

The above approach was designed to provide a maximum amount

of information concerning the hydrogeologic system and vertical extent of contamination, while performing the work within a relatively short time-frame and restricted budget. Borehole geophysical logging of site wells provided a cost-effective characterization of site geology. Lithostratigraphic and structural details were made available for interpretation (including a well that previously had no information) on the day that logging was performed. This approach provided a broader data base concerning the subsurface geology for the design of nine interval packer tests and one long-term pumping test that would later provide additional hydrogeologic data.

Scanning Electron Microscopy (SEM) was used to examine underlying bedrock petrography. Cuttings collected during drilling of groundwater monitoring wells were examined with emphasis placed on diagenetic changes specific to the sandstone and interbedded siltstones and shales.

The borehole geophysical program was designed by analysis of regional geology, site-specific well construction data and pump test requirements. Geophysical tool selection was guided by bedrock characteristics and included an examination of primary lithologies as well as fracture occurrence. For most wells at the site, there was little or no information available concerning the materials penetrated. Selection of geophysical tools was also based on engineering parameters (casing size, depth and integrity) of interest.

The most cost-effective logging suite for the investigation was then determined. To identify lithologies, logs selected were natural gamma ray, spontaneous potential and single point electrical resistance. To locate open bedding planes and fractures, a sensitive three-arm caliper tool was selected. Compressional wave acoustic logging was completed for specific monitoring wells as an independent verification of porosity and fracture occurrence.

Field data were acquired only after the optimum borehole geophysical logging program was designed. Operations included tool calibration, parameter measurement and recording, digital data processing and QA/QC logging runs.

Natural gamma ray values were recorded in standard American Petroleum Institute (API) units. Three-arm caliper measurements were made with a sensitive caliper device capable of detecting borehole wall geometry changes to 0.1 in. The caliper logs were plotted at an exaggerated scale for easy fracture/bedding plane identification.

Geophysical tool accuracy was assessed by repeating tool measurements over a critical 100-ft borehole section. Overlay comparison of the original geophysical data and repeat geophysical data for each measurement provided assurance that the recorded data were correct. Packer test intervals were determined on the basis of borehole geophysics interpreted lithologic changes as well as locations of fracture and weathered bedding plane locations. Packer test intervals were also selected based on the caliper logs such that packer locations would provide an effective seal against the borehole. Figure 4 presents interpreted lithologies as well as interval packer test results.

The interval packer test of the facility production well was designed using the data provided by the geophysical logging program. The packer was configured to isolate nine potential subsurface water-yielding zones. These zones were identified for isolation and testing based on interpreted borehole geophysical data.

A long-term, constant rate pumping test was conducted on the same facility production well after the step drawdown tests were completed. Information used in the design of the test included: (1) geophysical logs, (2) information obtained from the interval packer tests and (3) yield information from a step drawdown test performed after the interval packer test. The long-term pumping test was conducted for a period of approximately 3 days while continuously monitoring water levels in the plant production well and eight monitoring wells.

DISCUSSION OF RESULTS

SEM data for shale samples indicate that primary depositional fabrics have been destroyed by diagenesis. Specific grain boundaries of clastic silt and clay sized particles are obscured by silica overgrowth and alteration of feldspars to sericite and other clay mineral weathering products. Little or no intergranular porosity was observed within the

shale interbeds. In contrast, SEM data for sandstone samples indicate that, in addition to both silica cementation and feldspar alteration, secondary rhombohedral calcite precipitation has significantly reduced intergranular porosity (Fig. 2). Calcite filled fractures were documented during drilling at the site. It appears that little interconnected pore space exists in the sandstone matrix.

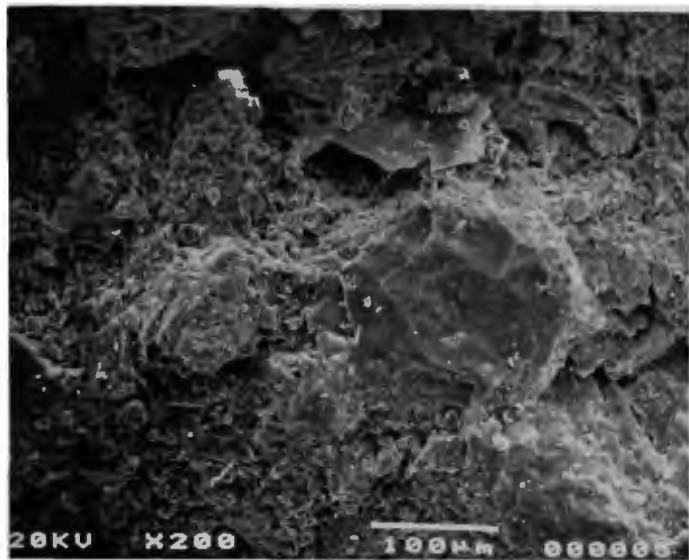


Fig. 2
SEM Photograph of Sandstone Encountered While
Installing Photograph of Sandstone Encountered
While Installing Monitoring Well.
Porosity Obscured by Sericite and Silica Overgrowth
(Photo Courtesy West Chester University).

Even though sandstone and shale were subject to varying degrees of diagenetic alteration, the effect on the hydraulic properties of the units are similar. Destruction of interconnected pore systems indicated that critical hydraulic characteristics of the rock beneath the site may not be wholly attributed to primary matrix porosity. The original depositional properties of the shales and sandstones did not appear to be a dominant factor influencing the groundwater flow system.

Interpretation of the geophysical logs was completed after the data had been verified as accurate and precise. Natural gamma ray, spontaneous potential, acoustic and single point electrical resistance logs were used to aid in lithology interpretation. The three-arm caliper log was used to identify fracture/bedding plane positions.

Figure 3 illustrates both lateral and vertical site stratigraphy. In general, the site is underlain by interbedded sandstone, siltstone and shale of varying fracture density.

Three major sandstone units were encountered by the wells at the site. Small interbedded silty shale units were identified in these sand units. Fractures and weathered bedding planes appeared to be better developed in the shale units rather than the overlying and underlying sandstone units. Open fractures and weathered bedding planes were well developed in shale sequences.

From the borehole geophysics completed at the site, outcrop examination and petrographic microscope work, it appeared that groundwater movement may be strongly controlled by fracture interconnection. Specific depth intervals were targeted for packer testing to determine relative hydraulic characteristics (transmissivity, and storativity).

As shown on Figure 4, packer test intervals were designed to provide coverage of the entire borehole. Each zone was pumped in step-drawdown fashion while recording the change in water level within each zone and in the open borehole above. Water quality samples were obtained for each zone that yielded a sufficient amount of water. The interval packer test data collected were used to evaluate the vertical distribution of VOCs entering the well, vertical head distribution of the nine zones tested, approximate yield of each zone and to estimate

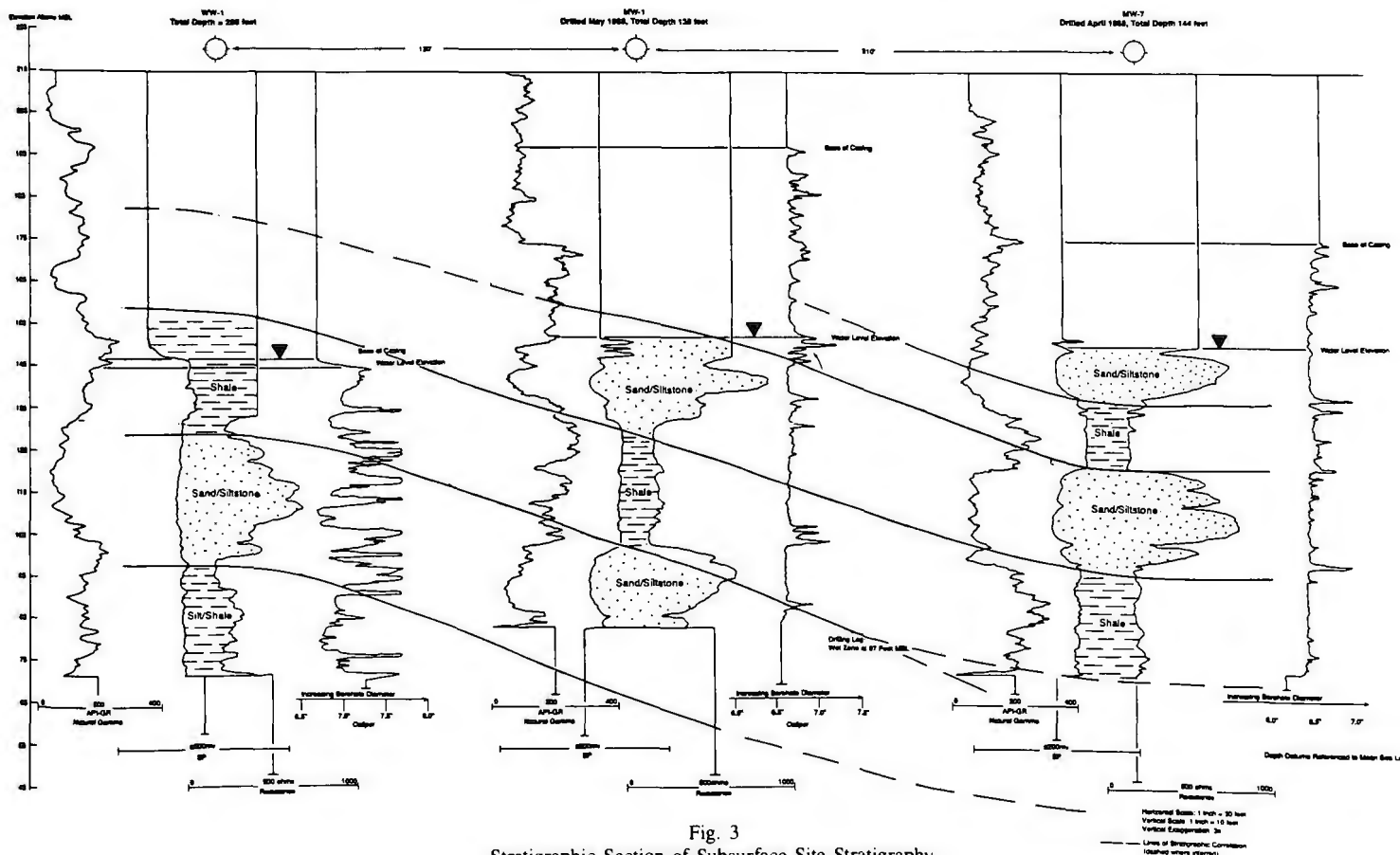


Fig. 3
Stratigraphic Section of Subsurface Site Stratigraphy.

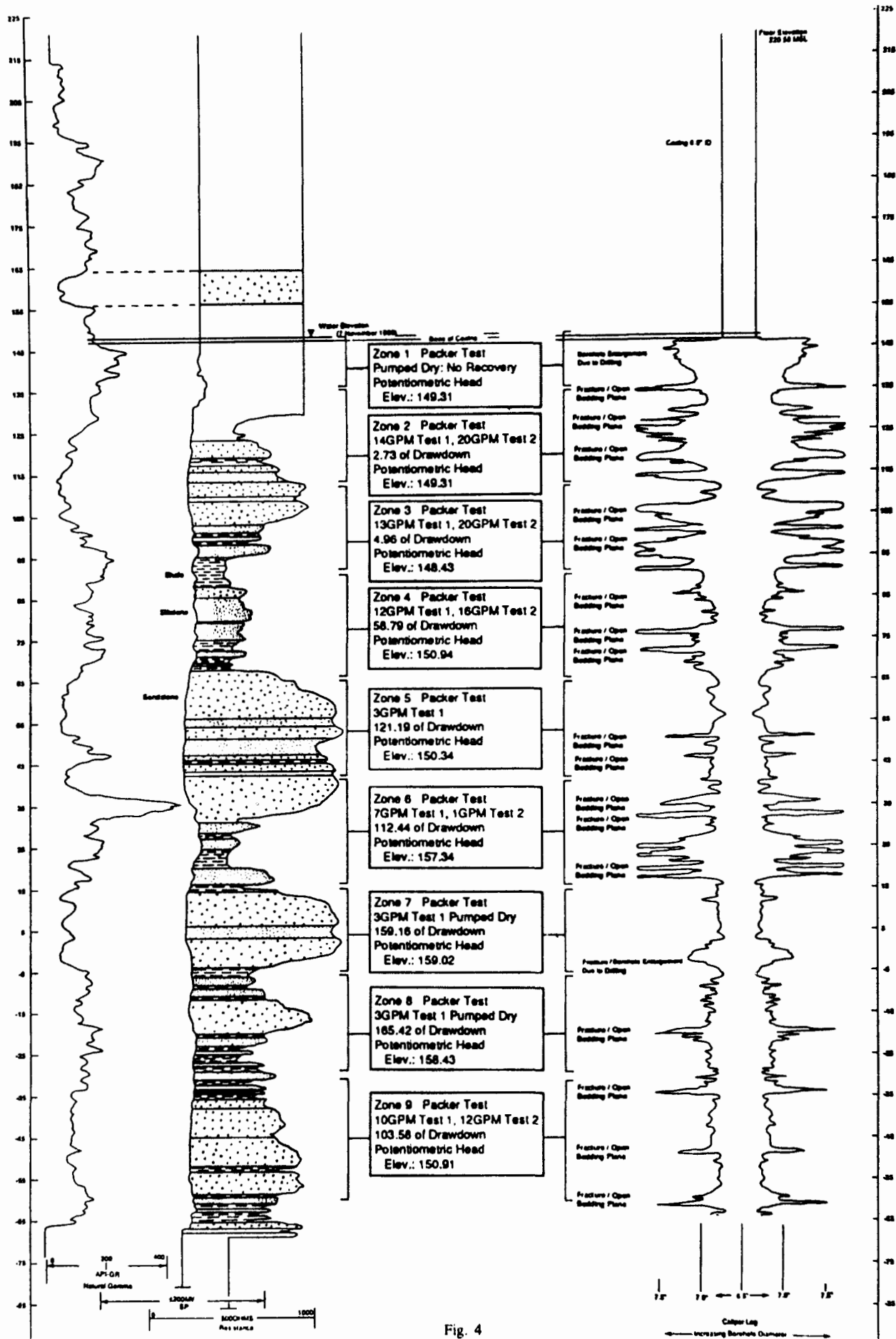


Fig. 4
Production Well Data Showing Interpreted Lithology,
Geophysical Logs, Packer Test Results.

the relative hydraulic conductivity of the zones tested. The results also provided information concerning the amount of vertical interconnection between water producing zones.

Based on the vertical profile of VOCs entering the well, it was determined that only the upper 200 ft of the plant production well were contaminated. A packer was placed in the well at 200 ft so that only the upper 200 ft of the well were tested during the long-term aquifer test.

An elongated cone of depression developed over the site during the long-term aquifer test. The orientation of the major axis of the water table surface at an angle to bedrock strike suggests that ground water-flow is fracture controlled. This is consistent with the observed features documented during geophysical logging and with the hydraulic properties of the zones packer tested.

In general, the geophysical logs delineated the locations of lithologic and structural features. Petrographic analysis indicated that sandstones and shales had little or no primary matrix porosity. This observation was further confirmed by the results of the packer testing, which showed very little yield from tested sandstone units, but relatively high yield from tested zones containing frequent open weathered bedding planes and fractures. This information indicated that the hydrogeologic system was heterogeneous and anisotropic. Further, the packer test results demonstrated the potential for sandstone units to act as confining units within the aquifer. This information aided in the selection of an appropriate analytical solution for determination of hydraulic properties from aquifer test data. The long-term aquifer test documented the

anisotropic nature of the flow system and helped define the dynamics of groundwater flow to a pumping well under the site conditions. This information and other data collected during the investigation were used in the selection and design of a remedial alternative for the site.

CONCLUSIONS

The geophysical logs provided a continuous, quantitative and qualitative record of the site geology. Subsurface stratigraphic correlations were more straightforward than available drilling logs and provided data on wells for which none were previously available. Aquifer tests were then designed to characterize the subsurface hydraulic characteristics of the lithologic and structural features identified using borehole geophysics.

The integrations of geophysical logs and pump test data were useful in defining the hydrogeologic system present beneath the site. Investigation results are being used to guide selection and implementation of a site remediation program. Based on pumping test results, the most effective remediation system was determined to target identified fracture systems rather than specific lithostratigraphic units.

REFERENCES

1. Rima, D. R., Meisler, H. and Longwill, S., "Geology and Hydrogeology of the Stockton Formation in Southeastern Pennsylvania," *Pennsylvania Geologic Survey Topographic and Geologic Survey Bulletin W-14*, 1962.

Remedial Action—A Success Story

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ABSTRACT

The cleanup of hazardous waste sites presents many challenges above and beyond typical construction projects. At the Petro-Chemical Systems site near Liberty, Texas, the remedial action was completed successfully. Elements of interest associated with the design and construction at the site include: health and safety issues; challenges of an expedited schedule and limited data; and projecting and monitoring costs. When the project was completed, the objectives of the remedial action, to improve site access and minimize potential for contaminant exposure, were effectively met with a final construction cost less than 2% above the original bid price.

INTRODUCTION

The Petro-Chemical Systems, Inc. site, originally the site of a waste oil processing company, was identified in 1970 as a potential environmental problem. While the company was in operation, waste oils were stored in several pits on approximately 4 to 6 ac of the site. Records indicate waste oils were also spread on the access road, Frontier Park Road, as a dust suppressant. All waste oil disposal operations were discontinued in June, 1970, at the request of the Texas Water Quality Board. The State granted a commercial disposal facility permit to Petro-Chemical Systems in 1971, but the permit application was subsequently withdrawn in 1974.

Preliminary sampling conducted in 1982 and 1984 by the Texas Water Commission (TWC) and the U.S. EPA indicated elevated concentra-

tions of several polyaromatic hydrocarbons in the formerly used disposal pits. The documented presence of hazardous constituents on-site led to placement on the NPL in late 1984.

In March, 1985, the State initiated a RI/FS for the Petro-Chemical Systems, Inc. hazardous waste site. The initial phase of this effort concentrated upon Frontier Park Road, the primary access to the site. Frontier Park Road was an unimproved road extending eastward from State Road FM-563 approximately 2 mi to a crossing at Turtle Bayou (Fig. 1). The area was heavily wooded along both sides of the road, except for sections cleared at residences. The area is relatively flat with little topographic relief. The crossing at Turtle Bayou, consisting of several culverts encased in concrete, had washed out. Due to the absence of an adequate drainage structure at Turtle Bayou and at localized drainage ways along the road alignment, the road was impassable much of the year.

The RI documented the extent of contamination along the road. The highly and moderately contaminated areas of the roadway are shown on Figure 1. Highly contaminated soils are defined as having greater than 100 ppm polyaromatic hydrocarbons (PAHs) or total volatiles (TVs), while moderately contaminated soils have between 10 to 100 ppm PAHs or TVs. The highest levels of contamination in these areas were generally within the upper 2 ft of the roadway.

Based on the findings of the RI/FS, a ROD was issued in March, 1987. The purpose of the remedial action authorized by the ROD was to provide access to the site so to conduct a thorough RI of the entire.

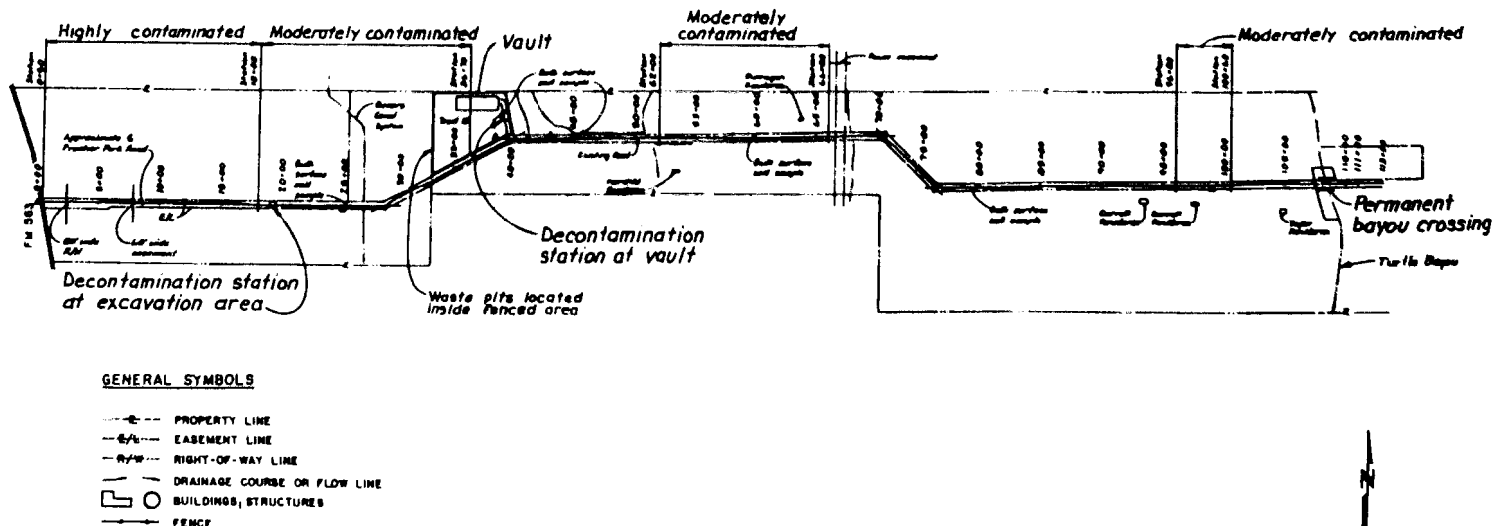


Figure 1
Site Map Petro-Chemical Systems, Inc. Site

The selected remedy for the remediation and reconstruction of the road highlighted the following features:

- Excavate contaminated soil to below 100 ppm PAHs and/or 100 ppm TVs.
- Temporarily dispose of contaminated soils in an on-site storage facility, designed in accordance with RCRA guidelines. (Final remediation of contaminated soil will be evaluated in the full site RI/FS.)
- Construct a new asphalt road over excavated areas and existing roadway.
- Temporarily relocate on-site residents during construction.

The work was authorized to be completed as an Expedited Response Action (ERA), which has a statutory limit of \$2 million and a 1-yr limit for design and construction. This fast-track approach was selected so that site access would be available for the second phase of the RI. Black & Veatch, as an associate firm of CH2M HILL under the REM IV Contract with U.S. EPA, prepared the design and served as Construction Manager (CM) for the project.

The scope of work for the construction subcontract was defined in detail in the plans and specifications that were developed. The design included the following elements:

- Excavate approximately 5000 yd³ of highly contaminated soil in Frontier Park Road between FM-563 and Station 18+00.
- Construct a double-lined on-site storage facility (vault) for temporary secure storage of the excavated material.
- Backfill the excavated area and other portions of the road which were below finished grade with uncontaminated native soils.
- Construct a road from FM-563 to east of Turtle Bayou, a length of approximately two mi. The road work consisted of excavation and filling to the subgrade elevation and construction of a lime stabilized subbase, a flexible crushed rock base course and an asphalt surface course.
- Shape and grade drainage ditches and install corrugated metal pipe culverts and a structural aluminum-plate crossing at Turtle Bayou. The existing drainage structure at Turtle Bayou was demolished and removed from the site.
- Construct two vehicle decontamination stations.
- Provide site security, including fences and a guardhouse.

Seven bids for the construction contract were received, with Tricil Environmental Response, Inc. selected as the lowest responsive, responsible bidder.

HEALTH AND SAFETY

Health and safety issues are of utmost concern when working at a hazardous waste site, and they differentiate remedial actions from standard construction projects. The remedial action must be designed to minimize potential exposure to contaminants and to provide protection to the health of residents and construction workers in accordance with OSHA regulations (40 CFR 1910).

Before initiating any on-site activities, the CM developed a site safety plan for activities by their personnel and the surveying and geotechnical testing subcontractors, while the Contractor was responsible for his own site safety plan. Based on the contaminants at the site and the activities being performed, the site safety plan specified the type of protective clothing to be worn and methods for health and safety monitoring. Most of the work in contaminated areas was conducted in Level D protection. Level C protection was used when there was a potential for respiratory exposure to contaminated dust, such as when the highly contaminated material was excavated from the roadway and placed in the vault. All personnel working on-site were required to be medically monitored and health and safety trained, including a 40-hr training course.

Because of concerns about protecting the health of the residents during construction, residents living along Frontier Park Road were temporarily relocated. The road was blocked and site security was set up at the entrance to control access to the site. A temporary bypass road was constructed around the first 1,600 ft of roadway, which was highly con-

taminated, to prevent contact with the contaminants during construction. Use of the temporary bypass road also controlled the spread of contaminants by limiting traffic through the highly contaminated area.

The plans and specifications also addressed methods for preventing the spread of contamination to other areas of the site. Vehicle decontamination stations were included near the section of roadway with the highly contaminated material and near the vault to avoid contaminating clean areas of the site while transporting highly contaminated material to the vault. A material tracking system was established to document that all excavated contaminated material was placed in the vault and that the transporting vehicles were decontaminated.

Water from vehicle and personnel decontamination areas, as well as water that contacted contaminated material in the excavation area and the vault, was collected and treated. The water had to meet discharge requirements established by the State before being released to Turtle Bayou. The Contractor provided large frac tanks for water storage. The first tank was used for contaminated water while the second was used for water treated by the on-site treatment system. The treated water was retained until laboratory results confirmed State discharge requirements were satisfied. Careful planning of construction activities to periods of dry weather minimized the volume of contaminated water requiring treatment.

The storage vault was constructed in conformance with OSHA guidelines to protect workers during construction and to prevent releases of contaminants. Following clearing and grubbing, a 12-in lime-stabilized subgrade was constructed. Since a portion of the area where the vault was constructed was contaminated, workers wore Level C protection for the subgrade construction and for construction of the first lifts of the 3-ft clay base. Equipment remained within the exclusion area until these activities were completed and was decontaminated prior to removal to clean areas of the site.

Levels of protection were downgraded for the remainder of the base construction since work was being performed on clean material and air monitoring showed no respiratory exposure from surrounding areas. This approach resulted in improved worker productivity while maintaining health and safety protection. A similar approach was followed for placement of the contaminated material in the vault. Compaction equipment remained in the vault for the duration of the filling.

Level C dermal and respiratory protection was worn during placement of the contaminated soil and installation of the first lifts of the multilayer cap. This protection was downgraded after the waste was covered and workers could work on clean imported material.

SCHEDULE AND DATA LIMITATIONS

One of the challenges of this project was the expedited schedule under which the project had to be completed. Because the project was initially pursued as an ERA, the schedule was established to satisfy the 1-yr completion requirement. Three months were allowed for design, 2 mo for advertisement, bid and award of the construction contract, and 7 mo for construction activities. A key element to completing the work on an expedited schedule was the cooperation among all entities involved, including the U.S. EPA, the CM, the Contractor, representatives from State and local agencies and the local residents.

The schedule constraints were a primary factor in developing the design approach. The key personnel on the design team visited the site soon after project initiation to evaluate existing conditions and to contact local utilities and agencies. Because some of the existing site data were not adequate to complete the design, methods were needed to collect the necessary data without impacting the schedule.

The geotechnical data for the site were limited to soil borings along the roadway. These data were adequate to establish the structural foundation requirements for the road and on-site vault. However, additional geotechnical data were required to design the lime-stabilized subgrade for the roadway and vault. The permeability of the native soils also needed to be established to evaluate design options for the RCRA vault.

Five bulk soil samples were collected and analyzed for these physical properties. In addition, geotechnical testing was required during construction to confirm that elements of work met the specified require-

ments. Considering the expedited schedule for the project, a single procurement was used for both design and construction phase geotechnical testing support. Because the extent of geotechnical testing during construction was not well defined at the beginning of the design phase, the subcontract was bid on a unit price basis, allowing for adjustments based on the final construction specifications and the field conditions encountered during construction.

Surveying was required during the design phase to assess the topography of the proposed vault area and to ensure that the vault was constructed within the appropriate property boundaries. Benchmarks were established along the roadway, and the road design was prepared based on a limited survey of the road conducted during the RI. The roadway was surveyed in detail by the contractor at the beginning of construction. Adjustments to the designed roadway and drainage patterns were made based on this detailed survey. For example, no drainage existed south of the roadway as projected on the USGS map. Consequently, the drainage design was adjusted to direct runoff in roadway ditches east to Turtle Bayou. During clearing of the roadway alignment and the subsequent survey, a number of additional driveway culverts were identified which had not been discovered in the RI survey. The timely discovery of the drainage and culvert features allowed early adjustments and eliminated schedule impacts. Unit prices bid for culverts and ditch construction allowed equitable cost adjustments, eliminating potential schedule delays due to change order negotiation.

Because the RI concentrated on the roadway, little data were available on the extent of contamination in the vault area. Grab samples of soil were collected and tested for organic and inorganic contaminants. The analyses results were used to evaluate whether clear and grub material from the vault area had to be processed as contaminated material. If untested, the clear and grub material would have had to be considered contaminated and placed in the on-site vault. The ultimate cost of final disposal of contaminated material justified the collection of samples so that a significant portion of the material could be handled as standard clear and grub material.

Other provisions were included in the contract documents to accommodate data gaps that could not be filled within the design period. In some cases, U.S. EPA helped define the scope of work and set guidelines so the work could proceed on an expedited schedule. For example, U.S. EPA directed that the limits of highly contaminated material excavated from the roadway be as defined in the RI. Although samples were collected at the bottom of this excavation to verify that the contamination was removed, the area could be backfilled immediately, without waiting for the analytical results. The U.S. EPA also made the necessary arrangements to get access to the property during construction. This process included both temporary access during construction and permanent extension of the roadway easement for extension of the ditch construction. The U.S. EPA also made arrangements to relocate local residents for the construction period and worked with the contractor to accommodate resident access needs during construction.

Good communications and timely decisions were important elements in keeping the project on schedule during construction. The on-site Construction Manager represented the U.S. EPA and the design team and worked with the Contractor on changes due to field conditions. Monthly project meetings with representatives of the Contractor, the CM and the U.S. EPA were held to expeditiously handle any problems that arose. Turn-around time for the review of shop drawings and preparation of change orders was minimized. Shop drawings had to be reviewed within 14 days of when they were received; often, however, they were reviewed immediately upon receipt. Geotechnical field testing was also conducted in a timely manner, with the testing firm available to perform field tests within 48-hr notice. This cooperative effort allowed the construction to be substantially complete in the required 7 mo.

COSTS

This project was initially authorized as an ERA and had a funding limit of \$2,000,000. All costs associated with the project had to be within this limit, including construction and other subcontracts, engineering fees, operation and maintenance costs and expenses incurred by the U.S. EPA. Based on the preliminary cost estimate for the project of

\$1.27 million presented in the FS, it appeared that the entire project could be completed under the \$2,000,000 limit. However, when all the elements of the design were included, it became apparent that the \$2,000,000 limit would be exceeded. The actual low bid for construction was \$1,690,889. In order to have enough funding to cover other project expenses, as well as allow for contingencies in the construction cost, it was determined that this project was better suited to be conducted as a Remedial Action (RA), which does not have budget limitations, rather than as an ERA.

Although it was recognized in the early stages of design that the cost would be more than \$2,000,000, it took time for the U.S. EPA to change the funding mechanisms. The overall schedule for the project was lengthened almost 4 mo, between the time the design and bid phases were complete and the time the contract could be awarded. This delay emphasizes the importance of making sure FS costs are realistic and account for design details, since budgets are often based on this estimate.

Because of the limited data available at the time of design, the construction contract was established with a mix of fixed prices and unit prices. For cases where the scope of work was well defined, such as the vault base and the decontamination facilities, fixed prices were used. Otherwise, unit prices were used to allow for field modifications and to account for actual quantities of materials used. Since the level of personnel protection required has a significant impact on productivity, a level of protection was listed on the bid form for each item to serve as a basis for estimating the probable cost of the work. For some items, the work was divided into two levels of protection. For example, the road subgrade was treated with lime in both moderately contaminated and non-contaminated areas. Therefore, unit prices were given for preparing the lime-treated subgrade in both Level C and Level D protection. Unit prices were also bid for upgrading or downgrading from the assumed level of protection that was listed on the bid form.

During construction, the on-site Construction Manager monitored the work, reviewed the Contractor's payment requests, negotiated the payment allowances based on personal observation and records of the work and made recommendations regarding payment. He also worked with the Contractor in responding to changed field conditions, and negotiated change order costs. Costs were controlled by this careful monitoring, so that the final construction cost (including 10 change orders) was less than a 2% increase over the bid amount.

EFFECTIVENESS OF REMEDY

In addition to the objectives stated in the ROD, the following criteria for the remedial action were developed in the RI/FS Report to meet the cleanup objectives established by TWC and the U.S. EPA for Frontier Park Road:

- Improve access for equipment to the site to facilitate the planned RI sampling and monitoring of the on-site waste disposal areas and to facilitate future remedial actions
- Prevent contact with highly contaminated soils, defined as PAHs and/or TVs in excess of 100 ppm
- Minimize direct contact with moderately contaminated soils, defined as PAHs and/or TVs between 10 and 100 ppm

The asphalt road was constructed to provide access to the site, including access across Turtle Bayou. Additionally, the decontamination station by the vault was left in place for use during future site investigations. Therefore, the remedial action effectively met the first cleanup objective for improved site access.

The highly contaminated materials were excavated to the limits indicated in the RI/FS, as directed by the U.S. EPA, with revisions made to the limits based on visual observations. Samples were collected from the bottom of the excavated area to document the level of cleanup obtained. The cleanup goal established in the ROD targeted the 100 ppm level of PAHs and/or TVs. Sixteen of the 18 samples, or 89%, met the combined cleanup criteria. The cleanup goals were based on a residential setting with the potential for multiple routes of exposure due to the unimproved condition of the road. The remedial action at the site has reduced this potential for exposure. The majority of the highly contaminated material has been removed from the roadway and

is secured in an on-site facility. The placement of clean fill and installation of an asphalt road over this area (and moderately contaminated areas) has further reduced exposure potential and effectively fulfills the second and third cleanup objectives.

Hence, the requirements of the ROD were met by the remedial action. Most of the highly contaminated soils were excavated and disposed of in the project-constructed on-site storage facility, thereby mitigating the

risk of human exposure to contaminants. A new asphalt road was constructed, providing access to the site and covering areas of moderate contamination. The residents were temporarily relocated during construction, and the Contractor cooperated with the residents to provide them access to their property. Through the cooperative effort of all entities involved with the remedial action, the work at Frontier Park Road was successfully completed.

Case History: Fort A.P. Hill Dioxin incineration Project

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ABSTRACT

Metcalf & Eddy Technologies, Inc., under contract to O.H. Materials Corporation, performed the remedial action in which dioxin-contaminated soil and building debris at Fort A.P. Hill, Virginia, were thermally treated and destroyed. The site, located 60 mi south of Washington, D.C., contained 190 tons of dioxin-contaminated material. Rotary kiln incineration was chosen as the most effective method to achieve the U.S. Army's goal of ultimately disposing of the dioxin-contaminated material stored at the Fort.

This paper describes the process Metcalf & Eddy Technologies, Inc. used to develop the engineering and design report as well as the process utilized in the field to perform the work. The U.S. Army Toxic and Hazardous Materials Agency represented Fort A.P. Hill for this project and required that all actions be performed in accordance with CERCLA and ARARs.

The Engineering and Design Report was written to consider the remedial design plan, incineration technologies, standard operation procedures, sampling and analysis plan, site-specific health and safety plan and the project management plan. As the report was developed, Metcalf & Eddy Technologies' field management was consulted on all details to assure a practical design.

The description of the process includes a discussion of materials handling operations, materials shredding operations, rotary kiln incinerator operations, ash handling operations and sampling operations. Brief description of the quality assurance and site-specific health and safety requirements also are presented.

INTRODUCTION

In February and March of 1989, Metcalf and Eddy Technologies, Inc., under contract to O.H. Materials Corporation, performed a remedial action in which dioxin-contaminated soil and building debris were thermally treated and destroyed on-site by rotary kiln incineration. The remedial action was performed at Fort A.P. Hill on behalf of the United States Army Toxic and Hazardous Materials Agency (USATHAMA).

BACKGROUND

The Fort A.P. Hill Site, a U.S. Army installation located in Bowling Green, Virginia, had a small storage building on the facility that was contaminated by leaking containers of herbicides which were stored inside. The herbicides included 2,4-D, 2,4,5-T and silvex. Dioxins, which are known contaminants of the herbicides, were discovered in the building's wooden floor, block foundations and soil adjacent to the building. The bulk of the material contained dioxins in concentrations of 0.001 to 0.002 ppm, with the highest concentration equal to 1.030 ppm.

The contaminated materials were excavated and isolated in 35-gal

fiberboard drums and subsequently over-packed into 55-gal steel drums. A total of 1138 drums of material was stored in a secure building on the site. USATHAMA initiated a FS in July, 1987 to analyze alternatives for ultimate disposal of the dioxin-contaminated materials being stored at Fort A.P. Hill. The study was performed in accordance with the NCP which governs procedures for such studies. The draft final FS was completed in March, 1988. The preferred disposal alternative identified in the study was on-site incineration. Following review by U.S. EPA Region III and the Virginia Department of Waste Management, the FS was finalized in August, 1988.

A two-phased contract task was awarded to O.H. Materials, Corp. to prepare operating and design plans (phase I) and conduct incineration of the dioxin-contaminated material (phase II). Metcalf & Eddy Technologies, Inc. was subcontracted to prepare the design and operating plans and direct the field activities.

ENGINEERING AND DESIGN REPORT

Metcalf & Eddy, Inc. was assigned to prepare the Engineering and Design Report for the project. The report describes the specific protocols for each task that was to be carried out as a part of the remedial action. Specifically, the report included the following sections.

- Summary report
- Remedial design plan
- Review of incineration of acutely hazardous wastes
- Standard operating procedures
- Sampling and analysis plan
- Site specific health and safety plan
- Management plan

The schedule set by USATHAMA required destruction of all dioxin by Apr. 30, 1989. In order to meet this schedule, it was necessary to prepare the first draft of the over 200-page document in a period of 6 wk. This draft report was completed on time and submitted to USATHAMA for review and approval.

REGULATORY REVIEW

Regulatory participation was an integral part of the successful disposal of the dioxin-contaminated material stored at Fort A.P. Hill. All plans and reports were reviewed by both federal and state regulators as well as various Army agencies and commands. Adequate review periods were incorporated into the schedule to allow draft plans and reports to be thoroughly evaluated by the necessary parties. Timely review was crucial to maintain the stringent schedule. The U.S. EPA, Region III and the Virginia Department of Waste Management were involved with meetings with the Army prior to the conduct of the FS. Once the FS identified incineration as a potential remedial alternative, the Virginia Air Pollution Control Board became involved with reviewing

plans and reports.

In accordance with the CERCLA and SARA, a public comment period which included a public meeting was held at the completion of the FS. When these events had been completed, the FS was finalized and a ROD was prepared. The ROD contained a Responsiveness Summary which documents all questions and comments received during the public comment period and responses to the questions which were provided through the USATHAMA Public Affairs Office. Information Repositories of convenient access (e.g., local libraries) were located near Fort A.P. Hill to allow the public to review plans and reports. The ROD documented the decision to implement on-site incineration using a mobile rotary kiln.

Multiple copies of the draft operating and design plans were submitted to USATHAMA as required under contract. USATHAMA retained a copy for review and forwarded the remaining copies to the Fort A.P. Hill Environmental Office for distribution to the appropriate reviewers. Copies of all plans and reports were sent to the U.S. EPA, Region III, the Virginia Department of Waste management, the Virginia Air Pollution Control Board, Fort A.P. Hill, the U.S. Army Toxic and Hazardous Materials Agency, the U.S. Army Environmental Environmental Hygiene Agency, the U.S. Army Forces Command Environmental Office and the Department of Army Environmental Office.

Once the comments about the draft design and operating plans were received, a meeting was held in January, 1989 to discuss issues. The draft plan was then revised to incorporate the appropriate changes. This revision was a very critical part of the program since it provided the reviewing regulatory agencies with the opportunity to input their recommendations and assured the Army that all federal, state and local regulatory requirements were met.

FIELD OPERATIONS

Field Operations starting with site preparation and equipment mobilization began after the design and operating plans were finalized. The USATHAMA project officer was present for the majority of the field operations to monitor the contract, to verify that field activities were in accordance with the operating plans and to provide timely decisions when modifications to the operating procedures were required. Fort A.P. Hill personnel routinely inspected the site to monitor progress. U.S. EPA Region III personnel and their contractor provided round-the-clock oversight.

The field operation, with the exception of preliminary site preparation and ash drum disposal, took place on a 24-hr schedule for 7 wk. During this period, a group of specialty subcontractors, brought together by Metcalf & Eddy Technologies, integrated their unique capabilities to successfully carry out this remedial action project.

Mobilization

Mobilization took place in a period of 2.5 wk. During this time, a chain link fence was installed to delineate the drum storage area and the exclusion work zone area. Electric power and telephone services were brought in from the road 650 ft away. Five site support trailers, two water supply trailers and four LPG tanks were set up. As the site was being prepared, equipment arrived. The thermal destruction unit (TDU) was the largest single piece of equipment. It included an incinerator trailer, a pollution control trailer, a feed hopper and conveyor, an ash discharge hopper and conveyor, a lamella separator and vacuum filter, and several tanks for caustic and water. All of the TDU equipment was supported on steel plates placed directly on the crushed stone and required no special foundations. The other major equipment utilized on-site was a trailer mounted low speed double shredder. Wood cribbing directly under the shredder portion of the trailer was all that was required to adequately support the shredder.

A 1200-ft² temporary building constructed of modular wood framing was erected on the area between the shredder and TDU. The building was placed directly on the ground and anchored. Three strategically-located HEPA filter exhaust fans were placed inside the building to maintain negative pressure and minimize dust within the building.

All 1138 drums were brought over from the storage site to the work area; a distance of 3 mi. The drums were placed in the drum storage

area. The warehouse where the drums had been stored was cleaned with HEPA filtered vacuum cleaners.

Finally, field quality control personnel set up their field sample collection facility. They also set up an on-site computerized drum monitoring data base designed to track the materials during operations. Health and Safety personnel reviewed the site conditions and made final revisions to the site Health and Safety Plan. All personnel attended on-site safety briefings, and the operations phase was ready to begin.

Operations

After a final walk through by the U.S. EPA, USATHAMA, Fort A.P. Hill personnel and contractor representatives, the site was declared operational. All work for the next 4 wk would be carried out in Level C protection.

The operations activities included the following:

- Feeding material into the shredder
- Shredding the material
- Staging discharged shredded material within the building enclosure
- Feeding material into the TDU hopper
- Incinerating the material
- Feeding ash discharge into drums
- Storing ash drums

The 55 gal steel drum overpacks were opened on the concrete decontamination pad which was set at the gate joining the work area (Level C) and the drum storage area (Level D). A forklift with a drum handling device carried each drum to the shredder and emptied the 35 gal fiber board drum into the hopper. The empty 55 gal steel overpack was returned to the decontamination pad for decontamination.

The material entering the shredder was reduced in size and discharged within the building enclosure adjacent to the shredder. The discharged material went into one of 10 steel bins used to supply a 12-hr supply of material for the TDU.

The bins within the building enclosure were emptied into the TDU feed hopper which also was located inside the building. The material was moved within the building by a small forklift and was discharged into the TDU feed hopper by means of a self dumping mechanism on each bin.

Material was fed continuously into the TDU 24 hr/day. Material entering the TDU was carefully controlled and regulated by means of a sophisticated control system which monitored and controlled primary kiln temperatures, secondary combustion chamber temperatures, gas flow and other parameters as required by the approved Engineering and Design Report and government regulations. The unit operated using rotary kiln combustion technology. Pollution control equipments including a wet scrubbers was monitored and controlled integrally with the combustion unit by means of a computerized control center. Automatic shutdown sequences and alarms built into the control system ensured an environmentally safe operation.

The ash from the rotary kiln was discharged into 55 gal shipping drums. Forklifts fitted with drum handling devices carried these ash drums to the decontamination pad where they were given an external cleaning and transferred into the drum storage area. A separate forklift in the Level D drum storage area carried each drum to its final staging area prior to off-site disposal.

During all operations, Metcalf & Eddy quality control personnel maintained records, gathered samples and checked the overall quality of work. Ash samples taken each day were sent to an off-site laboratory for 48-hr turn-around dioxin analysis.

Health and Safety personnel held daily briefings for each shift and continuously monitored on-site personnel for conformance to safety requirements. Everyone was required to present proof of OSHA CFR 1910.120 training before being allowed into the work area. No serious injury or exposure occurred during the remedial action.

Demobilization

All equipment was systematically decontaminated in order to minimize the potential for dioxin contamination after TDU shutdown. All equipment was demobilized in a period of 1.5 wk.

OFF-SITE DISPOSAL

The drums filled with ash residue were approved for disposal at a Class I hazardous waste landfill in Oklahoma. The ash drums were removed from the site in June, 1989. Carbon filtered process water also was removed from the site in June, 1989 and sent to an approved industrial water treatment facility in New Jersey.

CONCLUSION

The remedial action at Fort A.P. Hill met the U.S. Army's objectives of ultimately disposing of the dioxin-contaminated material stored at the Fort. In achieving this objective, the U.S. Army was extremely understanding of local community concern. A tour given to the news media of the mobilized site prior to the start of operations is one example of Fort A.P. Hill openness in carrying out this remedial action. All dioxin-contaminated material was treated and ash residues were removed from the site before the end of June, 1989.

Decontamination of Explosive Contaminated Structures and Equipment

U.S. Army Toxic and Hazardous Materials Agency

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ABSTRACT

As a result of past operations, the U.S. Army has numerous buildings and large quantities of process equipment which are contaminated with explosives. The Toxic and Hazardous Materials Agency has been conducting a three-phase study aimed at developing a safe, economical and non-destructive method of rendering explosive contaminated materials ready for reuse or disposal.

In Phase I of the study, 56 technologies were assessed for possible use. Of the 56, the five most promising technologies underwent laboratory scale testing in Phase II. A thermal process which uses hot gas to heat the contaminated materials to approximately 500°F emerged from the Phase II tests as the best technology. The hot gas process was selected because of its relative safety and low labor costs.

Phase II of the development program which is now in progress is full-scale pilot testing of the hot gas decontamination process. To test how well the process works on structures, an extensive test program on a building previously used for explosive munition demilitarization was completed in August, 1987. In order to determine how effective the hot gas process is on explosive contaminated processing equipment, a flashing chamber in the Western Area Demilitarization Facility at Hawthorne Army Ammunition Plant, Nevada, was modified for hot gas testing. The series of tests was completed in September, 1989.

A wide variety of materials such as contaminated sewer lines, piping, electrical motors and mixing kettles were successfully decontaminated. Exposing items to 500°F for 12 hr. removed all the explosive contaminants present (TNT, RDX, HMX, NC and NG).

INTRODUCTION

Probably the two most common methods in present use for removing explosive material contamination are steam cleaning and decontamination by fire (burn to the ground). Steam cleaning is, in most cases, effective but provides only surface decontamination and is not effective on hard-to-access areas. It is difficult to completely decontaminate concrete with steam. Steam cleaning of complex items such as motors cannot assure that interior areas are cleaned.

Burning of structures contaminated with explosives has several drawbacks. If other structures are nearby, burning the building may be risky. Additionally, buildings with asbestos should not be burned. Finally, open burning of a contaminated structure can be viewed as an uncontrolled release of toxic substances, local and state regulators may prohibit intentional building fires.

In 1982, the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) began a project aimed at developing new, improved procedures for decontaminating structures and equipment contaminated with explosives. The goal of this ongoing project is to develop a method which will be safe, will produce little or no waste and will assure a

high degree of decontamination. Target compounds for removal are all the major military explosives (TNT, RDX, HMX, NG, Teteryl, etc.). The process to be developed would have to effectively remove contaminants from metal, wood, painted concrete and bare concrete. An additional goal of the project is to develop a decontamination method which is universally applicable and thus can be used on large structures as well as process equipment. The first phase of this project was a review of existing techniques and the consideration of novel techniques.

Thermal Decomposition Concepts

Flashblast	Contact Heating	Hot Plasma
Microwave heating	Flaming	Hot Gases
Solvent Soak/Burn	Infrared Heating	CO ₂ Laser

Abrasive Concepts

Electropolishing	Acid Etch	Scarifer
Sandblasting	Demolition	Drill and Spall
Ultrasound	Cryogenics	Hydroblasting
Vacu-blast		

Extractive Removal Concepts

Solvent Circulation	Supercritical Fluids	Rad Kleen
Surfactants	Strippable Coatings	Manual Steaming
External Steam Generator	Vapor Phase Solvent Extract	

Chemical Concepts

Radical Initiated Decomp.	Base Initiated Decomp.	Decomp. with DS2
Molten Decomp.	Sulfur Base Reduct	Sodium Borohydride
Microbial	Reduction Cleavage	Reactive Amines
Ultraviolet and Cat.	Gamma Rad.	Chromic Acid
Nucleophilic Displacement	Ozone	Ascorbate
Solid State	Gels	Foams

PHASE I OF DEVELOPMENT PROGRAM, TECHNOLOGY SCREENING:

Under contract to USATHAMA, Battelle Columbus Laboratories performed an analysis of existing explosives decontamination techniques and also developed descriptions of novel concepts. Information was gathered from government and private industry manufacturers of explosives. Government facilities were visited to inspect contaminated structures and equipment. In a July, 1983 report, Battelle documented the detailed analysis of the following technologies:

Hydrogenation

Various combinations of methods also were considered. Each technology was evaluated based on destruction efficiency, mass transfer, safety, damage to buildings, penetration depth, applicability to complex surfaces, operating costs, capital costs and waste treatment costs.

Among the thermal decomposition concepts, hot gases received the highest ranking overall and received high scores in all categories. The hot gas process involves exposing contaminated materials to hot gases in order to vaporize or decompose the contaminants. The hot gases together with the vaporized explosives and breakdown products are sent to an afterburner for complete destruction.

The burn-to-ground method received high scores in most categories but received the lowest possible scores for safety and building damage. The only thermal concept recommended for further development was hot gas treatment.

All of the abrasive concepts received poor scores for waste treatment costs. The abrasive concepts also received low scores for penetration depth. None of the abrasive concepts were considered for further development.

External steam generator (pumping steam into the structure) scored the highest of the extractive removal concepts. However, the low solubility of some explosives in hot water prevents the steam method from being universally applicable. Vapor circulation was the only extraction technology selected for further development.

Three chemical decomposition techniques were selected for further development. The concepts selected were radical initiated decomposition, base initiated decomposition and sulfur based reduction.

From the combination methods evaluated, only a combined chemical/hot gas concept was considered to be worthy of further development.

In all, 55 technologies or combinations of technologies were considered. Six concepts were selected for further investigation. The selected technologies were hot gases, combination chemical/hot gas, vapor circulation, radical initiated decomposition, base initiated decomposition and sulfur based reduction.

PHASE II, LABORATORY TESTS

In Phase II, the technologies selected from Phase I were developed in more detail. Probably the most important aspect of the development work was the laboratory tests. Test coupons of steel, painted concrete and unpainted concrete were spiked with known quantities of 2,4 DNT, 2,6 DNT, TNT, TETRYL, RDX and HMX. The test coupons were then subjected to the processes under investigation. After appropriate treatment times, the coupons were inspected for residual explosives. Hot gases and the combination of chemical/hot gases yielded the highest degrees of explosives removal. In many cases the residual explosive levels were below detection limits. Although each of the six processes evaluated in the laboratory phase of testing offered some advantages and disadvantages for particular operations, it was the hot gas process which had a greater range of applications and provided the most complete decontamination.

The laboratory tests did identify some potential problems with the hot gas process. During testing, the formation of explosive crystals on the outside surface (originally uncontaminated) of concrete test coupons indicated that hot gases may cause explosives to migrate through concrete. This finding raises the concern that during decontamination of a concrete structure, the explosives may be driven out of the structure rather than destroyed. It was also noticed that the hot gas process dried out and thus weakened the concrete.

Pretreatment of concrete with a caustic chemical led to quicker destruction of explosives and allowed hot gas decontamination to proceed at lower temperatures. Quicker destruction of explosives reduces the possibility of migration. Operating at a reduced temperature lessens the drying effects on concrete. Thus, it was concluded that the combination of chemical treatment and hot gases would be the best route to complete decontamination without migration of explosives and with minimal damage to concrete.

The hot gas process, complemented by chemical pretreatment, emerged from the laboratory tests as clearly the most promising tech-

nology for widespread application. The next step was to see how well the process would perform outside the laboratory on a contaminated building.

PHASE II PILOT TESTS:

The Cornhusker Army Ammunition Plant (AAP) Tests:

Pilot tests of the chemical/hot gas decontamination method were conducted at Cornhusker AAP in 1987. The tests were conducted for USATHAMA by Arthur D. Little, Inc. The objectives of these first pilot tests were to:

- Determine the effectiveness of hot gas with and without chemical pretreatment
- Evaluate the effects of test conditions on the integrity of an actual structure
- Provide design criteria for full-scale systems
- Provide test data for regulatory permitting of the process

After numerous potential sites were considered, a projectile washout building at Cornhusker AAP was selected as the test site. The building has concrete walls, a concrete floor and a wooden ceiling. Dimensions of the building were 25 ft. long, 25 ft. wide and 11 ft. high. Some modifications to the building were necessary such as construction of a false ceiling to protect the wooden roof, replacement of the windows and doors with sheet metal and insulation of the outside of the building. Although inspection of the building revealed some TNT contamination, the level of contamination was too low to sufficiently challenge the decontamination method. This problem was resolved by placing TNT contaminated concrete blocks, which were removed from a sump cesspool, inside the test building.

Hot gas was supplied to the building through ductwork by a 3.0 million BTU/hr. propane-fired burner. Gases exited the building into a propane-fired afterburner. Gases entering the building, exiting the building and exiting the afterburner were analyzed. In tests where chemical pretreatment was used, a solution of sodium hydroxide and dimethylformamide was employed. Thermocouples were used to monitor temperatures inside the building during treatment. Concrete samples were subjected to mechanical properties tests before and after hot gas treatment.

Conclusions drawn from the Cornhusker pilot tests were:

- Hot gas decontamination of a building is safe and feasible.
- Although treatment of surfaces with caustic chemicals did increase explosive removal on the surface of concrete, it has no effect on interior contamination. Further, longer treatment with hot gas alone should be capable of providing complete decontamination.
- The hot gas decontamination process caused the concrete block to lose 5% of its compressive strength and 20 to 30% of its bend (tensile) strength. The effects of this loss in strength would have to be judged on a case by case basis for each building treated. Of course, if the building is not going to be reused, the condition of the concrete after treatment is of no concern.
- Initial design criteria and cost estimates for decontamination of small and large buildings were developed.
- Process data, such as composition of effluent gases from the afterburner, was collected and can be used for applying for regulatory permits for future operations.

The Hawthorne AAP Pilot Tests:

Further pilot tests of the hot gas process (without chemical pretreatment) were conducted in the summer of 1989 at Hawthorne AAP. These tests were conducted for USATHAMA by Roy F. Weston, Inc. This test series was directed towards the decontamination of process equipment used in explosives operations. The objectives were to:

- Test the process on a variety of materials (vitrified clay, steel and aluminum) with variety of contaminants (TNT, NC, NG and ammonium picrate).
- Test the process on a variety of items including intricate equipment which has areas inaccessible to other treatment processes (pumps, pipes, ship mines, risers and transfer containers).
- Determine the temperatures and treatment times required to reduce

contaminant levels to below detectable limits. Define a process that will render equipment items fit for unrestricted use or disposal.

- Render large quantities of contaminated equipment fit for unrestricted use or disposal.

A flashing chamber at Hawthorne AAP was modified to accommodate the hot gas process. The same burner and afterburner that were used at Cornhusker AAP were used at Hawthorne AAP. Hawthorne AAP has a large store of equipment and munition items which require treatment. Test items were selected from Hawthorne AAP's stores, placed in the modified flashing chamber and treated with hot gas. Test samples also included highly contaminated clay pipe removed from what was once the West Virginia Ordnance Works.

Test items were sampled for explosives prior to testing. Some items were spiked with explosives. After testing, the items were sampled for residual explosives. The detection limit for explosive contamination was approximately 10 mg/m².

Conclusions for the Hawthorne pilot tests were:

- The hot gas process successfully decontaminated all items tested. TNT, RDX, HMX, DNT, NC and NG were completely removed for both exterior and interior surfaces.
- Heating contaminated items to 500°F for 12 hr. rendered the items completely decontaminated.

Stabilization of Petroleum Sludges

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ABSTRACT

Petroleum refineries historically have produced large quantities of waste acidic petroleum sludges which typically were disposed of in open pits. These practices have resulted into the need to develop a cost-effective method to prevent the migration of these materials into the environment. This paper describes the work performed in the first half of a 3-yr research effort designed to investigate methods to effectively stabilize and solidify acidic petroleum sludges.

Specific additives to achieve stabilization and solidification have been investigated including several commercial products and processes, generally proprietary in nature. Conventional stabilization agents, such as cement and fly ash, along with more innovative agents such as organically modified clays (organophilic clays) were utilized in these laboratory investigations.

A large number of stabilization agents was evaluated with regard to their effectiveness in stabilizing petroleum sludge. The solidification was evaluated quantitatively in an unconfined compression test. The Toxicity Characteristic Leaching Procedure was used to evaluate the leachability of the treated material. Results of these laboratory studies are presented along with recommendations for further testing.

The laboratory tests were found to be limited in their ability to differentiate the stabilization effectiveness for the materials tested. Despite the limitations of the test techniques, the effectiveness of a variety of stabilization mixes was assessed in relative terms, based upon comparisons of the stabilization mix test results.

In general, the organically modified clay mixes have shown the most promise in stabilizing the petroleum sludge. In the case of the organophilic clay mixes, the higher the cost of the mix, the better the performance with regard to the measured test parameters. These clays, used in conjunction with some type of binder material such as portland cement, appear to provide the system necessary to adequately stabilize and solidify organic-bearing hazardous wastes. In this system, the organic contaminants are contained by the clay and also are trapped in the physical matrix formed by the cement or other pozzolanic material.

INTRODUCTION

These investigations consisted of an evaluation of various stabilization agents for effectively stabilizing and solidifying an acidic petroleum sludge, typical of those produced by oil refineries in the period from approximately 1920 to 1970. This paper describes the results of the studies conducted during the first half of a 3-yr project designed to develop a stabilization technique which effectively stabilizes and solidifies the organic (hydrocarbon) constituents of a specific acidic petroleum sludge.

At the start of the investigation, a bibliography of applicable literature was compiled and reviewed and a survey of commercial vendors was undertaken to identify applicable candidate technologies available in the marketplace. These literature and vendor surveys provided the basis for selecting and evaluating additives and processes to be further studied in the laboratory¹.

Table 1.
Stabilization Mix Summary

MIX NO.	MIX COMPOSITION
1	Sludge/Attapulgite/fly Ash/Quicklime (1/0.42/0.31/0.08)
2	Sludge/Bondtone/fly Ash/Quicklime (1/0.4/0.3/0.08)
3	Sludge/Bentonite/fly Ash/Quicklime (1/0.4/0.3/0.08)
4	Sludge/Bondtone/Bentonite/fly Ash/Quicklime (1/0.4/0.2/0.3/0.08)
5	Sludge/Claytone APA/fly Ash/Quicklime (1/0.4/0.3/0.08)
6	Sludge/Attapulgite/fly Ash/Quicklime (1/0.4/0.3/0.08)
7	Sludge/Suspentone/fly Ash/Quicklime (1/0.4/0.3/0.08)
8	Sludge/Claytone 40/fly Ash/Quicklime (1/0.4/0.3/0.08)
9	Sludge/Bondtone/Diatomaceous Earth/Quicklime (1/0.4/0.3/0.08)
10	Sludge/Bondtone/fly Ash/Hydrated Lime (1/0.4/0.3/0.08)
11	Sludge/Attapulgite/Cement (V) (1/0.4/0.25)
12	Sludge/Bondtone/Cement (V) (1/0.4/0.25)
13	Sludge/Bentonite/Cement (V) (1/0.4/0.25)
14	Sludge/Suspentone/Cement (V) (1/0.4/0.25)
15	Sludge/Claytone 40/Cement (V) (1/0.25/0.4)
16	Sludge/Claytone APA/Cement (V) (1/0.4/0.25)
17	Sludge/Bentonite/Microfine Cement (MC-500) (1/0.4/0.25)
18	Sludge/Attapulgite/Microfine Cement (MC-500) (1/0.4/0.25)
19	Sludge/Sorbond CRS II (1/0/0.65)
20	Sludge/Sorbond CRS II (1/0/0.77)
21	Sludge/Attapulgite/fly Ash/Quicklime (1/0.4/0.3/0.08)
22	Sludge/Attapulgite/fly Ash/Quicklime (1/0.7/0.3/0.08)
23	Sludge/Cement (I) (1/1.5)
24	Sludge/Cement (II) (1/1.5)
25	Sludge/Suspentone/Cement (I) (1/0.4/0.5)
26	Sludge/Fujibeton & Claytone APA (1/0.6)
27	Sludge/Fujibeton & Claytone APA (1/0/1.0)
28	Sludge/Cement Kiln Dust (1.0/1.0)
29	Sludge/Cement Kiln Dust (1.0/1.5)
30	Sludge/Bentonite/Microfine Cement (MC-500) (1/0.4/0.25)
31	Sludge/Bentonite/Microfine Cement (MC-100) (1/0.4/0.25)
32	Sludge/Cement Kiln Dust/Soluble Sodium Silicate (1/1/0.1)
33	Sludge/Cement Kiln Dust/Soluble Sodium Silicate (1/1/0.2)
34	Sludge/Cement (I)/Soluble Sodium Silicate (1/1.5/0.375)
35	Sludge/Claytone APA/Cement (I)/Soluble Silicate (1/0.4/0.25/0.15)
36	Sludge/P-40/P-27 (Silicate Technology) (1/0.3/0.3)
37	Sludge/P-40/P-27 (Silicate Technology) (1/0.6/0.6)
38	Sludge/Sorbond CRS II (1.0/1.0)
39	Sludge/2H/Cement (I) (1/0.4/0.5)
40	Sludge/TS-55/Cement (I) (1/0.4/0.5)
41	Sludge/Claytone 40/Microfine Cement (MC-500) (1/0.4/0.25)
42	Sludge/Claytone 40/Microfine Cement (MC-100) (1/0.4/0.25)
43	Sludge/Suspentone/Cement Kiln Dust (1/0.4/0.5)
44	Sludge/Bondtone/fly Ash/Quicklime/Silicate (1/0.3/0.5/0.1/0.1)
45	Sludge/Claytone APA/MC-500/Soluble Silicate (1/0.4/0.25/0.15)
46	Deionized Water/Claytone 40/Cement (I) (1/1.2/0.75)
47	Deionized Water/Bentonite/Cement (I) (1/1.2/0.75)
48	Sludge/Cement (I)/Bentonite/fly Ash (1/0.4/0.1/0.1)
49	Sludge/Cement (I)/Bentonite/fly Ash (1/0.4/0.1/0.1)
50	Sludge/Cement (I)/Bentonite/fly Ash (1/0.4/0.1/0.1)

A laboratory testing program was developed which included physical and chemical characterizations of the untreated sludge and of the treated material after mixing and after a 2-wk curing period. Results of these initial laboratory studies will be used to refine the stabilization methods in the second half of the investigation which will include full-scale field studies.

The stabilization agents employed in the investigation include those used in mixes described in the literature. Products from commercial vendors as well as other generic materials were incorporated into this investigation. The mix ingredients are listed on Table 1 and described more fully elsewhere². In summary, the testing program included mixes from previous studies³ and custom mixes employing sorbents such as processed clays, organically modified clays, binding agents, soluble silicates and proprietary agents from vendors. The ingredients were mixed with the sludge in various combinations and proportions aimed at stabilizing the acidic petroleum sludge. The mixing procedures and methods of evaluating the treated material are described elsewhere⁴. Studies also were conducted to evaluate the sorption capacity of the various organophilic clays⁵.

The laboratory testing program consisted of physical and chemical testing of both the untreated sludge and the stabilized product. Table 1 presents a summary of the first 50 stabilization mixes, including the proportions by weight of each of the stabilization mix ingredients.

The unconfined compression test results for those mixes which contained sludge ranged from 2 to 90 psi. These data emphasize the inhibition of hydration reactions due to the presence of the organic sludge. For the mixes which contain sludge, five of the six strongest mixes, as evaluated by the unconfined compression test, contain an organophilic clay. This result indicates the strength benefits which result from the addition of an organophilic clay.

The chemical testing consisted of performing a modified TCLP test on each specimen after it had been tested in unconfined compression. The concentrations of the identified chemical constituents were compared with those limits specified in the TCLP. In all cases, the reported concentrations of the selected organic compounds were below the maximum concentration levels specified by the TCLP.

ANALYSIS OF TEST RESULTS

The following sections view the data from the perspective of specific groups of mixes. Average values for the entire set of mixes are compared to the average values for each subset of mixes (Table 2). The subsets consist of mixes which contain specific stabilization agents.

Fly Ash and Lime Mixes

Fifteen of the 50 stabilization mixes contained fly ash. The fly ash and lime mixes initially were stronger than the mixes without these ingredients but, with curing, this strength advantage disappeared. High phenol concentration and sum of organics values indicate that the organic constituents present in the sludge were not contained by the mixes with fly ash and lime as well as by some of the other mixes.

Cement Mixes

Of the 50 stabilization mixes, 23 contained cement. As seen in Table 2, there are only slight differences between the averages for the cement mixes and the averages for all the mixes, with regard to the strength and chemical parameters. These similarities in average values between the cement mixes and the entire set of mixes are due, in part, to the large number of cement mixes contained in the data set.

Most of the stabilization mixes with Type I, II or V portland cement resulted in mixes with favorable total organic carbon values but the relative hydrocarbon concentration values for these mixes varied. The mixes containing microfine cement, MC-500 or MC-100, had favorable relative hydrocarbon concentration numbers but mixed total organic carbon results. The strengths, as measured by the unconfined compression test, were inconsistent for both the cement and the microfine cement mixes. The stabilization mixes were intentionally designed to limit the amount of cement (binder material) so that the effects of the adsorbent (primarily the organically modified clays) could be observed. With the addition of more binder material, it is believed that the strength of the treated product would increase.

Organically Modified Clay Mixes

The mixes containing an organically modified clay include 24 of the 50 stabilization mixes. The as-compacted strengths for the organoclay mixes are similar to those of all of the mixes. However, after the organophilic clay mixes had been cured, their strengths were higher than those of the other mixes. The ability of the organophilic clay to adsorb the organics reduces the organic inhibition for the cement hydration process.

In the chemical analyses, the carbon analyses, phenol concentrations and sum of organics are lower for the organoclay mixes than for the entire data set but the relative hydrocarbon concentration averages are approximately the same. The results for the mixes containing an organically modified clay generally are favorable with respect to containing the organic constituents of the sludge.

Table 2.
Test Average for Stabilization Mix Groupings

GROUPING	NO. OF MIXES	INITIAL	VOLUME	WET	DRY	CURED	UNIT	TOTAL	TOTAL	RHC	PHENOL	SUM OF
		POCKET. PENETR.	CHANGE	DENSITY	DENSITY	POCKET. PENETR.						
		(psi)	(%)	(g/cm ³)	(g/cm ³)	(psi)	(psi)	(%)	(PPM)	(PPM)	(PPM)	(PPB)
ALL MIXES	48	10.9	44.6	1.34	1.03	38.6	15.5	7.3	118.15	130.92	1.32	289.18
FLY ASH/LIME	15	15.3	45.5	1.29	1.00	35.9	11.7	8.1	130.14	147.84	1.42	418.36
CEMENT	23	10.0	42.3	1.36	1.02	38.9	16.9	8.1	112.61	118.04	1.21	292.17
ORGANOCLAYS	24	13.4	45.1	1.27	0.97	43.6	21.5	6.0	76.21	81.03	1.33	248.91
BENTONITE/ATTAPULGITE	15	13.7	38.7	1.33	0.99	33.3	10.9	10.1	172.53	190.39	1.13	461.10
SODIUM SILICATE	6	11.8	58.7	1.38	1.06	51.0	22.4	3.5	111.23	121.17	1.45	197.00
CEMENT KILN DUST	5	5.3	49.4	1.50	1.20	42.4	9.5	4.7	156.84	198.25	1.44	258.20
PROPRIETARY	7	5.8	42.2	1.35	1.03	30.6	18.1	9.1	105.87	110.97	1.04	69.17

Bentonite and Attapulgite Mixes

The mixes which contained an unmodified clay, either bentonite or attapulgite, comprised 15 of the 50 stabilization mixes. The unmodified clay mixes were weaker and more plastic, on average, than all of the mixes being studied.

With regard to the chemical analyses, the average values for the carbon, phenol and organics summation analyses are higher for the unmodified clay mixes than for the entire set of mixes. However, the average relative hydrocarbon concentration value for these mixes is slightly lower than for all of the mixes.

Soluble Sodium Silicate Mixes

Of the 50 mixes prepared in these investigations, 6 contained soluble sodium silicate. The average cured strength of the silicate mixes is higher than the average cured strength of all of the mixes. The soluble sodium silicate brought about a noticeable increase in the strength of the stabilization mixes. The chemical analyses revealed that the average test parameter values for the soluble sodium silicate mixes did not significantly vary from the average values for the entire set of mixes. It is concluded, therefore, that, should strength increases be needed, soluble sodium silicates may be added to the stabilization mix.

Cement Kiln Dust Mixes

Cement kiln dust mixes accounted for five of the 50 stabilization mixes analyzed. The average computed bulk densities for these mixes were greater than the overall mix averages. In the case of most soil-like materials, denser materials correspond to greater strengths but these values indicate that, for the cement kiln dust mixes, the densities are higher, on the average and the unconfined compressive strengths are lower than the entire set of mixes.

The chemical parameters indicate that the average leachate total organic carbon values for the cement kiln dust mixes are higher than the overall average mix values. This indicates that, with respect to the carbon analyses, the cement kiln dust mixes are less effective in containing the organic constituents of the sludge than the entire set of mixes.

Proprietary Mixes

The proprietary mixes accounted for seven of the 50 mixes tested. These mixes included ingredients from American Colloid Company, Waste Solutions International and Silicate Technology Corporation. These mixes were grouped together to compare the results of commercial mixes to those of generic products. Overall, the proprietary mixes are not as strong as the other mixes.

The chemical analyses reveal that, for the proprietary mixes, the average values for relative hydrocarbon concentration, phenol concentration and summation of organic constituents are lower than the overall average mix values. A few of the proprietary mixes were exceptionally soft and plastic and, as a result, did not provide an acceptable surface area for leaching in the TCLP.

These leach test results are artificially low as a result of the plastic nature of the material. In general, the data revealed that the proprietary mixes contained the petroleum sludge to a greater degree than the entire set of mixes.

TEST RELATIONSHIPS

The strength of the samples, as measured by a pocket penetrometer and an unconfined compression test, was analyzed. Figure 1, As-Compacted Pocket Penetrometer vs. Unconfined Compressive Strength, did not reveal a well-defined relationship. This result demonstrates that the pocket penetrometer is of limited usefulness in predicting the unconfined compressive strength of these stabilized sludges.

The relationship between the chemical test parameters and the unconfined compressive strength of the samples was also examined. The total organic carbon was plotted against the unconfined compressive strength in Figure 2. No relationship was apparent between these two test parameters. The graph of relative hydrocarbon concentration versus unconfined compressive strength is shown on Figure 3. The data are scattered, with relative hydrocarbon concentration values varying for similar unconfined compressive strength values. The stronger sam-

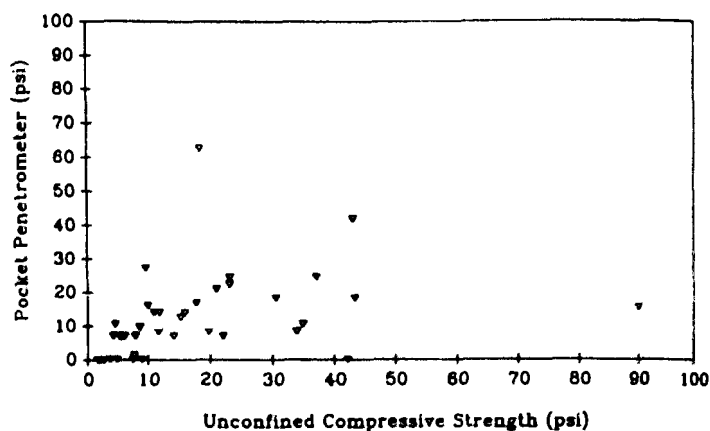


Figure 1.
As-Compacted Pocket Penetrometer vs. Unconfined Compressive Strength

ples had similar relative hydrocarbon concentration values which were approximately in the middle of the range of recorded values.

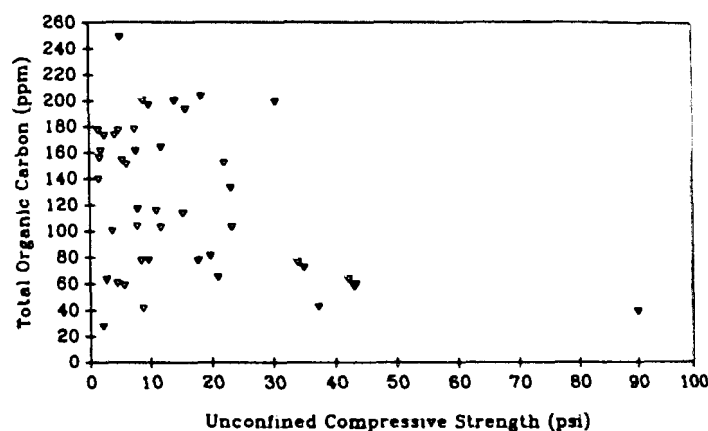


Figure 2.
Total Organic Carbon vs. Unconfined Compressive Strength

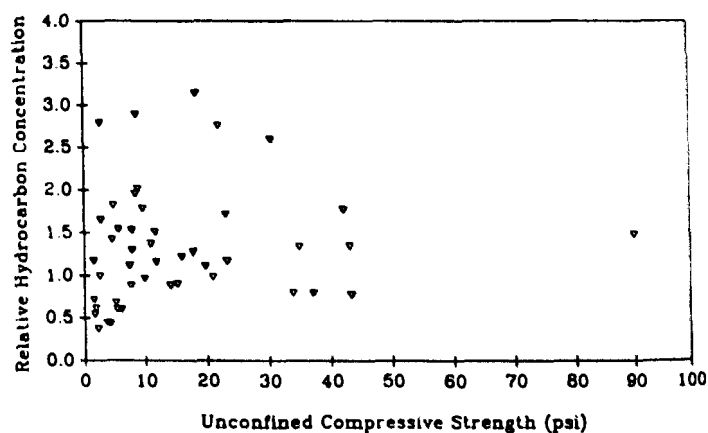


Figure 3.
Relative Hydrocarbon Concentration vs.
Unconfined Compressive Strength

Phenol concentration data and unconfined compression test data were compared in Figure 4. There was no distinct relationship between these two test parameters.

The relationships between the chemical test parameters were also investigated. Total organic carbon and total carbon concentrations were plotted on Figure 5. A strong relationship existed for these data. For lower values, the total carbon values were approximately equal to the total organic carbon values. As the concentrations increased, the total

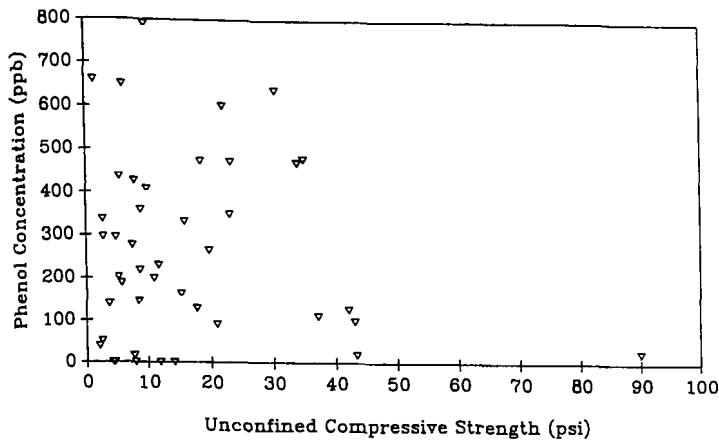


Figure 4.
Phenol Concentration vs. Unconfined Compressive Strength

carbon values were slightly greater than the total organic carbon values. In general, most of the carbon measured in the leach extract was organic carbon.

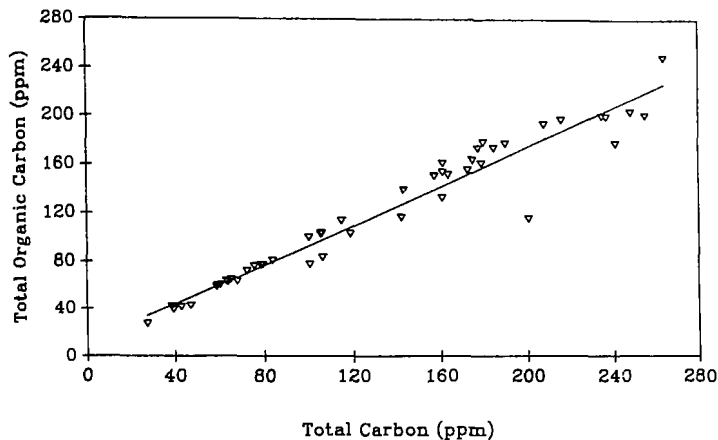


Figure 5.
Total Organic Carbon vs. Total Carbon

Since total organic carbon was related to the sum of organics, Figure 6 and the sum of organics was weakly related to the relative hydrocarbon concentration, Figure 7, it was anticipated that the total organic carbon and the relative hydrocarbon concentration would be related in some way. As shown in Figure 8, there is no distinct relationship between the total organic carbon values and the relative hydrocarbon concentration values. The data points are scattered, with low relative hydrocarbon concentration values existing with both high and low total organic carbon values. This finding gives rise to the dilemma as to which parameter is a better indicator of performance, total organic carbon or relative hydrocarbon concentration.

In summary, there is not a well-defined relationship between strength, as determined by an unconfined compression test and organic concentration in the mix extract, measured by total organic carbon, total carbon, relative hydrocarbon concentration, phenol concentration or summation of organic concentration. Mixes with high strengths did not necessarily have low total organic carbon or relative hydrocarbon concentration values. As expected, when greater quantities of cement were added, the strength of the stabilization mix increased. However, it was not necessarily true that the stronger mixes prevented contaminants from leaving the solidified matrix during a leach test. The possible exception may be indicated by the observation that at strengths above 35 psi, leachability generally was reduced.

MIX REPRODUCIBILITY

The ability to obtain consistent test results for the same mix design

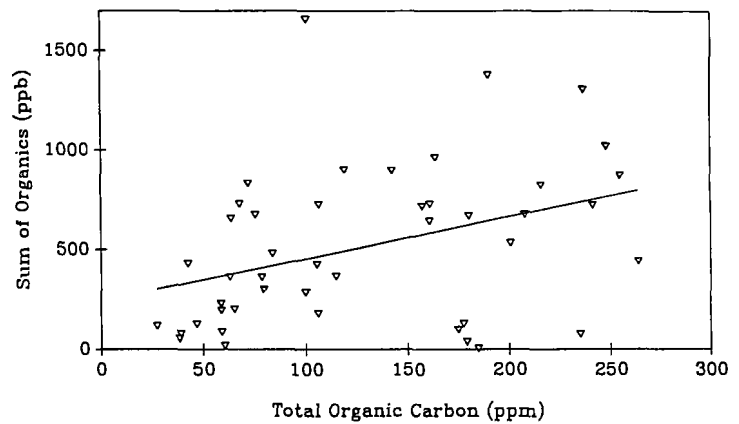


Figure 6.
Sum of Organics vs. Total Organic Carbon

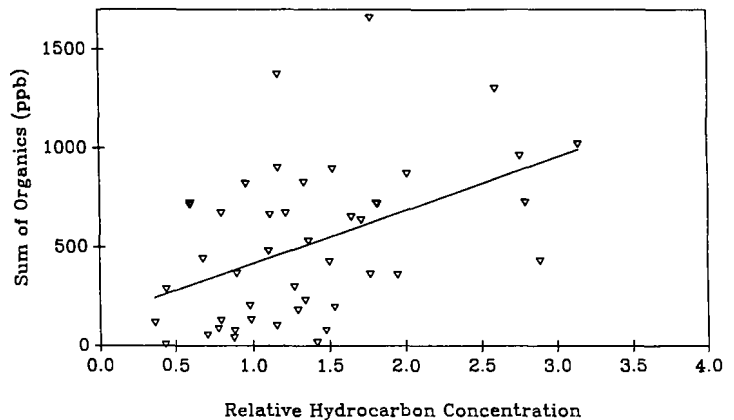


Figure 7.
Sum of Organics vs. Relative Hydrocarbon Concentration

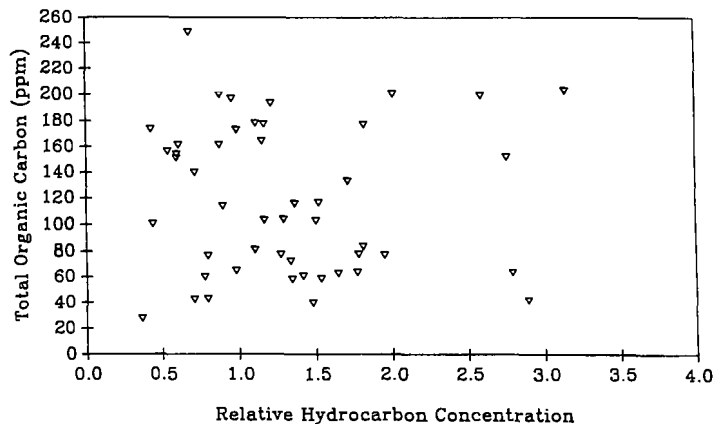


Figure 8.
Total Organic Carbon vs. Relative Hydrocarbon Concentration

was evaluated by testing replicate samples. All of these mixes are shown in Table 3, along with the corresponding test results. In general, the physical test parameters reveal that good reproducibility exists among the replicate samples. The chemical results also reveal that there is generally good reproducibility. In summary, this limited replicate testing indicates a high degree of confidence in the results of the chemical analyses.

Table 3
Mix Reproducibility

		UNTREATED SLUDGE				TREATED SLUDGE (2-WEEK CURE)					
REPLICATE MIXES AND BLANKS		BULK		WATER		LOSS ON		WET		DRY	
MIX NO.	MIX COMPOSITION	pH	DENSITY (g/cm ³)	CONTENT (%)	IGNITION (%)	pH	DENSITY (g/cm ³)	DENSITY (g/cm ³)	CONTENT (%)	IGNITION (%)	UCS (psi)
6	Sludge/Attapulgite/Fly Ash/Quicklime (1/0.4/0.3/0.08)	7.0	0.99	43.3	88.8	9.0	1.26	0.87	30.8	35.7	23.13
21	Sludge/Attapulgite/Fly Ash/Quicklime (1/0.4/0.3/0.08)	6.0	1.01	47.7	93.2	11.0	1.29	0.95	26.0	36.8	30.52
17	Sludge/Bentonite/Microfine Cement (MC-500) (1/0.4/0.25)	6.0	1.02	24.4	90.9	dry	1.33	0.95	28.2	40.2	6.22
30	Sludge/Bentonite/Microfine Cement (MC-500) (1/0.4/0.25)	6.0	1.01	44.7	87.9	dry	1.23	0.85	31.2	44.7	4.29
46	Deionized Water/Claytone 40/Cement (1) (1/1.2/0.75)	*	*	*	*	dry	1.34	0.96	26.8	24.8	505.61
47	Deionized Water/Bentonite/Cement (1) (1/1.2/0.75)	*	*	*	*	dry	1.59	1.09	31.6	7.3	266.76
48	Sludge/Cement (1)/Bentonite/Fly Ash (1/0.4/0.1/0.1)	5.0	1.04	37.6	86.0	8	1.49	1.18	20.8	36.1	1.59
49	Sludge/Cement (1)/Bentonite/Fly Ash (1/0.4/0.1/0.1)	6.0	1.03	36.4	87.5	8	1.43	1.10	22.9	34.1	1.96
50	Sludge/Cement (1)/Bentonite/Fly Ash (1/0.4/0.1/0.1)	6.0	1.03	36.8	87.6	8	1.45	1.07	25.9	32.6	1.75

		SELECTED CHEMICAL ANALYSES OF THE TREATED SLUDGE (2-WEEK CURE)													
		TOTAL	RELATIVE												
		ORGANIC	HYDROCARBON												
MIX NO.		CARBON	CONC.	PHENOL	DECANE	BENZYL	METHYL	BENZYL	ACETATE	NAPHTHALENE	DIBUTYL	CHROMIUM	LEAD	NICKEL	CADMIUM
		(PPM)	(RHC)	(PPB)	(PPB)	(PPB)	(PPB)	(PPB)	(PPB)	(PPB)	(PPB)	(PPM)	(PPM)	(PPM)	(PPM)
6		133.1	1.708	348	ND	38	257	ND	12	ND	0.02	0.00	0.00	0.00	0.10
21		199.2	2.592	658	4	ND	614	29	9	ND	0.07	0.00	0.00	0.00	0.00
17		150.8	0.596	650	15	3	ND	29	7	ND	0.64	0.10	0.00	0.00	0.00
30		173.3	0.431	ND	ND	ND	ND	ND	ND	2	0.50	0.00	0.20	0.00	0.03
46		2.7	0.159	*	*	*	*	*	*	*	0.00	0.00	0.05	0.00	0.00
47		2.5	0.111	*	*	*	*	*	*	*	0.27	0.10	0.34	0.00	0.07
48		139.4	0.712	*	*	*	*	*	*	*	0.11	0.00	0.32	0.00	0.02
49		161.2	0.608	*	*	*	*	*	*	*	0.00	0.00	0.00	0.00	0.00
50		155.6	0.540	*	*	*	*	*	*	*	0.00	0.00	0.43	0.00	0.00

ND - NON-DETECTABLE
* - NOT AVAILABLE

CONCLUSIONS AND RECOMMENDATIONS

Test Applicability

The stabilization mixes in this study were evaluated based upon a chemical leach test (a modified form of the Toxicity Characteristic Leaching Procedure) and a strength test (unconfined compression test). The results from these tests did not correlate well with each other. There was not a well-defined relationship between strength and organic concentration in the TCLP mix extract, measured by total organic carbon, total carbon, relative hydrocarbon concentration or specific compound concentrations.

Stabilization Mix Investigations

From the investigations described herein, the effectiveness of a variety of stabilization mixes was assessed and some general conclusions were reached:

- Mixes with greater quantities of cement generally were stronger. However, the stronger mixes did not necessarily prevent contaminants from leaching from the solidified matrix during the leach test.
- The mixes containing fly ash did not have high strengths and did not effectively immobilize some of the organic contaminants, as reflected by the relative hydrocarbon concentration values and the phenol concentration values.
- The unmodified clays, attapulgite and bentonite, also had little success in containing the organics, as indicated by their total organic carbon values.
- Soluble sodium silicates may be added to the stabilization mixes to increase strength.
- The microfine cement mixes provided some success with regard to containing the hydrocarbons, as quantified by the relative hydrocarbon concentration values but had mixed success with regard to other

organic parameters.

- In general for the mixes which contain an organophilic clay, the more expensive the mix, the better the mix performance with regard to the measured test parameters.

The organically modified clays have shown the most promise and will be investigated further in order to optimize their impact on organic contaminant immobilization. These clays, used in conjunction with some type of binder material such as portland cement, may provide the system necessary to adequately stabilize and solidify organic-bearing hazardous wastes.

The principal problem with the organophilic clays is their high unit costs. These clays were much more expensive than any of the other stabilization agents and, although technically more successful than some of the other mixes, were not economically feasible as a treatment alternative. As a result, mixes with lower proportions of organophilic clays will be investigated in an attempt to reduce the total mix cost while effectively stabilizing the acidic petroleum sludge.

The conclusions reached in this paper are based upon the initial test data, which have limited statistical significance. Further testing is necessary to strengthen and confirm these findings. Also, these conclusions may only be directly applicable to the specific petroleum sludge used in these studies. However, the findings may be useful as a starting point for stabilization studies involving other types of hazardous organic wastes.

ACKNOWLEDGEMENTS

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REFERENCES

1. Pancoski, S.E., Evans, J.C., LaGrega, M.D. and Raymond, A., "Stabilization of Petrochemical Sludges," *Hazardous and Industrial Waste*, Proceedings of the Twentieth Mid-Atlantic Industrial Waste Conference, Ed. Ma. M. Varma and J. H. Johnson, Jr., June, 1988, pp. 299-316.
2. Pancoski, S.E., "Stabilization of Petroleum Sludge," Masters Thesis, Civil Engineering, Bucknell University, Lewisburg, PA, May, 1989, University Microfilms International.
3. Van Keuren, E.L., "Advanced Laboratory and Pilot Field Study of Hydrocarbon Refining Waste Stabilization with Pozzolans," Masters Thesis, Civil Engineering, Drexel University, Philadelphia, PA, June 1987.
4. Evans, J.C., LaGrega, M.D., Pancoski, S.E. and Raymond, A., "Methodology for the Laboratory Investigation of the Stabilization/Solidification of Petroleum Sludges," Superfund '88, Proceedings of the Ninth National Conference, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 403-408, November, 1988.
5. Evans, J.C.; and Pancoski, S.E., "Organically Modified Clays," Transportation Research Board Publication, Preprint Paper No. 880587, Jan, 1989.

Composting as a Method for Hazardous Waste Treatment

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ABSTRACT

Westinghouse Environmental Services and Geotechnical Services, Inc (Westinghouse) conducted a bench-scale compost treatability study of an ethylene glycol waste sludge from a CERCLA site associated with a fiber manufacturing plant. The study was performed as part of a feasibility study of remedial alternatives for disposing of the sludge. The site required remediation because leachate from the landfill contaminated an aquifer supplying drinking water to nearby residences. The waste sludge's composition changed with location in the landfill, but contained up to 3,200 mg/kg ethylene glycol, 128,000 mg/kg TOC and 6,400 mg/kg antimony. The objectives of the treatability study were:

- To evaluate the potential for biodegradation of the ethylene glycol sludge using the compost process
- To determine the degree to which metals in the sludge would be immobilized
- To determine sludge to bulking agent mix rates and other operating parameters

Results indicated that more than 99% of the BOD, COD and TOC were removed. Ethylene glycol was reduced by more than 94%. With the exception of Barium, RCRA metals were not leachable. However, Barium in the leachate was below the U.S. EPA EP toxicity standard of 100 mg/L. A mix of 15% waste sludge to wood chips, by weight, was identified as an optimal mix for the composting process. Pile temperatures of up to 110°F were observed for that mix.

INTRODUCTION

Composting is a biological process used primarily for the stabilization of organic materials that are relatively high in volatile solids such as manures and sludges (Sikora and Sowers, 1985)¹. The degradation of the volatile solids results in the production of heat and in a subsequent temperature increase characteristic of the composting process. The use of composting as a means of degrading organic industrial wastes has received considerable attention recently. An in-vessel composting system may be beneficial for the degradation of toxic constituents that may be subject to volatilization and/or leaching. Rose and Mercer (1986)² found that the insecticides diazinon, parathion, and dieldrin degraded rapidly when composted with cannery wastes. Deever and White (1978)³ found significant reductions in toluene-hexane extractable grease and oil after composting petroleum refinery sludges. Sikora et al. (1982)⁴ showed in a preliminary laboratory study that composting however was no more efficient in degrading pentachlorophenol and pentachloronitrobenzene than degradation at a constant temperature of 25°C. Although composting as a treatment method for municipal wastes and sludges has been done for some time, (Wilson and Dalmat, 1984)⁵, composting of industrial and hazardous wastes is rarely

done. This paper details the bench-scale testing procedures and results of a study conducted by Westinghouse Environmental and Geotechnical Services, Inc. (Westinghouse) on the composting of ethylene glycol wastes at a Superfund site.

BACKGROUND

A remedial investigation (RI) conducted by Westinghouse in June, 1986, found groundwater contamination linked to material landfilled at the industrial plant in North Carolina. The primary source of the contamination was wastes from the Glycol Recovery Unit (GRU) buried in trenches during the early 1960s. The RI, feasibility study (FS) and remedial design (RD) for groundwater remediation at the site have been completed and are the source of another paper. This paper focuses on the treatment of the GRU material.

The FS for the source material identified composting as a method applicable for ethylene glycol waste treatment. To verify that theory, a treatability study was conducted on the GRU material.

The objectives of the treatability study were:

- to assess the ability of composting to degrade organic materials in the GRU sludge
- to determine the proper mix ratios of GRU sludge to bulking agent, inoculants, etc.
- to determine operational parameters such as run time, optimal pH and moisture content, peak temperature, etc.
- to determine if the resulting residual from the composting operation system would be classified as hazardous based on U.S. EPA's definition of hazardous waste
- to determine operational efficiencies for the development of cost estimates for full-scale operation

MATERIALS AND METHODS

The GRU material used in this study was white to grey in color and had a consistency ranging from soft cottage cheese-like material to dry friable material. The GRU material had an average content of ethylene glycol, chemical oxygen demand (COD), and total organic carbon (TOC) of 1,900 mg/kg, 120,000 mg/kg and 120,000 mg/kg, respectively.

Additives used for composting included wood chips, top soil and sewage sludge, dry molasses, ammonium nitrate, 10-10-10 fertilizer and lime. The purposes of the additives are as follows:

- The wood chips were added as a bulking agent and an additional source of carbon.
- The top soil and sewage sludge were added as a source of diverse microorganisms or "inoculants."
- Dry molasses was added to provide a readily available carbon source to stimulate microbial growth during acclimation.
- Ammonium nitrate and 10-10-10 fertilizer were added as a supplemental source of nitrogen, potassium and phosphorus.
- Lime was added periodically to maintain the pH above 6.0 for maximum microbial activity.

Reactors were constructed using 32-gal plastic trash cans. Air was

(1) Westinghouse Environmental and Geotechnical Services, Inc.

(2) U.S. Department of Agriculture, Agricultural Research Service
Beltsville, Maryland

supplied using a blower and PVC pipe diffuser and distribution system. Air was controlled using valves located at each reactor. Excess moisture was removed using an underdrain. Ten reactors were used for this study. A typical reactor is shown in Figure 1.

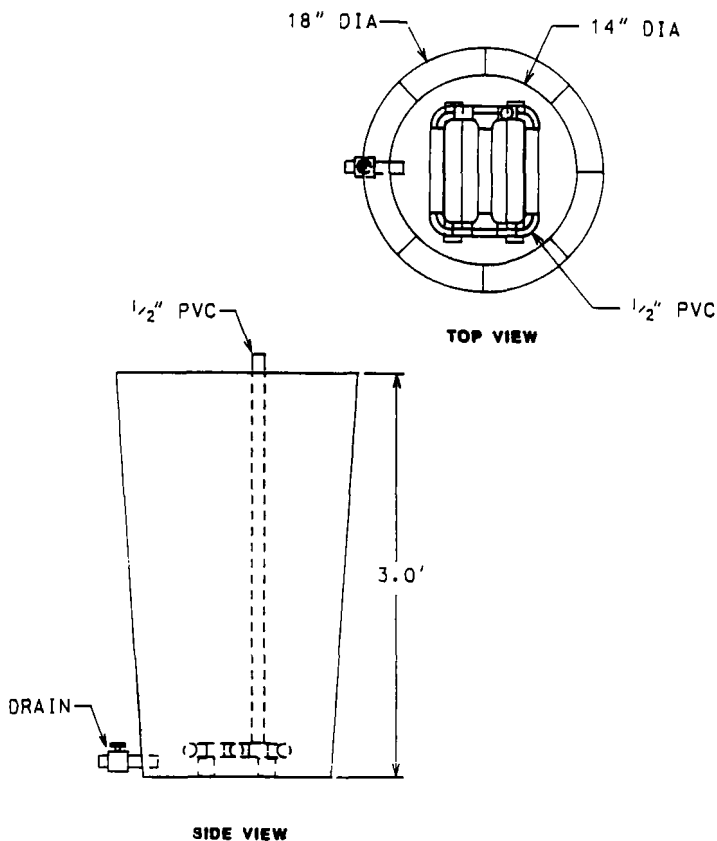


Figure 1
Compost Reactor Design

The reactors were set up to simulate composting using different concentrations of GRU material and wood chips. Parallel reactors at 20%, 10%, 5%, 2.5% and 0% GRU material by volume were evaluated. The reactors containing no GRU served as controls. Table 1 contains data on the compost mixes.

Table 1
Compost Mix Ratios

Volumetric Ratio of GRU Sludge to Wood Chips	Reactor	Gallons of GRU Sludge	Gallons of Wood Chips	Gallons of Dry Molasses	Gallons of Sewage Sludge	Gallons of Soil	Cups of Ammonium Nitrate	Cups of 10:10:10 Fertilizer
0:100%	1, 10	0	40	5	2	3	1 1/2	3/4
2.5:97.5%	8, 9	1	39	2	2	3	3/4	1/2
5:95%	6, 7	2	38	2	2	3	1	3/4
10:90%	2, 3	4	36	2	2	3	1 1/4	3/4
20:80%	4, 5	8	32	2	2	3	2 3/4	1 1/2

The samples were mixed in a portable mixer. To thoroughly coat the wood chip particles, the GRU sludge material was first mixed with tap water until fluid. Fertilizer, lime and molasses were added to the liquefied GRU sludge. This mixture was then blended in the mixer with the wood chips. The sewage sludge and soil were then added. Water was added into the mixer to a predetermined moisture content. A 20-gal sample of the mix was placed in the reactor.

For process control, temperature, percent oxygen, moisture and pH were monitored throughout the test. The temperature was monitored daily as an indication of biological activity. The percent oxygen was monitored daily, and the air flow was adjusted so that at least 10% oxygen

was maintained in the exhaust gases. Moisture and pH were measured once a week to assure that the pH was maintained above 6 and that the moisture was sufficient for microbial growth (40-60%, w/w) but not in excess so as to result in anaerobic conditions.

Analyses were conducted using methods similar to that found in Standard Methods (1975)⁶ to determine:

- removal efficiencies of biochemical oxygen demand (BOD), COD and toxic organic compound (TOC)
- degradation rate of ethylene glycol
- nutrient levels - to assure sufficient nutrients to maintain growth
- initial and residual compounds and the mobility of those compounds

RESULTS

Summary of removal efficiencies is presented in Table 2. Figures 2, 3, 4 and 5 present changes in BOD, COD, TOC and ethylene glycol concentration plotted against the test time. The data indicate:

- Removal efficiencies generally were in excess of 95% for the parameters evaluated.
- The removal of the ethylene glycol was accomplished in less than 30 days with all reactors except the 20% mixtures took considerably longer for acclimatization than the other reactors.

A consistent and strong increase in temperature was observed in all reactors except the 20% mixture indicating microbial activity. Reactor temperatures exceeded 105°F which is indicative of the biological activity and the insulation of the mass in the reactor. Percent oxygen in the reactors which proved useful for controlling process airflow rate also indicated significant microbial activity throughout the test.

Table 2
Contaminant Removal Efficiencies

Reactor	BOD Removal Percent	COD Removal Percent	TOC Removal Percent	Glycol Removal Percent
1	97.9	81.1	92.9	N/A
2	96.5	92.1	96.9	100.0
3	88.9	89.2	97.1	100.0
4	82.1	96.8	92.1	97.6
5	75.1	98.7	89.3	94.4
6	98.6	88.9	96.3	100.0
7	96.6	91.8	96.2	100.0
8	93.4	95.4	96.3	100.0
9	96.3	90.7	94.5	100.0
10	98.4	74.0	93.7	N/A

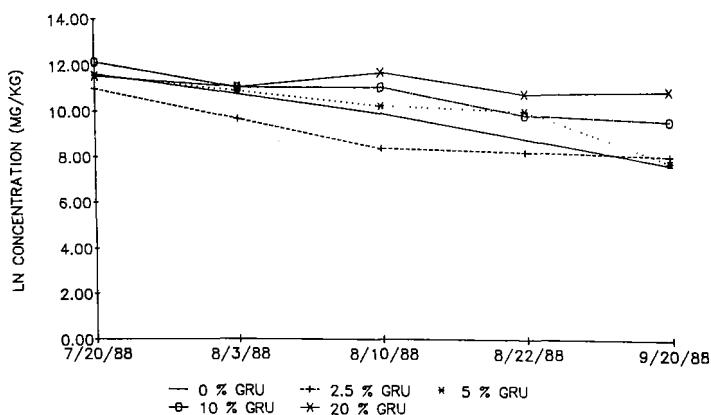


Figure 2
BOD5 vs. Time
GRU Compost

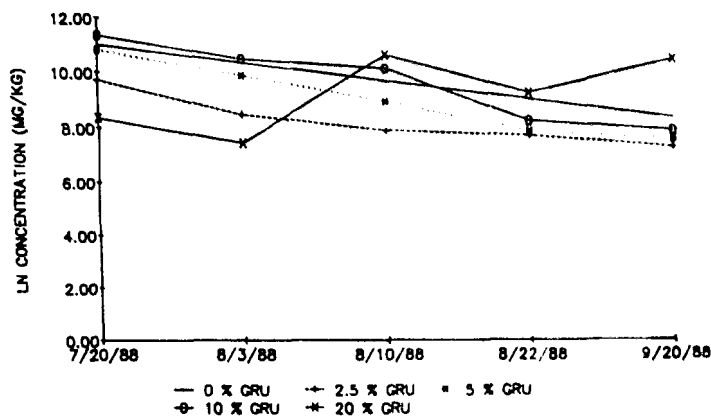


Figure 3
TOC vs. Time
GRU Compost

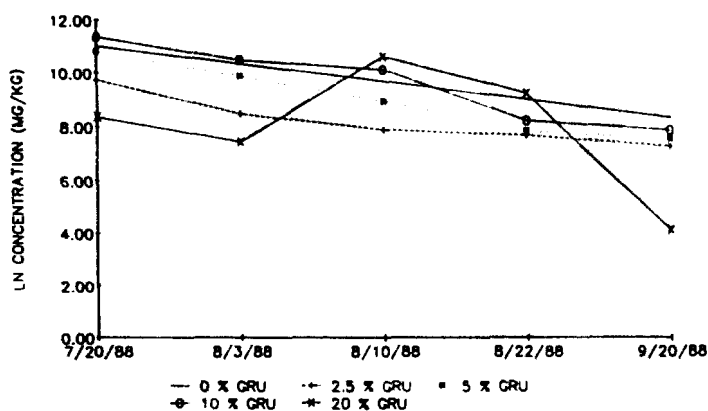


Figure 4
TOC vs. Time
GRU Compost

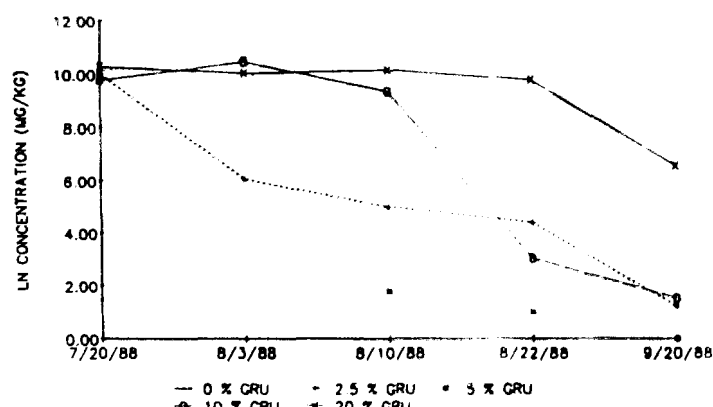


Figure 5
Ethylene Glycol vs. Time
GRU Compost

Moisture and pH controls were adequate for the microbial growth during the test. Results of pH monitoring indicate that a pH of 7 to 8.3 results in rapid BOD reduction, that the pH of the reactors dropped approximately one pH unit during the course of the process, and that 100 grams of lime a per pound of GRU sludge is adequate to maintain the pH. Moisture content did not appear to have a significant effect on the test as long as it was kept within a range of

40% to 60%.

Composting with a bulking agent would necessitate a screening step to reduce the volume of the final product for disposal. Sieve analysis indicated that 30% to 40% of the final product would pass a No. 4 sieve. Literature suggests that an overall volume reduction of 20% to 30% can be achieved during composting (Sikora et al., 1981); however, in the bench-scale tests a 10% increase in volume was observed, probably because of handling of the mixtures to add lime that took place during the runs.

EP Toxicity extractable metals analysis indicated extractable, RCRA controlled, metal levels present in the compost equal to that in the control. The concentrations allow the compost to be land disposed. Extractable Target Compound List (TCL) compounds were detected in the compost but only at concentrations from about 700 ug/kg and 3700 ug/kg. Subsequent analysis of screened compost materials indicated the presence of benzoic acid and di-n-butyl phthalate near their respective detection levels of 1000 ug/kg and 230 ug/kg. The concentrations of these components would allow land disposal of the compost.

CONCLUSIONS

Data indicate that microbial activity was occurring in the compost reactors, and that over 95% removal rates is achievable for the parameters evaluated. All mixes composted rapidly except the 20% mix by volume, which experienced a considerable lag period before showing microbial activity.

Based on the data a number of conclusions can be drawn:

- Composting is possible for use in treating the GRU sludge in preparation for land disposal
- The 10% (volumetric) GRU mix would be the best mix
- Process control data and monitoring procedures for composting were developed
- Analytical data indicate the final product can be landfilled or land applied

RECOMMENDATIONS

Although bench-scale test results show substantial degradation of the organic components of the ethylene glycol wastes, pilot-scale testing is recommended prior to full-scale use. To further test the applicability of this technology and further define operational parameters, the following tests are recommended:

- Conduct tests using concentrations between 10% and 20% GRU by volume to determine a possible higher concentration than 10% which can achieve give acceptable results
- Test the effect of an acclimated seed on the process
- Field test mixing and sieving equipment
- Consider the use of a mechanically-mixed system versus the static pile method
- To confirm test results, send a sample of the wastes to a commercial vendor of composting equipment for testing

REFERENCES

1. Sikora, L. J. and Sowers, M.A. "Effect of temperature control on the composting process." *J. Environ. Qual.* 14:434-438, 1985.
2. Rose, W. W. and Mercer, W.A. Fate of pesticides in composted agricultural wastes, National Canners Association, Washington, D.C., 27p., 1968
3. Deever, W. R. and White, R.C. Composting petroleum refinery sludges. Texaco, Inc., Port Arthur, TX. p. 24, 1978.
4. Sikora, L. J., Kaufman, D.D., Ramirez, M.A. and Willson, G.B. Degradation of pentachlorophenol and pentachloronitrobenzene on a laboratory composting. In *Proc. of the Wight Ann. Research Symp.*, Cincinnati, OH. EPA-600/9-82-002, pp. 372-381, 1982.
5. Willson, G. B. and Dalmat, D. Sludge composting facilities in the U.S.A. *Biocycle J. of Waste Recycling*, Sept/Oct issue. pp. 20-24, 1983.
6. *Standard Methods For The Examination Of Water And Wastewater*. 14th Ed. Amer. Public Health Assoc. Washington, D.C., 1193p.
7. Sikora, L. J., Willson, G.B., Colacicco D. and Parr, J.F. Materials balance in aerated static pile composting. *Jour. Water Poll. Control Fed.* 53:1702-1707, 1981.

Recycling of Battery Casings At A Superfund Site

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ABSTRACT

The NL/Gould site is a former battery recycling facility located in Portland, Oregon. As secondary lead smelting facility was in operation on the site between 1949 and 1980. Facility operations consisted of: lead-acid battery recycling; lead smelting and refining; and lead oxide production. Approximately 80,000 tons of battery casing materials remain on-site.

The Record of Decision for this site includes predesign studies to:

- Define recyclability criteria for the casings that will be used to determine the volumes that can be recycled
- Determine process requirements to separate casings in a manner that minimizes fugitive emissions
- Determine the modifications required to adapt existing separation technology to conditions at the site

Predesign studies currently are being performed. The bench-scale test program indicated approximately 20% of the waste on the site is recyclable by separation alone. This recyclable material consists of lead oxide/sulfate sludge (17%) and a lead concentrate (3%). Additional cleanup can be achieved by treating the excavated material. At the present time, approximately half of the waste would require stabilization in order to be left on-site. This material includes 14% matte and 23% that is treatment products.

INTRODUCTION

The Gould uncontrolled hazardous waste site is located in the Doane Lake area of Portland, Oregon. A secondary lead smelting facility went into operation in 1949. Activities included lead-acid battery recycling, lead smelting and refining, zinc alloying and casting, cable sweating (removal of lead sheathing from copper cable) and lead oxide production. Operations continued under a variety of owners until 1980. In 1981 U.S. EPA and State of Oregon DEQ began investigating the site; it was placed on the NPL in 1983. NL Industries, Inc. and Gould, Inc., under an administrative order on consent with U.S. EPA, contracted with Dames & Moore to perform an RI/FS.

During the smelter's period of operation, of 86,900 tons of battery casings and 6,570,000 gal of battery acid were estimated to have been disposed of at the site. In addition to acid and battery casings, a third waste product called matte was produced by the smelting operation. Matte disposal was estimated at 11,800 tons¹.

The battery casings consist of hard rubber, ebonite, plastic casings, metallic lead, lead oxides and associated soil and debris. Lead concentrations (mostly lead oxide) ranged from 7,600 mg/kg (0.76%) to 190,000 mg/kg (19%). All of the battery casing samples had EP Toxicity (EP Tox) results for lead above the regulatory limit of 5.0 mg/L. These values ranged from 21 mg/L to 220 mg/L¹.

Figure 1 shows the locations the casings and other wastes. Approx-

mately 2% of the total volume of battery casings is located in surface piles on the Gould property, the remaining 98% is located as fill on the Gould and adjacent properties and in the sediments of East Doane Lake. The subsurface casings are in direct contact with groundwater underneath the site. The characteristics of the surface piles of casings differ somewhat from the subsurface piles. During the RI, the surface piles were found to contain a higher percentage of plastic and metallic lead relative to subsurface casings on the Gould property or from the Rhone-Poulenc property, which contain a higher percentage of rock and slag. The metallic lead, plastic, ebonite and lead oxide components of these casings have been considered potentially recyclable. The estimated fractions of the various components in the surface and subsurface casings as determined in the RI are shown in Table 1.

The matte materials consist of metallic sulfide chunks containing primarily iron and lead. Lead concentrations in the matte samples ranged from 6.4% to 11%. All of the samples had EP Toxicity results for lead above the regulatory limit of 5.0 mg/L. Low concentrations of arsenic and cadmium also were detected in the EP Toxicity leachates. These concentrations were within the regulatory limits (5.0 mg/L and 1.0 mg/L, respectively).

In addition to battery casings and matte, large quantities of soil at the site are contaminated with lead and can serve as secondary sources for lead transport. The quantity of surface soil at the site considered to be a secondary source is approximately 3,400 yd³. The volume of subsurface soils estimated to be a secondary source is 12,800 yd³.

Sediment samples collected from East Doane Lake contained total lead concentrations ranging from 160 mg/kg to 12,000 mg/kg. Based on these results, the estimated quantity of contaminated sediment in East Doane Lake is 5,500 yd³.

Lead contamination at the site has impacted groundwater in the shallow fill aquifer as well as an alluvial aquifer deeper down. Lead concentrations at points in these aquifers has exceeded the MCL for lead of 0.05 mg/L. Total lead migration from the site into the groundwater is estimated to be from 0.3 to 0.6 lb/yr¹.

U.S. EPA'S DECISION ON REMEDIATION

In March, 1988, U.S. EPA issued an ROD for this site. The remedy that U.S. EPA selected focused on attempting to recycle the battery casings at the site. It included:

- Excavation of all of the battery casing fragments and matte from the Gould property and adjacent properties where casings have been identified
- A phased design program to determine the amount of material that can be recycled and to minimize the amount of material that must be RCRA landfilled
- Separation of the battery casing fragments

- Recycling of those components (or portions of components) that can be recycled, off-site disposal for non-recyclable components that fail the EP Toxicity test and on-site disposal of non-hazardous, non-recyclable components
- Excavation, fixation/stabilization and on-site disposal of the remaining contaminated soil, sediment and matte

SURVEY OF RECYCLING AT SUPERFUND SITES

Prior to beginning predesign studies at the Gould site, a survey of battery recycling attempts at waste sites and general industry capabilities was performed². Several previous recycling and/or separation attempts on battery scrap piles were identified by personnel from the U.S. EPA and other environmental agencies. These prior recycling attempts include efforts at the Sapp Battery site in Marianna, Florida, in September, 1984, to separate approximately 4,000 yr¹ of battery scrap. Separation equipment also was used to conduct an engineering study on separating battery scrap components at the Granite City, Illinois, Superfund site. Neither of these attempts to recycle ebonite casings was successful. An attempt to use a commercial facility to recycle casings from the Gould site was also performed during the RI/FS. The casings did not pass EP Tox.

A number of commercial vendors were contacted in the search for a process that could recycle the Gould battery casings. Several facilities feed the ebonite component of the battery casings directly to a smelting furnace as a source of fuel and carbon. When this is done, the lead content of the ebonite is not a factor; in fact, higher lead contents of the feed to the furnace are desired to make the process more profitable. Most of these companies expressed reluctance to accept the Gould battery casings because the amount of recoverable lead in the ebonite is low and it would slow down lead production capacity².

Current industry recycling practices are shown in the generalized process flow diagrams in Figure 2. The battery casings pass through several steps designed to protect the process equipment by removing large rocks, chunks of slag, large pieces of scrap metal and other debris such as automobile bumpers, discarded equipment and wood. These steps usually include an electromagnet to remove ferrous metals, a screen to remove large items and a manned inspection station to further remove possibly damaging materials.

A hammer mill reduces the remaining material to 1/2-in. to 1-in particles and helps loosen and remove some of the lead oxide caught in cracks covering the surface of the ebonite. The particles are passed over a screen and washed with various agents such as water, surfactants or acid, with water only being most common of the processes. The solution washes out the fine particles of lead oxide and soil, which are then clarified and dewatered.

A series of wet classification separators is used to separate the plastic, lead and ebonite components. The separators are usually flotation separators or heavy-medium countercurrent separators with a screw auger or drag chain to remove settled solids. However, air separators and separators using clean water washing rather than a heavy-medium also are used. If a flotation separator is first, the plastic is removed and the lead/ebonite stream is sent to a heavy-medium or other separator. If a heavy-medium separator is first, the lead is removed and the plastic/ebonite stream is sent to a flotation separator. Once the ebonite has been separated from the other battery casing components, it can be washed again with water or surfactants².

None of the companies contacted had successfully separated a waste battery pile and produced an ebonite product that meets the EP Toxicity standard for lead. Even a company that successfully processes whole batteries or battery casings will have trouble cleaning battery wastes from a Superfund site for the following reasons:²

- The presence of rock and slag; these materials will have to be removed to avoid damaging the process equipment
- The presence of soil present will two problems: foaming and degradation of the lead oxide product. The soil will usually remain with the lead oxide because of similar particle size. Foaming problems can be solved by adding appropriate anti-foaming chemicals.
- Lead oxide may be more firmly embedded in the ebonite as a result of storage in the ground for a long time. These two materials may

thus be very difficult to separate.

The Bureau of Mines has successfully cleaned casings at the bench-scale level. Using a 1 hr pre-wash with a carbonate solution, granulation to less than -3/8 mesh and soaking 1 hr in a nitric acid solution resulted in casings with a lead level of less than 100 ppm and an EP Tox level of less than 0.2 mg/L¹.

PREDESIGN STUDIES

In 1989, U.S. EPA and NL signed a consent decree which required NL to perform a series of predesign studies. The work is being performed by Canonie Environmental and Hazen Research. Key features of the studies include:

Site Reference Materials. Because of the high variability of lead content in casings and soils on-site, Samples of Site Reference Materials (SRM) were prepared which are representative of the materials that will require treatment. SRM samples include battery casings, subsurface soils, surface soils and matte. SRM materials were evaluated for physical and chemical characteristics.

Recycling Pilot Studies. A series of bench-, pilot- and demonstration-level studies is being developed. The purpose of these studies is to investigate the requirements and feasibility of separating the buried battery casings into output streams of ebonite, plastic, lead oxide and metallic lead. Major features of these pilot studies include:

- Optimizing throughput capacity
- Water washing, crushing and screening techniques for cleaning the ebonite and plastic casings enough to that they can pass the EP Toxicity test for lead
- Evaluation of fugitive emissions during the processing of the casings and an investigation of the effectiveness of various mitigation measures; the purpose of this task is to investigate the feasibility of reducing airborne lead levels and suspended particulate matter to meet applicable standards

This work is being performed in three phases. Bench-scale and pilot-scale studies are being performed at the Hazen Research facility in Golden, Colorado. Demonstration-scale studies will be performed at the Gould site.

BENCH-SCALE STUDIES

The purpose of the bench-scale studies was to develop a treatment process which will meet the three criteria mentioned earlier. The RI indicated that the contaminated material on site is extremely heterogeneous, consisting of a mixture of casings and furnace wastes which were randomly landfilled over a period of some 30 yr. The first task was to sample the wastes at the site. Casings at four areas of the site are the focus of the bench-scale work. These samples include casings from the Gould surface piles, Gould buried casings, Doane Lake casings and Rhone-Poulenc buried casings. A summary of the waste composition is presented in Table 1.

Once the materials had been characterized, the approach for the process development was determined. This approach, illustrated in Figure 1, involved extracting the components of the waste which are recyclable and treating the remaining components to produce recyclable products or clean material which can be backfilled without stabilization. The remaining materials could be stabilized for on-site disposal in a monolith.

The bench-scale test program indicated approximately 20% of the waste on the site is recyclable by separation alone. This material consists of lead oxide/sulfate sludge (17%) and a lead concentrate (3%).

The remaining 80% of the waste required treatment to produce additional products for recycling and clean products for on-site disposal. The treatment process was developed by inspecting the materials to be treated and selecting a variety of unit operations to accomplish the cleaning task. These processes were tested using different combinations of flow rates, liquid solids ratios, etc., until an optimal combination of parameters was reached which resulted in cleaning to meet the required criteria of 5 mg/L lead in the EP Tox extract.

Using this method, an additional 20% of recyclable material was generated. The material consisted of 2% plastic and 18% clean ebonite.

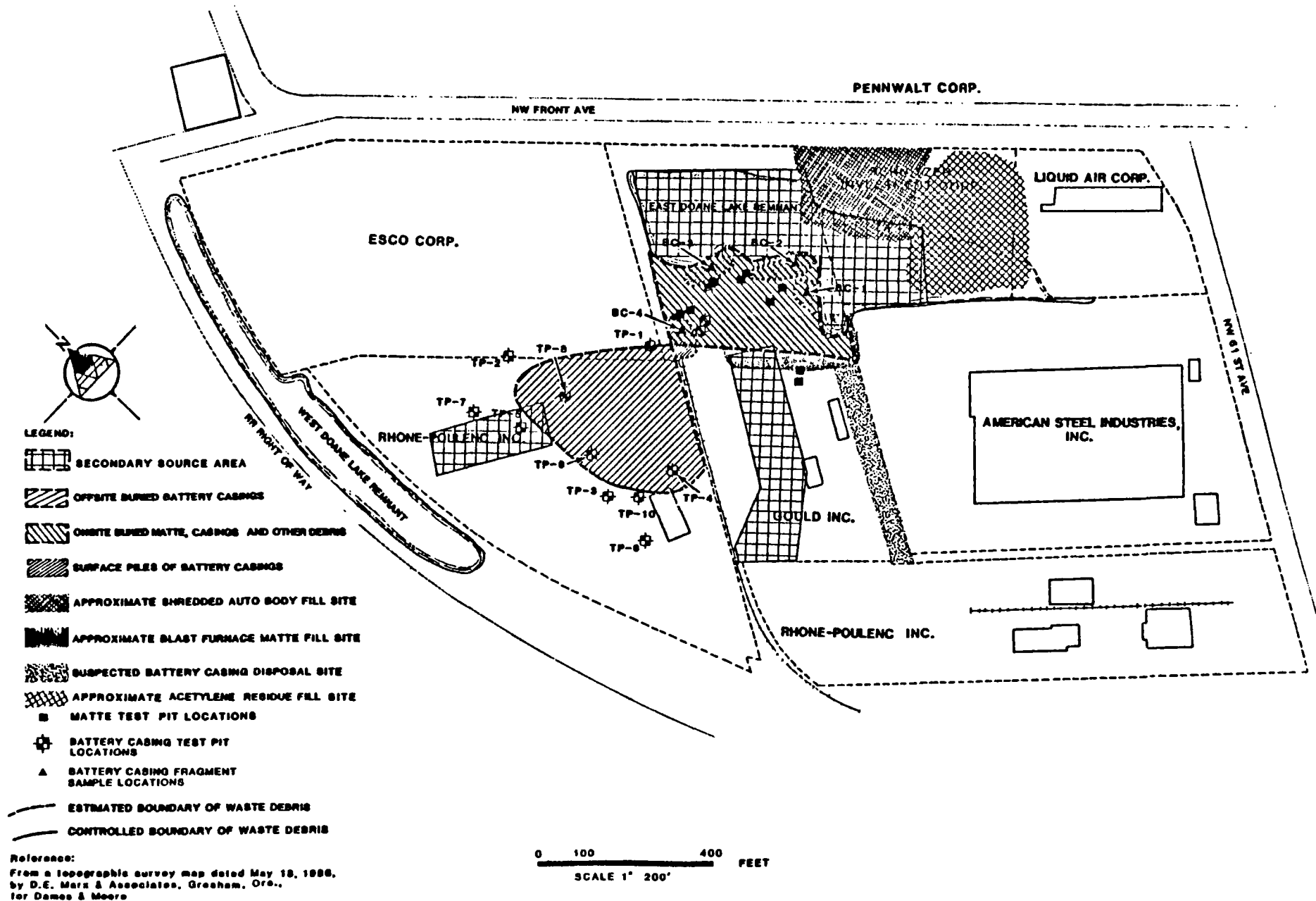


Figure 1
 Location of Battery Casings & Matte

Table 1
Estimated Battery Component Quantities

Rhone-Poulenc & Gould Subsurface	Density (lbs/cu. ft)	Volume (cu. yds)	Weight Tons	Per Cent (weight)
Ebonite	68.00	69,008	63,349	74.3
Plastic	46.56	4,070	2,558	3.0
Metallic Lead	297.46	117	469	0.6
Lead Oxide/Mud	238.37	2,703	8,700	10.2
Rock/Slag	105.56	1,938	2,762	3.2
Other	74.28	1,264	1,268	1.5
Moisture	62.30	0	6,113	7.2
Total	79.80	79,100	85,218	

Gould Surface

Ebonite	65.81	899	799	50.0
Plastic	45.06	595	362	22.5
Metallic Lead	287.88	6	24	1.5
Lead Oxide/Mud	230.69	52	161	10.0
Rock/Slag	102.16	148	204	12.7
Moisture	62.30	0	59	3.7
Total	70.07	1,700	1,609	

Table 2
Physical Makeup of Battery Waste Materials

Material	Weight (Percent)			
	Gould Surface Casings	Gould Buried Waste	East Doane Lake Waste	Rhone-Poulenc Waste
Plastic	8.8	1.0	2.9	0.0
Ebonite	63.1	32.5	44.4	73.8
Matte, Rocks, and Trash	1.1	26.3	29.0	1.6
Rocks and Battery Posts	5.3	16.3	7.1	4.8
Metallic Lead and Debris	5.1	9.6	3.6	3.8
Lead Sulfate/Oxide Slimes and Dirt	16.6	13.2	13.0	16.0
Total	100.0	100.0	100.0	100.0

Table 3
Lead Distribution of Ebonite and Plastic Water Wash Products

Feed Materials	Gould Surface Casings		Gould Buried Waste		East Doane Lake Waste		Rhone-Poulenc Waste	
	Pb, %	EP Tox	Pb, %	EP Tox	Pb, %	EP Tox	Pb, %	EP Tox
Ebonite and Plastic	0.46	64.9	1.74	76.4	0.94	70.6	1.27	122.4
Cleaned Materials:								
Plastic	0.064	2.9	0.139	---	0.141	3.88	---	---
Ebonite	0.031	1.64	0.050	3.52	0.026	2.64	0.042	2.26

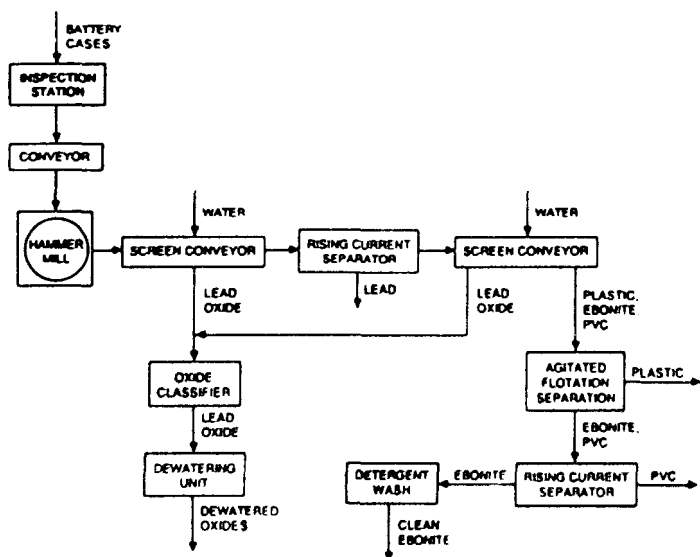


Figure 2
M.A. Industries Simplified Process Flow Diagram

CONCLUSIONS

It is not certain at this time whether the cleaned ebonite can be recycled. At a minimum, however, this material is sufficiently clean to allow backfilling on-site without stabilization. The lead concentration and EP Tox levels of the material before and after cleaning are presented in Tables 2 and 3.

The remaining material which cannot be treated consists of the matte and waste products produced by the stabilization process. Trials with several different processes did not successfully produce a recyclable lead product or clean material from the matte which would pass the EP Tox test. Significant progress was made in identifying the specific portions of the waste stream which cause this material to fail the EP Tox test. As indicated in Table 4, it was possible to significantly reduce the toxicity of this material even at high lead contents.

During the treatment of the materials, the lead removed from the casings was concentrated in a fine fraction which does not pass the EP Tox test for lead. Treatment of this material has not successfully produced either a lead concentrate or a clean tailing. The bench-scale test work indicated that 23% of the waste on-site consisted of this fine fraction. It is anticipated that the amount of fines can be reduced significantly by improving size reduction methods during the pilot plant phase of the program. At the present time, approximately half of the waste would require stabilization in order to be left on-site. This materials includes the 14% matte and 23% treatment products.

The proposed technology as designed will enable approximately 40% of the waste to be recycled, resulting in removal of 89% of the lead on the site. A summary of the disposition of products is presented in Table 5.

Table 4
Toxicity Reduction of Matte by Treatment Based on Lead

<u>Material/Project</u>	<u>Percent pb</u>	EP Tox <u>pb (ppm)</u>
Gould matte as received	6.41	1,460
Quenched matte	6.98	496
Slowly cooled matte	5.08	146
Silica stabilized matte	3.69	64

Table 5
Preliminary Material Balance Based on the Results of the Bench-Scale TES Work

	<u>Tons</u>	% by <u>Weight</u>
Excavated Materials	127,577	
Potential Recycle Products:		
Lead Slimes	21,630	17
Clean Plastic	2,670	2
Clean Ebonite	22,579	18
Metallic Lead	3,827	3
Potentially Stabilized Materials		
Matte, Rocks, Lead, and Trash	3,601	3
Ebonite Fines	20,774	16

Note:

1. The separation between coarse and fines is made at 10 mesh.
2. Disposition of contaminated is not included in the material balance.

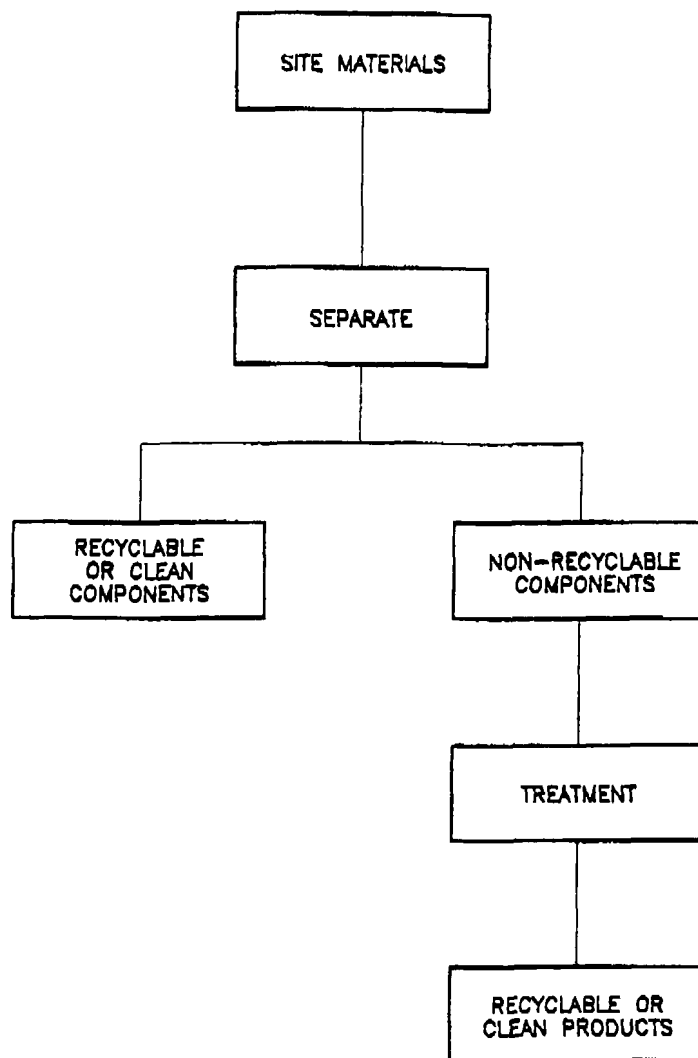


Figure 3
Bench-Scale Testing Approach to Cleanup of the Gould Site

It is anticipated that future work through pilot and field demonstrations will increase the amount of recyclable material and the amount of lead removed from the site.

REFERENCES

1. Dames and Moore, *Remedial Investigation and Feasibility for NL/Gould Superfund Site, Final Report*, February, 1988.
2. LPEI, *Technical Assistance to U.S. EPA Region 10 for the Gould Superfund Site, Portland Oregon - Survey of Commercial Battery Recyclers*, draft Report, PEI Associates, Inc, Cincinnati, OH, contract # 86-03-3419, Work Assignment # 19, 1988.
3. Bureau of Mines, Personal Communication between David Tetta, U.S. EPA Region 10 and Ernie Cole, Bureau of Mines, 1989.

Start-up of an Innovative UV/Peroxidation Groundwater Treatment System in the Era of Superfund and RCRA Corrective Action Programs

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ABSTRACT

Site remediation under RCRA presents new challenges for design professionals. In some cases of remediation, such as at Reichhold, Tacoma, well established technologies are not always available to meet the performance objectives that have been established.

The challenge at the RCI Tacoma site has been the treatment and destruction of pentachlorophenol contaminated groundwater. Due to the land ban restrictions, all technologies which resulted in significant volumes of solid generation were avoided due to the inability to dispose of this material at this time. This criteria ruled out a significant number of well established technologies.

Chemical oxidation, although not a commonly used technology, was selected as an applicable technology at this facility. This involves destruction of organics through chemical oxidation using hydrogen peroxide and ultraviolet light. The initial start-up phase of this unit has been completed and many performance and operational questions still remain unanswered. A rigorous performance testing program is currently in progress to evaluate the entire treatment system. The results of this test program will provide a better understanding of the parameters which affect the performance of this technology.

INTRODUCTION

Reichhold Chemicals, Inc. (RCI), owns and operates a manufacturing facility on about 52 ac. in the Tacoma, Washington Commencement Bay industrial area. Since the facility began operations in 1956, a variety of chemical products have been manufactured at the facility.

Pentachlorophenol (PCP) was a major product of the Tacoma facility over the years. PCP is a chlorinated phenolic compound, used extensively in the treatment of wood and lumber products. RCI discontinued PCP production and dismantled the production area in 1985.

In January of 1988, Reichhold Tacoma applied for a U.S. EPA RCRA Part B permit to address past practice issues. This permit was granted in November of 1988 under RCRA. The Part B permit contains many conditions which apply to the operating plant under RCRA. Most important to this discussion is the Interim Corrective Action Plan (ICAP) incorporated into the Permit which establishes the framework under which the current interim control measures and site remedial activities are being conducted.

The interim corrective actions underway at the Reichhold facility are based on the conditions of the Permit and on site assessment work conducted under a previous consent order. The current interim corrective actions underway involve control and isolation of surface water and groundwater. Additionally, final corrective action measures implemented to date include soils treatability technology screening and scheduled pilot demonstrations of several remedial technologies for on-site treatment of soils.

The constituents present on-site in the soils and groundwater include pentachlorophenol and other phenolic compounds. Regulatory restrictions on wastes containing pentachlorophenol from manufacturing (F021) under 40 CFR Part 261 do not permit off-site incineration, disposal or treatment. Therefore, the interim corrective measures were proposed for isolation and containment of soils and groundwater until the appropriate technologies for permanent destruction or detoxification of the hazardous constituents in the site soils are selected and implemented.

INTERIM CORRECTIVE ACTION PLAN

As stated previously, the purpose of the interim corrective actions currently being implemented at the site are to protect human health and the environment until implementation of the on-site soils cleanup and final closure. The objectives of the ongoing interim corrective actions are to divert precipitation, surface water and groundwater away from contaminated soils to prevent contact of clean water with hazardous constituents found in the site soils and groundwater; and to prevent off-site migration of contaminated groundwater. The specific actions which have been implemented or are currently under construction at the facility include:

- grading and placement of a site cover (concrete, asphalt and gravel sections) over the contaminated soils to divert precipitation and surface runoff away from these areas.
- installation of a french drain through the shallow aquifer at the facility perimeter. The drain intercepts contaminated water before it moves off-site. Recovered water from the shallow aquifer is pumped to the on-site water treatment system.
- installation of intermediate aquifer extraction wells in areas where contaminants above action levels have been detected in the groundwater. Eight extraction wells have been installed to date.
- installation of an on-site water treatment system to process recovered groundwater prior to discharge to the local public sewer system.

WATER TREATMENT SYSTEM DESIGN AND INSTALLATION

Design Basis

Prior to selection of the most appropriate treatment technology, it was necessary to establish the objectives of the treatment system, and assess the site specific regulatory and physical restrictions under which the treatment plant would be required to function.

The Water Treatment System (WTS) is regulated under Section 307(b) of The Clean Water Act, and is not specifically regulated under RCRA since it is considered a wastewater pretreatment system for discharge to the sanitary sewer. However, the provisions of the RCRA permit require the groundwater in the system to be managed as a hazardous waste.

This affects the health and safety practices of plant operations. It also requires that all solids removed from the process or any material which comes in contact with the process feed water (recovered groundwater) be managed as a listed hazardous waste. In this case, the land ban requires that all waste or solids be stored indefinitely or treated on site. Given the thirty year planned operating life of the system, water treatment processes generating large amounts of solids were not considered during the technology screening analysis.

Pending final negotiations with the local sewer district, discharge criteria to the public sewer system were initially assumed to be at or near OCPS pretreatment criteria. For PCP, a discharge limit of 20 to 50 parts per billion (ppb) was used for the initial technology screening. An ultimate plant influent flow rate of between 100 and 200 gallons per minute, and 5000 parts per billion influent PCP concentration were used as initial design assumptions. Due to the complexity of the site geology and to meet the tight schedules for implementation of the interim corrective actions, these initial assumptions were used for the treatment system technology screening evaluations. At the same time, parallel hydrogeological assessments were conducted concurrently to refine the estimates of groundwater recovery rates and influent water quality. These design parameters have been reevaluated later as more data becomes available.

Initially, the scope of work and schedule were established with the following tasks identified to implement the water treatment portion of the groundwater recovery and treatment system:

- Technology assessment and screening
- Bench-scale treatability testing
- Technology/vendor selection
- Revise design basis
- Field pilot demonstration
- Evaluate performance and revise design basis
- Engineering/procurement/construction of full-scale system
- Start-up and handover

This initial work plan was established at the onset of the project with the expectation that further revision to this plan may be necessary. The complexity of the site geology, the uncertainty associated with using an innovative treatment technology, and the regulatory aspects involved with implementation of the ICAP dictated that the scope of work remain flexible to accommodate new developments in the overall implementation of the ICAP.

Technology Screening and Assessment

The initial screening studies identified several technologies that were technically and economically feasible. Biological degradation (activated sludge), carbon adsorption, and various methods of chemical oxidation were selected as potential treatment technologies. Solids disposal issues quickly eliminated both biological treatment and activated carbon adsorption as impractical choices due to the regulatory restrictions placed on solids handling. Chemical oxidation, although not a commonly used technology, was selected as a potentially applicable technology for use at the Reichhold facility. This technology involves the use of one or several oxidants to destroy organic constituents in a water stream and therefore does not generate a waste stream or solids.

Treatability Testing

Three vendors of chemical oxidation water treatment systems were selected to perform bench-scale treatability testing on groundwater samples collected from the site. Small quantities of groundwater were transported to vendors' treatability labs. All tests were witnessed by CH2M Hill technical staff, and parallel chemical analyses of the test waters were conducted at the CH2M Hill CLP (Contract Lab Program) analytical laboratories under rigid quality assurance protocol for confirmation of the vendors' results. Field visits to operating facilities were conducted using the enhanced oxidation units to evaluate full-scale systems in operation and discuss system performance with operating personnel. Upon completion of the witnessed bench-scale treatability testing and the site visits, each vendor submitted proposals for both demonstration-phase and full-scale treatment systems. A comparative

technical and economic evaluation was performed. Peroxidation Systems, Inc. was chosen to provide a leased demonstration unit for the demonstration-phase installation.

Revise Design Basis

Initially, the field pilot demonstration system was scoped as a 10 gal/min unit. However, it was determined that a larger system would be necessary to treat substantial amounts of water generated during construction activities, and testing of the well and sump systems. The final design throughput for the demonstration-phase treatment system was revised to 70 gpm with an influent PCP concentration of 5,000 ppb.

A plan for a phased installation of the treatment system was then adopted. It was compatible with other ongoing field investigations, construction, and the start-up of the many components of the interim corrective action implementation. Per the revised plan, the demonstration-phase system would be designed to treat groundwater in batches, and, if the system met performance objectives, would later be expanded and modified to operate continuously after start-up of the entire groundwater recovery system. The objectives established for the demonstration-phase treatment system were established as follows:

Perform a field demonstration of the selected equipment under actual site conditions prior to final commitment to a full-scale system.

- Collect operating data to be incorporated into the design basis for the full-scale system expansion.
- Provide a water treatment system to treat and discharge wastewater generated during ongoing hydrogeological assessments and construction activities.

Demonstration-phase Installation

Design and installation of the demonstration-phase water treatment system proceeded after selection of the Peroxidation Systems, Inc. chemical oxidation system. In March of 1989 the initial startup of the demonstration-phase UV/hydrogen peroxidation system began. The start-up of the system was to occur in three steps:

- Mechanical shakedown of the completed system with potable water to insure that the system was mechanically complete and functional before introducing contaminated process streams into the system.
- Batch processing of water which was collected during on-site construction activities.
- Batch processing of groundwater received from the intermediate aquifer extraction wells. Two wells located in one of the areas with higher detected contaminated levels were completed in May. Installation of the treatment system would allow continuous pumping of these wells to obtain additional hydrogeological and chemical data on the groundwater.

A start-up and testing plan was prepared prior to completion of the installation. This plan was established as a guideline. Flexibility was written into the plan to accommodate changes which might be necessary due to water quality conditions, schedule changes, and other constraints imposed by other ongoing site activities. Objectives were established as a basis for the test program:

- Equipment performance guarantee.
Demonstrate that the vendor-supplied UV/hydrogen peroxide treatment system can perform in accordance with the performance guarantee.
- System Optimization and Operation.
Demonstrate that the entire water treatment system and each individual component function according to the performance criteria established.
- Baseline Data Collection.
Collect initial chemical and physical data on the recovered groundwater from intermediate aquifer extraction wells.
- Effluent Discharge Compliance.
Establish a discharge monitoring and performance history for evaluation by the local sanitary district. As negotiated with the City, discharges would be on a batch by batch basis during the demonstration

phase program. Each batch would be approved for discharge by the City during this demonstration program.

Final issue of the long-term discharge permit would follow a successful record of discharges during the demonstration-phase program.

The initial start-up proceeded cautiously with a mechanical shakedown of the various process components. Potable water was used in the system to eliminate the possibility of any accidental discharges of groundwater or contaminated construction water during this period.

The first available source of water for testing the system was construction water. Well water was then processed after successful treatment and discharge of the construction water. Routine operations proceeded as batches of construction and well water generated from other site activities were treated and discharged. It was soon noted that the water coming to the treatment system from various sources exhibited a large variability in water and chemistry. It was not well understood at the time exactly which chemical parameters had the largest impact on system performance, but large variations in system performance were observed as the influent water characteristics varied. Given the variability of the feed water, it was only possible to establish generalizations about system performance during this operating period. Although the system was adequately providing treatment of construction water to allow other site activities to progress, the changing contaminant levels and chemistry of the groundwater resulted in ambiguous pentachlorophenol destruction rate data. It was not possible to conduct an adequate assessment of system performance under the variable operating conditions.

It was observed during this period that several variables in the feed water seriously affect system performance. Although monitoring well

data had indicated the presence of iron in the intermediate aquifer groundwater, iron concentrations in water pumped from the wells have been up to four times higher than the initial estimates. Since performance of a UV/hydrogen peroxide system is a function of ultraviolet light transmission, treatment of turbid water with suspended iron particulate has proven especially difficult. Other variables such as the presence of other organic compounds and the presence of suspended silt have also affected the rate of pentachlorophenol destruction. The effect of other water quality variables such as alkalinity and pH are unknown at this time.

Prior to initiating the system expansion, a rigorous performance test program is being performed to evaluate the effect of various operating parameters. The test plan is based on testing three discrete and homogeneous water sources under a variety of operating conditions. The results of the test will be used to establish a predictive operating model to facilitate routine system operations. This level of understanding is essential prior to proceeding into design of the expanded system.

CONCLUSIONS

As with any plant design and construction project, careful attention should be given to establishing a work plan for a remedial corrective action. However, uncertainty of scope, a shifting regulatory environment, uncertain and complex site conditions, and the use of new, untested technologies can require substantial alteration to that plan at any stage of the project. It is essential to acknowledge this and build contingencies into work plans and schedules. Due to schedule constraints, it may be impossible to resolve issues related to establishing a design basis, and thus may require that the engineer design considerable flexibility into a system.

Pilot Scale In Situ Vitrification at Arnold Engineering Development Center Arnold AFB, Tennessee

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ABSTRACT

The Department of Defense has the Installation Restoration Program (IRP) to identify and permanently remediate hazardous material disposal sites at its military bases across the United States. Pursuant to this guidance, Arnold Engineering Development Center (AEDC) selected In Situ Vitrification (ISV) to remediate an old fire training area, Fire Protection Training Area (FPTA) No. 2 at Arnold AFB in Tennessee.

The ISV technology was developed by Pacific Northwest Laboratory (PNL), Richland, WA for the U. S. Department of Energy (DOE) and will result in for the destruction and encapsulation of the petroleum-oil-lubricants (POL) and heavy metal-constituents found at the FPTA and adjacent over-flow pond. ISV operates by passing a measured current of electricity into the ground through a set of electrodes. The resulting heat causes the soil to melt and form a solid vitreous (glass) mass similar to naturally occurring obsidian or basalt. In the process, organic constituents will be pyrolyzed (changed by heat) by the ensuing heat whereas the non-organic material will be incorporated into the glass matrix. Successful bench-scale tests were accomplished during the summer of 1988, and a successful pilot-scale test was accomplished in February of 1989.

INTRODUCTION

Situated in the rolling countryside of middle Tennessee lies the Air Forces' best kept secret—Arnold Engineering Development Center (AEDC) at Arnold AFB, Tennessee. AEDC is located in Coffee and Franklin Counties, Tennessee, midway between Chattanooga and Nashville (Fig. 1). The entire AEDC reservation encompasses 39,081 ac devoted to testing, research and development facilities. AEDC was constructed in the early 1950s with initial testing starting in 1953. The Center has, since its beginning, conducted a wide range of tests and simulations in aerodynamics, propulsion and aerospace systems.

The U. S. Department of Defense (DOD) has developed a program to identify and evaluate past hazardous material disposal sites on DOD property, to control the migration of hazardous contaminants and to control hazards to health or welfare that may result from these past disposal operations. This program is known as the Installation Restoration Program (IRP). The IRP initially had four phases consisting of: Phase I, Installation Assessment and Records Search; Phase II, Confirmation and Quantification; Phase III, Technology Base Development; and Phase IV, Operations and Remedial Actions. The U.S. DOD now follows the terminology of the U. S. EPA: PA/SI, Preliminary Assessment and Site Inspection; RI/FS, Remedial Investigation and Feasibility Study; RD/RA, Remedial Design and Remedial Action; and LTM, Long-Term Monitoring.

During the investigation of Arnold AFB, 17 sites were initially identified as being potentially hazardous. Subsequently, two sites were added as a result of discoveries made by base and/or contractor personnel. Five of the original sites were subsequently dropped from any further investigative work after the initial investigation. With the exception of the two newest sites, all others are well into the RI phase of investigation. One site is in the RD phase and one site is getting ready to begin RA. This paper concerns the activities at the site in the RA-Site 10, composed of three identifiable activity areas: Fire Protection Training Area (FPTA) No. 2, Burn Area No. 1 and Landfill No. 1.

Site 10, which comprises approximately 14.5 ac is located northwest of the Model Shop (Bldg 451) and northeast of Gate 5 (Fig. 2). The FPTA was constructed in 1973 and was closed in April, 1988. The training area consisted of an unlined gravel burning area connected by drains to a small overflow pond.

During a typical fire training exercise, water was first applied to the burn area surface. Combustible material, typically lighter than water, was added then ignited. The ignited area was then used as a training exercise for AEDC fire protection personnel. Contaminated petroleum fuels, fuel filters, waste oils, thinners, solvents, and some propellants were burned up to the late 1970's. Since then, the materials burned have consisted primarily of JPD4 fuel and some sodium-potassium alloys.

A typical burn consumed 500 to 600 gal of fuel and occurred up

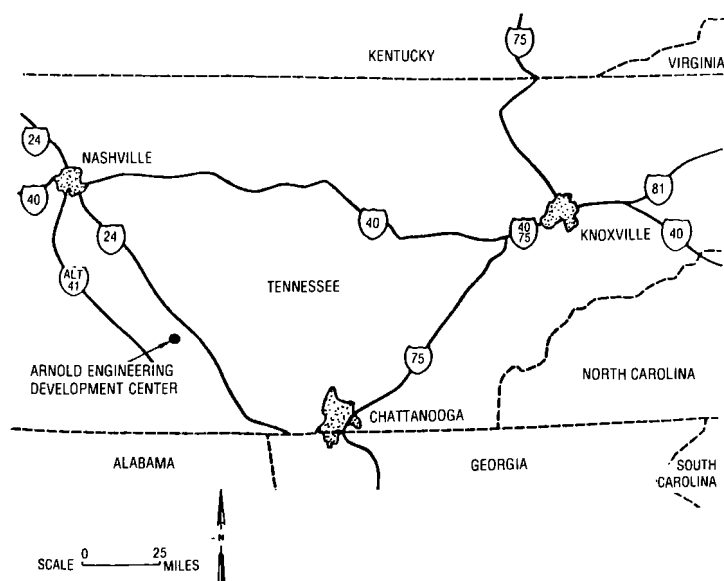


Figure 1
Arnold Engineering Development Center Location

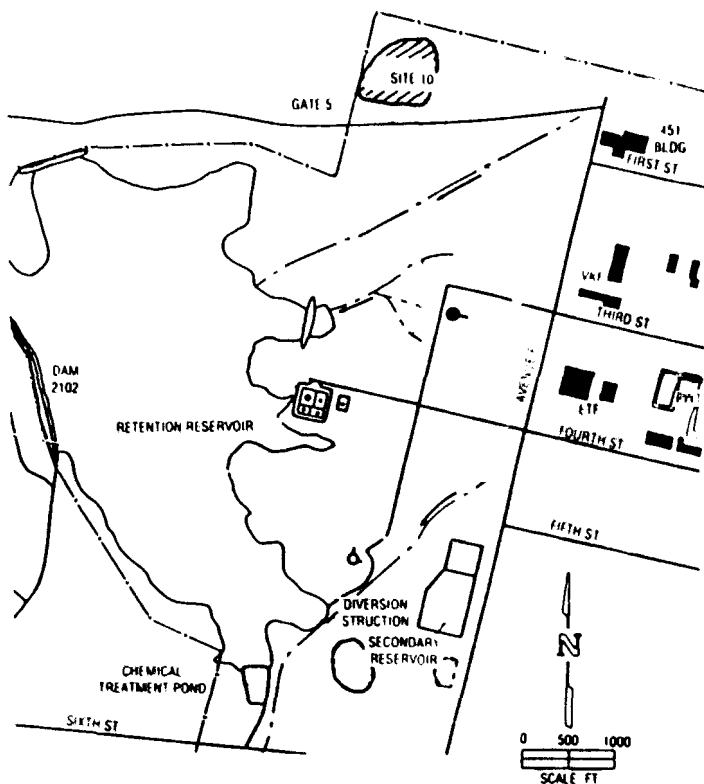


Figure 2
Site 10 Location

to 21 times per year. Landfill No. 1 served as a disposal site for many installation wastes, including refuse, garbage, construction debris and some shop wastes. The shop wastes generally were placed in a trench located at or near Landfill No. 1 and burned (this area is known as Burn Area No. 1). Some of the shop wastes included waste oils, contaminated fuels, solvents thinners and other combustible wastes.

IN SITU VITRIFICATION (ISV)—HOW IT WORKS

ISV is a thermal treatment process that converts contaminated soil into a chemically inert, stable glass and crystalline solid. Four electrodes are inserted into the ground in the form of a square array to a predetermined treatment depth (Fig. 3). Since soil is not electrically conduc-

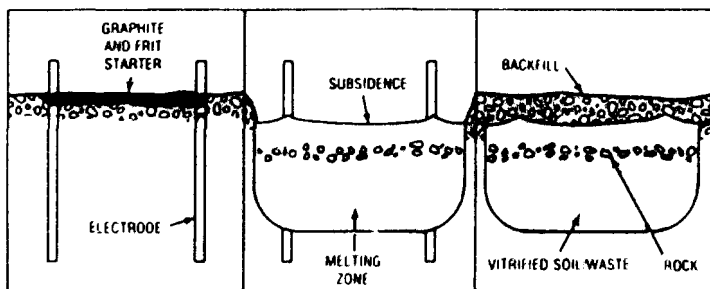


Figure 3
In Situ Vitrification Process

tive once the moisture has been driven off, a conductive mixture of flaked graphite and glass fit is placed between the electrodes to act as a starter path. A high silica content, fiber material acting as an insulating thermal blanket is placed on top of the starter material and soil to aid in initial heat retention (the blanket is consumed in the melting process).

An electrical current is applied to the path. The resulting power heats the starter path and surrounding soil up to 3600°F, well above the soil's initial melting temperature. The starter eventually will be consumed by oxidation with the current being transferred to the now electrically conductive molten soil.

During the growth of the vitreous zone, non-volatile elements (compounds) are incorporated into the melt while organic components are destroyed by pyrolysis. The pyrolyzed by-products migrate to the surface of the vitrified zone, where they oxidize in the presence of oxygen. A hood placed over the processing area provides confinement for the combustion gases which are drawn into the off-gas treatment system. The hood area is larger than the area to be vitrified to assure that the gases driven off during the process are captured. The hood has a skirt along the bottom edge to contain the gases and to aid in developing a partial vacuum, both important criteria in the treatment system for off-gases.

As the melt grows downward and outward, power is maintained at sufficient levels to overcome the heat losses from the surface and to the surrounding soil. In general, the melt grows outward to a total width of approximately 50% of the spacing of the electrodes. Therefore, if the electrode spacing is 18 ft center to center, a melt width of approximately 27 ft would be observed under normal conditions. The molten zone is a roughly square with slightly rounded corners, reflecting higher power densities around the electrodes. As the resistance decreases during the melting process, the voltage is constantly monitored and adjusted via electrical transformer voltage taps to maintain a constant operating power.

The equipment necessary to produce a vitrified mass can be divided into five major groups: (1) electrical power supply, (2) off-gas hood, (3) off-gas treatment, (4) off-gas support and (5) process control. All of these components, except the off-gas hood, are contained in three standard size trailers (Fig. 4).

The off-gas hood and associated piping are dismantled and transported on a flat-bed trailer between sites. The off-gas trailer is the most expensive and complex of the three. This system cools, scrubs and filters the gaseous effluents exhausted from the hood. A glycol cooling unit cools the scrub solution to extract built-up thermal energy. This cooling process allows the scrub solution to be recycled back through the system. Equipment necessary for the off-gas hood includes a small crane to lift and position the hood for each melt and a small bulldozer (if necessary) to grade and level the area before the hood is set in place. Craft support, such as electricians, pipefitters, riggers, operators, etc., is required to set up the ISV equipment as well as move the equipment from setting to setting.

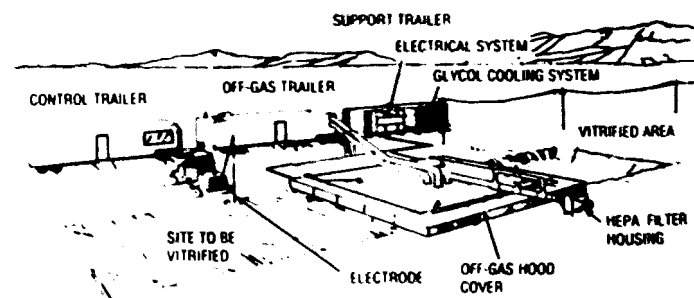


Figure 4
Large-Scale Process Equipment for In Situ Vitrification

The long-term stability of the glass is, of course, a significant factor in this process. The glass has been subjected to a variety of leach tests, including the U.S. EPA Extraction Procedure Toxicity Test (EP Tox) and Toxic Characteristic Leach Procedure (TCLP). These tests show a uniformly low leach rate for heavy metals of approximately 1 x 10⁻⁵ lb/ft²/day or lower. Additional testing along with comparisons to naturally occurring obsidians indicate that the mean life of the vitrified material would be on the order of 1,000,000 yr¹.

BENCH-SCALE TESTING

Bench-scale testing was performed on AEDC soils. Initial bench-scale testing was conducted at AEDC during May, 1988. A follow-up bench-scale test was performed at PNL in July, 1988. Soils were tested from both IRP Site 10 and IRP Site 1. IRP Site 1 is a landfill/leach pit area. The initial bench-scale test at AEDC was unsuccessful. The

problem was identified as the lack of electrically conductive elements or fluxing agents (e.g., sodium carbonate) in the AEDC soils. Additional bench-scale testing using fluxing additives was conducted at PNL using a modified single-phase electrical connection of the engineering-scale power supply. The engineering-scale system was used instead of the bench-scale system because the power supply better simulates the power density, melt rate and control of the larger scale of operational ISV systems.

The assessments of Site 1 and Site 10 soil compositions showed the AEDC soil to have a high alumina/silica content. This material is suitable acceptable for making a good glass product, but ISV also requires a sufficient quantity of alkali elements (Li, Na and K) to lower the melt temperature and provide electrical conducting. Typically, 5% of the alkali material is required for ISV to perform effectively. AEDC soils assessed for bench-scale testing contained $\pm 1\%$ of these materials; therefore, soil fluxing additives were required. Ten percent (by weight) sodium carbonate was added to ensure successful ISV processing.

As a result of the bench-scale testing, the following was concluded: (1) with the addition of a fluxing additive such as sodium carbonate, ISV could process the contaminated soils from Sites 1 and 10 into a more compact and environmentally stable (immobilized) form, (2) organic contaminants were effectively destroyed, (3) leach testing results from the Extraction Procedure (EP) Toxicity and Toxic Characteristic Leach Procedure (TCLP) showed that metals of concern were below the maximum permissible limit which indicates that inorganic contaminants are immobilized and (4) 5% to 10% sodium carbonate additions are necessary to process AEDC Sites 1 and 10 soils. Based on the results of these tests, it was recommended to perform a pilot-scale test at the AEDC Site 10 fire training pit to verify the efforts of the bench-scale tests prior to actual remediation of the site with ISV².

PILOT-SCALE ISV TEST

The pilot-scale test was conducted at AEDC during February 1989. The pilot-scale test system used at AEDC utilized four electrodes with 3 ft, separation and consisted of a power control unit, off-gas containment hood over the test site and an off-gas treatment system housed in a portable semi-trailer. The actual pilot-scale setup at AEDC IRP Site 10 is shown in Figure 5.



Figure 5
Pilot-Scale Setup at AEDC IRP Site 10

The pilot-scale power system utilizes a Scott-Tee connection to transform a three-phase input to a two-phase secondary load on diagonally opposed electrodes in a square pattern. The 500-kW power supply may be either voltage or current regulated. The alternating current primary is rated at 480 V, 600 A, three-phase, and 60 Hz. This three-phase input feeds the Scott-Tee connected transformer providing a 2 phase secondary. The transformer has four separate voltage tap settings—1000 V, 650 V, 430 V and 250 V. Each voltage tap has a corresponding amperage rating of 250 A, 385 A, 580 A and 1000 A per phase, respec-

tively. The amount of three-phase input delivered from the transformer is controlled by silicon controlled rectifiers (SCRs). During the pilot-scale test, this power system very effectively maintained a balanced load to the electrodes.

The upper section of the off-gas containment and electrode support hood (Fig 6) is 10 ft by 18 ft long, and is constructed from seven panels of 20 gauge stainless steel bolted together. The lower structure is a support structure covered and sealed with a high temperature fiberglass-based, silicon coated fabric. The fabric was bolted to the upper structure and covered with soil at the base to form a seal with the ground. The overall hood height was 6 ft.



Figure 6
Off-Gas Containment And Electrode Support Hood

The off-gas system is shown schematically in Figure 7. The off-gas passes through a venturi-ejector scrubber and separator, Hydro-Sonic scrubber, separator, condenser, another separator, heater, one stage of HEPA filtration, one stage of activated carbon filtration and a blower. Liquid to the two wet scrubbers is supplied by two independent recirculation tanks, each equipped with a pump and heat exchanger. The entire off-gas system has been installed in a 45 ft long semi-trailer which makes the system portable. Equipment layout within the trailer is illustrated in Figure 8.

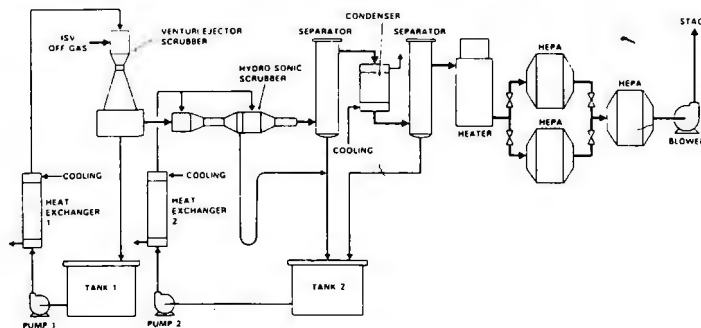


Figure 7
Off-Gas System Schematic for the Pilot

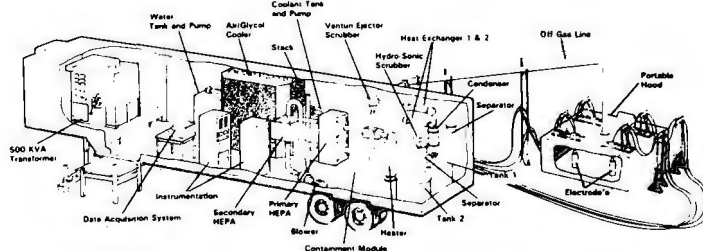


Figure 8
Pilot-Scale Process Equipment

The primary objective of the pilot-scale test was to confirm the bench-scale testing results on the actual Site 10 Fire Training Area contaminated soils. The testing evaluates process operations effectiveness and off-gas behavior of volatile or entrained materials. The earlier tests showed the need for additional fluxing additives to increase the electrical conductivity to allow ISV processing.

The additives were placed differently in the pilot-scale test than they were in the initial tests. The initial tests were of a smaller scale and allowed total blending of the fluxant (Na_2CO_3) with the entire soil volume. AEDC did not want to disturb the contaminated soil at Site 10, therefore a "cover layer" method was used to blend the fluxant. For the pilot-scale test, the fluxant was mixed with clean soil and placed over the contaminated soil. The depth of the "cover layer" was 3 ft and had a fluxant concentration of 27%. The fluxing additives have been shown to mix with the contaminated soil as the melt progresses. The cover soil also serves to enhance the process destruction efficiency of the organic contaminants and allows ISV to establish a molten zone of soil prior to contacting the organic. This thermal inertia mass of molten soil achieves pyrolysis of the organics as opposed to volatilizing the organics if ISV were started at the contaminated soil surface.

Four 2-in diameter molybdenum cores with 6-in diameter graphite collar electrodes were placed to the 10-ft depth from the cover soil surface. The electrodes were positioned on a 3-ft square separation. Two of the electrodes had fiber optic, depth monitoring transmitters attached to them which enables the depth progress of the ISV melt to be tracked.

The test was performed on the southern edge of the Fire Training Area. This location was chosen to allow application of ISV to an actual portion of the contaminated site and to allow thermal transport monitoring to the clean surrounding soil. Pretest and post-test soil core sampling was performed to obtain before and after soil profiles. A surface view of the ISV block after processing is shown in Figure 9.



Figure 9
Surface View of ISV Block After Processing

PILOT-SCALE TESTING

Analyses of the data from the pilot-scale test regarding the perfor-

mance of the ISV process to AEDC Site 10 soils provide the following conclusions:

1. Fluxing additions are needed to process AEDC soils. Addition of fluxing additives to the 3 ft of cover soil allowed ISV to treat a portion of the Site 10 soil, but did not result in efficient ISV process operations or effective fluxant mixing to the desired depth with AEDC soils. Therefore, to ensure achieving the desired depth, these fluxing additives should be added to the entire vitrification volume by soil mixing or injection techniques instead of concentrating them in the cover soil layer.
2. The pilot-scale ISV electrical and off-gas treatment system operated effectively within design constraints throughout the 168-hr operating period.
3. The operation produced a 15-ton vitrified block measuring 5 ft deep and 8 ft wide on each side. A greater melt depth was desired, but soil composition variations, the amount and type of fluxants added and the method of adding the fluxants affected the depth achieved.
4. Inorganic particulate releases from the melt to the off-gas system were minor. No detectable particulate releases were measured out the stack after off-gas treatment. The ISV process effectively retains inorganic materials within the melt. Of the small quantities released (0.25 lb), the off-gas treatment system performs a very efficient scrubbing and filtering of the particulates.
5. Organic contaminants were effectively destroyed to the 89% level for the fuel oil-contaminated Site 10 soil solely by the ISV melt exclusive of any off-gas treatment. The overall ISV system destruction and removal efficiency (DRE) was 99.85% which included the off-gas treatment system.
6. Leach testing results passed both the Extraction Procedure (EP) Toxicity and Toxic Characteristics Leach Procedure (TCLP) leach tests and showed that all metals of concern are below leach release limits. This result indicates that inorganic contaminants are immobilized to a level that should allow the site to be listed as non-hazardous material according to regulatory criteria.
7. Pretest soil samples showed the highest organic concentration in the surface soil samples at the original surface grade position. Post-test analyses showed that the samples in the close proximity region to the vitrified block (<1 ft away) displayed a noticeable decrease in the organic concentration between the pre and post-test samples from the same relative positions. The available data indicate that ISV processing will deplete a zone near the block of organic material but does not thermally transport the organic species away from the vitrification zone.

In summary, pilot-scale testing confirms the potential for ISV treatment of organic contaminates soils from the Fire Training Area at IRP Site 10. Based on the results of the bench-scale and pilot-scale tests, ISV is a potential solution that could be used to remediate the soils at the AEDC Site 10 Fire Training Area.

REFERENCES

1. Lominac, J. K. and Julius, J. F. K., "In Situ Vitrification at the Arnold Engineering Development Center, Arnold AFB, Tennessee," *Proc. 6th National Conference on Hazardous Wastes and Hazardous Materials*, New Orleans, LA, pp 377-379, HMCRI, Silver Spring, MD, 1989.
2. Timmerman, C. L., "Feasibility Testing of In Situ Vitrification of Arnold Engineering Development Center Contaminated Soils," Pacific Northwest Laboratory Project No. 14384 for Oak Ridge National Laboratory, Oak Ridge Tennessee, March 1989.

Combining Innovative and Traditional Technologies for Effective Remediation of PCBs and VOCs Contamination

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INTRODUCTION

The presence of PCBs and VOCs in the soil and groundwater present a challenge in designing a complete and effective remediation program due to the different chemical nature and mobility of these compounds. This paper discusses the problem in a case study of a site in Pennsylvania that has PCBs and VOCs contamination in a complex hydrogeologic setting. Innovative and traditional technologies were evaluated

and applied to effectively remediate the site. All investigations and remedial plans were developed with the concurrence of the State Regulatory Agency in this voluntary site cleanup.

Through the implementation of a phased hydrogeologic investigation, the nature of the subsurface aquifer system and the extent of the contamination were defined and characterized. It was determined that PCBs and VOCs were present in the unsaturated zone soils, a perched water

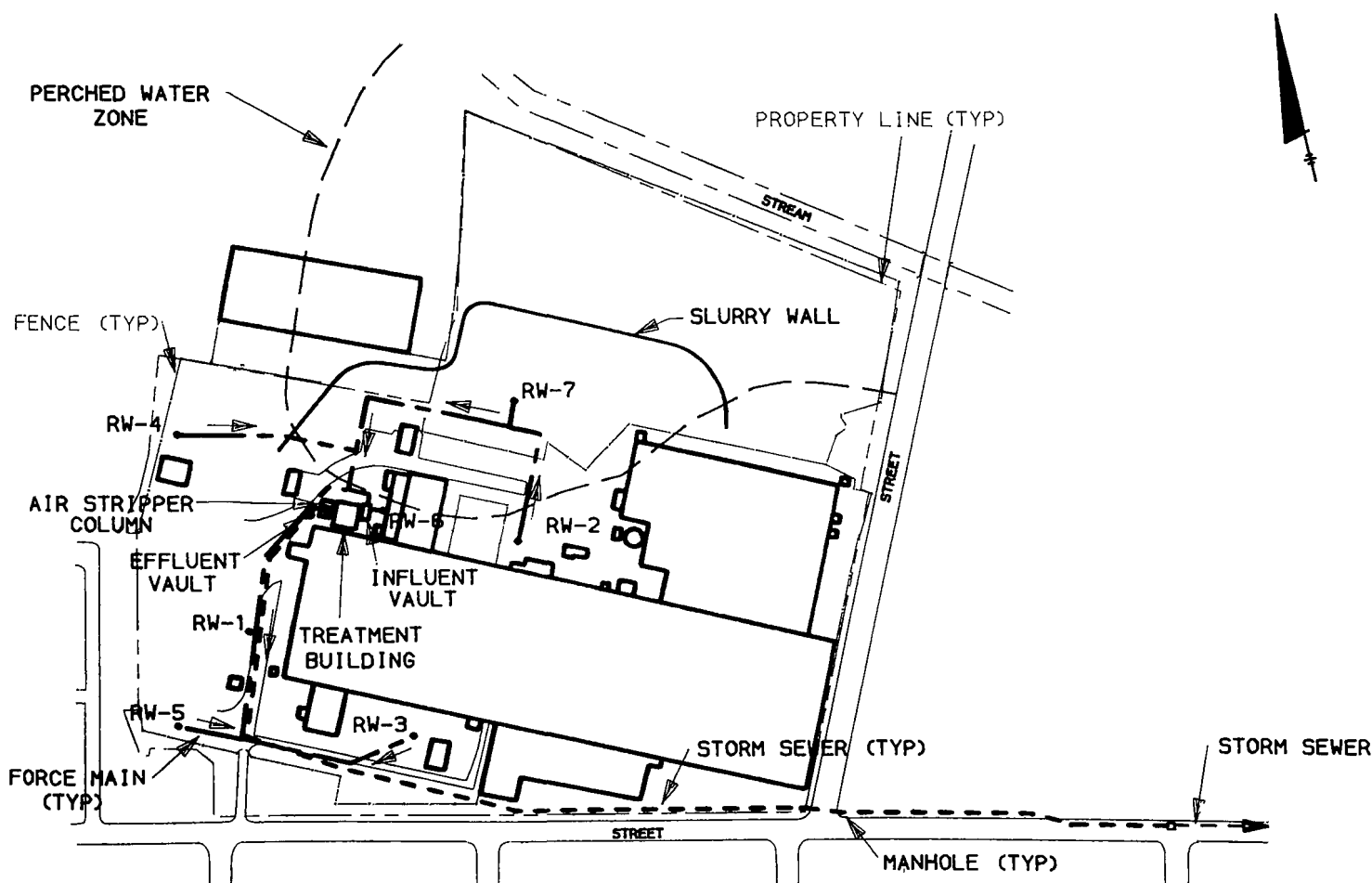


Figure 1
Manufacturing Facility Site Plan

table, the regional sand and gravel aquifer and a lower bedrock groundwater zone. Also, two separate free-phase petroleum product pools were detected on the groundwater.

Remedial program challenges required simultaneous treatment of soils in place, recovery and treatment of groundwater, recovery of the free phase product and immobilization of the PCBs. These goals were successfully accomplished by employing a creative combination of in situ air stripping, soil bentonite slurry cut-off walls, granular activated carbon treatment and counter-current packed column air stripping technologies.

BACKGROUND

This machining facility had, in the past, four types of disposal and chemical usage areas, including the following:

- Underground storage tanks and pits
- Electrical transformers
- Drum storage area
- Miscellaneous construction debris and rubble disposal sites

The analysis of the soils beneath the removed tanks and pits prompted a hydrogeologic investigation. Electrical transformers and waste oil tanks had existed on-site and may have contributed to the PCBs detected. Overflow of drums had stained surface soils which were later removed in 1975 and 1980. Miscellaneous disposal areas also had existed and consisted of a variety of materials including construction debris, and rubbish.

A hydrogeologic investigation conducted at the site during 1987 identified a contaminated soil volume of approximately 18,000 yd³ containing up to 50 ppm VOCs (Fig. 1). Approximately 2,000 lb of VOCs are projected to be contained in the soils located within a half paved-half grassed 125,000-ft² area.

The hydrogeologic investigation also identified three contaminated groundwater zones:

- Perched water table
- Overburden Aquifer
- Bedrock Aquifer

Because silt and clay are the upper natural soil unit at the site, rain-water that percolates through the overlying fill material is trapped in the perched zone above this clayey zone. The perched zone is approximately 12 to 17 ft below ground and is configured approximately a half circle with a radius of about 400 ft. A PCB concentration up to 18 mg/L and VOCs up to a concentration of 113 mg/L were detected in the perched zone soils.

Underlying the perched zone is a regional groundwater table occurring at depths of 16 to 32 ft. The water table in the overburden was determined to be unconfined and exhibited a saturated thickness of 25 to 30 ft. The concentration of VOCs and PCBs from this aquifer ranged from 21 mg/L VOCs and 0.083 mg/L PCBs. Flow in this aquifer flows to the southwest and discharges to the river opposite the perched zone. Two product pools were found on this water table in two locations. Approximately 15,000 to 25,000 gal of product contain from 5 to 7 mg/L PCBs.

Pump test analysis conducted within the overburden aquifer showed a range of transmissivity values of 12,000 to 21,500 gal/day/ft for the coarser material while values for the finer grained soils ranged from 2,400 to 12,000 gal/day/ft. Average hydraulic conductivities ranged from 416 to 125 gal/day/ft².

Beneath the overburden aquifer, groundwater is in the fractures of the underlying limestone and shale bedrock. Groundwater within the bedrock flows toward the river and produces yields of 75 gal/min in shallow levels to 300 gal/min in deeper levels. The groundwater in the bedrock contains VOCs and no detectable concentrations of PCBs.

SOIL AND GROUNDWATER CLEANUP OBJECTIVES

The objectives of the soil remediation portion of the project were to remove the source of VOCs in the soil to prevent continued additional contamination of the groundwater and to permanently immobilize in place the PCBs in the soils to prevent them from further migrating into the groundwater.

The objective of the groundwater portion of the project were to remove and treat the contaminated groundwater and prevent the contamination plume from migrating to off-site receptors.

SCREENING OF REMEDIAL ALTERNATIVES

In developing a remedial plan for soils and groundwater, a screening of remediation techniques was conducted to determine which techniques are applicable, which techniques require pilot or bench testing to determine their applicability, and which techniques can be eliminated as potential treatment components of the remedial plan.

There is a limited number of remedial alternatives for the treatment of soils containing a mixed matrix of VOCs and PCBs. The following alternatives were evaluated for consideration:

- No action
- Construction of physical barriers
- In situ treatment (biological treatment)
- In situ air stripping
- Excavation and disposal off-site
- Excavation and incineration

The No Action alternative was eliminated as a remedial alternative since it would allow the soil contaminants to migrate into the groundwater which was not considered to be acceptable.

The construction of physical barriers consisting of an impermeable cap and slurry cut-off wall would be appropriate for preventing recharge of the perched zone from either rainfall or seasonal overflows from a nearby stream. The presence of a natural silty clay layer below the perched zone would allow the slurry cut-off wall to be "keyed" in providing complete encapsulation. Since PCBs are only slightly soluble in water and would migrate primarily in particulate form, this technology would be effective. However, this technology might not be effective for the VOCs since the transport of the VOCs through the soil is not entirely governed by the moisture in the soil.

While in situ biological treatment was eliminated based on its failure to degrade PCBs and chlorinated VOCs, in situ treatment employing air stripping has been extensively proven effective in the field for VOCs but not effective for PCBs.

For small quantities of VOC- and PCB-contaminated soil, disposal off-site or incineration is a viable alternative. However, since the volume of material is significant at this site to incinerate or dispose of the soil off-site would result in an enormous cost.

In addition to the cost of incineration, it frequently is difficult to obtain sufficient landfill or incinerator capacity at the time of disposal and there is additional liability associated with transporting the material to an acceptable facility. For these reasons, incineration and disposal off-site were not considered except for small quantities of material.

There are a number of alternatives for the treatment of groundwater containing elevated levels of VOCs and PCBs. Considering site-specific conditions and contaminants of concern, the following alternatives were evaluated for consideration:

- No action
- Construction of physical barriers
- In situ treatment (biological treatment)
- Pump-and-treat with ozone
- Pump-and-treat with carbon adsorption
- Pump-and-treat with air stripping

The No Action alternative was eliminated since it would allow the VOC- and PCB-contaminated groundwater to migrate off-site to possible receptors. Physical barriers including low permeability caps and groundwater cut-off walls could be constructed to inhibit migration of contaminants off-site. The low permeability caps would prevent rainfall from leaching additional VOCs and PCBs into the soil and the groundwater. The cut-off walls would prevent horizontal seasonal migration of groundwater from the nearby stream to the perched zone and subsequent migration of VOCs and PCBs in a horizontal direction.

Although the capping and cut-off wall are appropriate for preventing intercommunication between the seasonal stream bed and the perched zone, they would not prevent the intercommunication of groundwater

between the overburden aquifer and the bedrock at the site.

Like biological treatment of soils, treatment of groundwater can be effective only if the microorganisms can use the contaminants as a food source. For the same reasons biological treatment was not applicable to VOC- and PCB-contaminated soil, it also would not be effective for groundwater cleanup.

Using ozone to oxidize the VOCs and PCBs could be effective. However, since ozone is not selective in its oxidizing ability, excess ozone would be required to achieve the stringent water discharge limits for PCBs. The health and safety issues relating to ozone usage in this industrial atmosphere also do not support its application.

Adsorption of VOCs onto granular activated carbon(GAC) is a potential method for meeting the required effluent criteria. The adsorption tendency of organic compounds is a function of molecular weight and water solubility. Most of the VOCs found in the groundwater at this site are not efficiently adsorbed onto GAC and therefore do not provide a high loading capacity onto GAC. However, PCBs found on-site are readily adsorbed onto GAC and will preferentially replace VOCs under loading conditions. Since there are high levels of VOCs and low levels of PCBs in the groundwater, GAC treatment to remove the PCBs coupled with a technology to remove the VOCs may be the most cost-effective solution.

Air stripping has widespread application for the removal of VOCs from groundwater since the technology makes use of the moderate to high volatility of VOCs. Typically, air stripping columns are able to remove 90% or more of the VOCs but are not able to effectively remove PCBs. This alternative in conjunction with GAC treatment provides the capability to remove the VOCs and PCBs to the required discharge limits.

Based on the preliminary screening of alternatives, the following treatment components were proposed.

Soil treatment

- In situ air stripping for VOC removal (pilot testing required)
- Asphalt capping and cut-off wall for PCB containment (pending in situ air stripping testing)

Groundwater Treatment

- Pump-and-treat with GAC for PCB removal
- Pump-and-treat with air stripping for VOC removal

PILOT TESTING

An in situ air stripping pilot program was conducted to determine if this technology would be effective for in situ treatment of VOCs at the site, therefore enabling design of a full-scale system to remediate the balance of the contaminated soils. The goal was to remove 95% of the VOCs from the soils by in situ air stripping.

The design of the in situ air stripping system incorporated air withdrawal wells and air inlet wells. A portable trailer⁹ mounted blower was connected to one of the five withdrawal wells. Flow and concentration data from the withdrawal well and pressure readings from the air inlet wells were collected to determine the effectiveness of the system during a 1-mo period.

The concentration of Trichloroethylene (TCE) in the air removed from the withdrawal well verses time is given in Figure 2. The figure shows that the concentration of TCE in the discharge air initially ranged from 60 to 100 ppm TCE, but was reduced over time to a level of 30 ppm. The initial large changes in concentrations were a result of increases in blower speed.

The mass flow rate of TCE verses time is given in Figure 3. The Figure shows that the mass flow rate of TCE discharged, which initially ranged from 0.5 to 0.8 lb/hr of TCE, was reduced with time to approximately 0.2 lb/hr. Initially, the large changes in mass flow rate of TCE were attributed to the increases in blower speed.

The cumulative mass of TCE discharged from the withdrawal well verses time which reflects the change in concentration and air flow rate is given in Figure 4. The slope of the graph shows that the TCE removed was initially at the highest rate and asymptotically reduced over time.

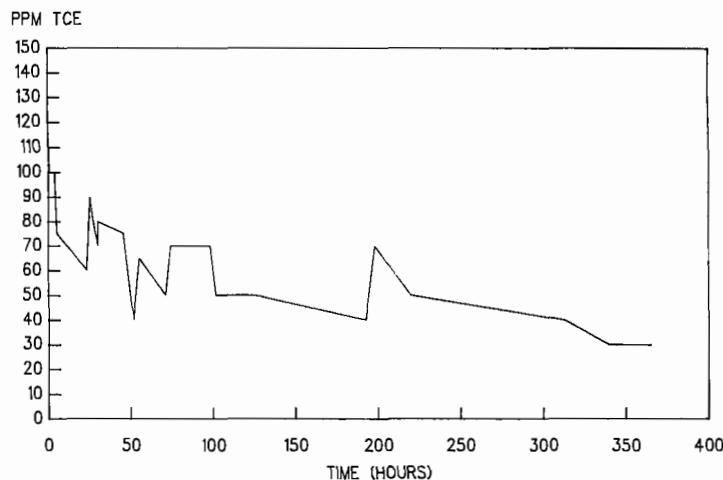


Figure 2
Concentration TCE vs. Time

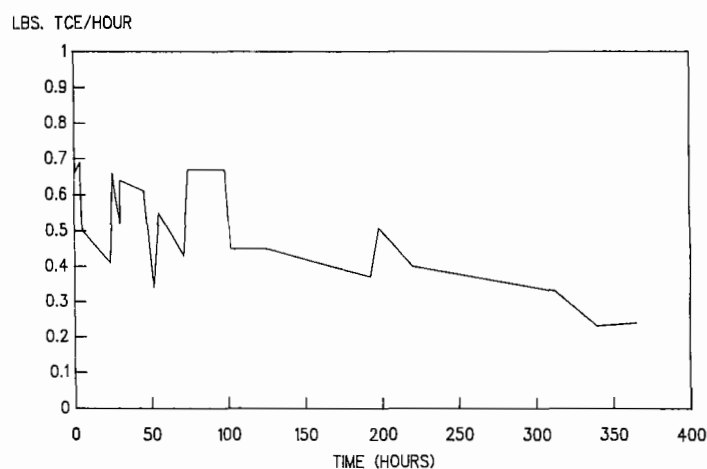


Figure 3
Mass Flow Rate TCE vs. Time

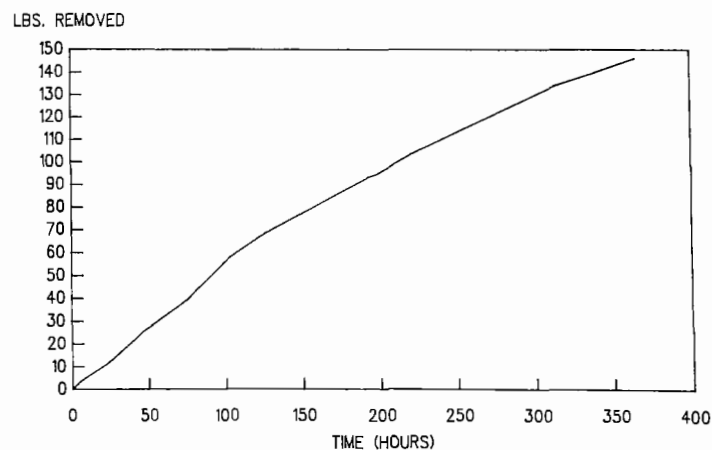


Figure 4
Cumulative Mass
TCE Discharge vs. Time

Based on observed differential pressure readings in the air inlet wells, a minimum radius of influence of 20 ft was realized.

The data collected during operation of the in situ air stripping system show that the technology effectively removes VOCs. According to mass balance calculations using pre-treatment soil boring data and in situ treatment system data, soils subject to treatment during the pilot test

were remediated from approximately 20 ppm to 1 ppm. Therefore, full-scale in situ treatment will be a component of the final remedial plan.

REMEDIAL DESIGN FOR SOILS

To remediate the soils, a full-scale soil air stripping system will be installed in the perched zone to remove VOCs from the unsaturated soils. The system will consist of a series of withdrawal (air is withdrawn from the soils) wells and air inlet (air is permitted to flow into the soils) wells. The system will use a total of 32 air withdrawal wells to remediate the soils coupled with their respective air inlet wells.

An asphalt cap and slurry cut-off wall was constructed atop and around the PCB contaminated portion of the perched zone. This construction effectively isolated the area of the perched zone containing PCBs from percolating rainwater and inflow from the nearby stream.

Approximately 25% of the ground surface above the perched zone was bare ground or covered with gravel. This area was covered with new asphalt material. In addition to this area, asphalt capping was installed following the installation of: (1) underground pipelines for the groundwater treatment system; (2) the in situ air stripping system; and (3) the slurry cut-off walls within the perched zone area.

The slurry cut-off wall was approximately 800 ft long (Figure 1), extended 15 to 20 ft below ground and was keyed into the undisturbed silty clay below the perched zone. The slurry cut-off wall consisted of a soil bentonite mixture that achieved a permeability rate of 1×10^{-7} cm/sec.

REMEDIAL DESIGN FOR GROUNDWATER CLEANUP

Seven recovery wells were installed at various predetermined locations at the facility to collect groundwater for treatment. The wells were constructed of carbon steel casings with stainless steel screens. One recovery well was located in the perched water zone, four in the over-

burden aquifer and two in the bedrock aquifer. Due to the presence of an oily product in the overburden aquifer, three of the recovery wells included product recovery pumps and groundwater pumps while the remaining recovery wells only included groundwater pumps. Oily product is pumped to above ground storage tanks for off-site disposal.

Groundwater from the seven recovery wells is pumped to an influent vault where two submersible pumps (one operating and one in standby status) transfer the groundwater to one of two multimedia filters. The multimedia filters (one operating with one in standby status) remove solids, oil and grease in the groundwater prior to its entering two GAC contactors, operated in series. PCBs are preferentially adsorbed in the GAC units prior to entering the packed column air stripper where VOCs are removed. Treated effluent from the air stripper is discharged to a river via the existing municipal storm sewer system in compliance with strict (NPDES) discharge limits. As shown in Figure 5, the process equipment is housed in a 40-ft by 40-ft structure.

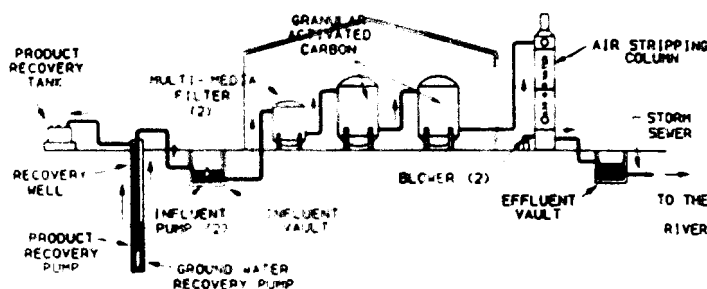


Figure 5
Treatment System Schematic

Table 1
Groundwater Analytical Results
(Concentrations in ppb)

		1,1 DCE	1,1 DCA	t-1,2 DCE	1,1,1 TCA	TCE	VC	CA	MC	TOTAL VOCs	PCBs
INFLUENT VAULT	1/12/89	230	620	19000	14000	1700	0	0	0	35550	15
	2/7/89	160	490	13000	5200	1600	0	0	0	20450	1.3
	3/10/89	0	350	9100	3500	900	0	0	0	13850	0
	4/20/89	0	270	6400	2800	610	0	0	0	10080	0
	5/10/89	0	220	6800	2600	630	0	0	0	10250	0
	6/8/89	140	150	5000	2100	590	0	0	0	7980	0
	7/11/89	0	160	6100	2700	640	0	0	0	9600	0.4
	8/2/89	0	190	6000	2800	680	0	0	0	9670	0
	9/6/89	0	100	5000	3200	1300	0	0	0	9600	0.9
GRANULAR ACTIVATED CARBON #2 EFFLUENT	1/12/89	0	0	0	0	0	0	0	0	0	0
	2/7/89	0	0	0	0	0	0	0	0	0	0 *
	3/10/89	0	0	0	0	0	0	0	0	0	0
	4/20/89	0	0	0	0	0	0	0	0	0	0 *
	5/10/89	0	1	0	0	0	6	7	5	19	0 *
	6/8/89	14	260	2900	0	0	24	0	0	3198	0 *
	7/11/89	150	130	5300	2000	0	0	0	0	7580	0 *
	8/2/89	0	210	6200	560	0	0	0	0	6970	0 *
	9/6/89	0	0	4300	1200	0	0	0	0	5500	0 *
AIR STRIPPER EFFLUENT	1/12/89	0	0	0	0	0	0	0	0	0	0 *
	2/7/89	0	0	0	0	0	0	0	0	0	0 *
	3/10/89	0	0	0	0	0	0	0	0	0	0 *
	4/20/89	0	0	0	0	0	0	0	0	0	0 *
	5/10/89	0	0	0	0	0	0	0	0	0	0
	6/8/89	0	0	6	0	0	0	0	0	6	0
	7/11/89	0	0	25	0	0	0	0	0	25	0
	8/2/89	0	0	14	0	0	0	0	0	14	0
	9/6/89	0	0	7	0	0	0	0	0	7	0

NPDES LIMITS

36 200 300

450

525

16

NA

NA

0.2

LEGEND:

1,1 DCE - 1,1 Dichloroethene
1,1 DCA - 1,1 Dichloroethane
t-1,2 DCE - t-1,2 Dichloroethene
1,1,1 TCA - 1,1,1 Trichloroethane

TCE - Trichloroethene
VC - Vinyl Chloride
CA - Chloroethane
MC - Methylene Chloride
PCBs - Polychlorinated Biphenyls

* - No Samples Taken
NA - Not Applicable

Backwash from the multimedia filters is discharged to an off-line backwash holding tank. Solids are allowed to settle in the tank prior to pumping the decant through a bag filter and into the influent vault. The average and maximum design flow of the treatment system components are 400 and 600 gpm, respectively. Empty bed contact time (EBCT) for each GAC contactor at average and maximum flow is 9 and 13 min, respectively.

Analytical data collected since January, 1989 indicate that the system is meeting design and regulatory requirements. VOC and PCB concentrations in the influent vault ranged from 35 to 8 mg/L and 15 mg/L to non-detectable (less than 0.0002 mg/L), respectively, while the VOC and PCB concentrations in the second GAC contactor effluent ranged from 7.5 mg/L to non-detectable for VOCs and non-detectable for PCBs.

Effluent from the air stripper indicated maximum VOC and PCB con-

centrations of 0.025 mg/L and non-detectable, respectively, as shown in Table 1.

CONCLUSION

The presence of PCBs and VOCs in the soil and groundwater present a challenge in designing an effective remediation program. Evaluating, selecting and implementing the proper innovative and traditional technologies can provide an effective and reliable treatment system as described above. The groundwater and recovery pumps and groundwater treatment system has been operating for approximately 7 mo. The slurry cut-off wall and asphalt cap have been installed. Full-scale operation of the in situ air stripping system is anticipated to begin in late 1989 and continue through 1990.

Membrane-Like-Material Extraction of Oily Wastes From Soils and Solids.

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ABSTRACT

Membrane-Like-Material (MLM) is a new kind of Liquid Membrane, but it is not like those that have been investigated in recent years. It has, instead, very low permeability to gases and oily compounds and has the property of picking up a layer of oily material that is adherent to a solid surface and leaving in its place a layer of water. The material that has been picked up is then used in the process of formation of the membrane, which occurs at ambient temperature.

The MLM effect has been used to strip many different oil compounds from solid surfaces and experiments have shown that as much as 40% bentonite clay can be present, and the water/oil exchange process still works. The very first successful separation that was achieved in the laboratory was on an oil-soaked Bentonite clay, for which the oil content was reduced to below the values that were obtained on the same sample, using Soxhlet Extraction.

The process is emerging from the laboratory and offers the promise of a new way to reduce the volume of materials contaminated with such things as oils, PCBs, dioxin and other materials found at Superfund sites, or at the aftermath of oil spills such as the Valdez Disaster. For each of these applications, the key point is that once an oil-wet surface has been converted to a water-wet surface. Further applications of oil or solvents will not re-contaminate the solid surface.

MEMBRANE-LIKE-MATERIAL

This paper is based on the discovery that a temporary membrane will form at the interface between certain solvents, water and a compound extracted from Athabasca Bitumen. The membrane, called MLM, for Membrane-Like-Material, will partition solvent and oily solutions from aqueous mixtures, capture and hold oily materials from solid surfaces and depress the residual amounts of partly water soluble solvents in water. Two applications of the technology are represented in the proposal: (1) one to remove oily contaminants from solid surfaces such as soils and (2) the other to separate the oily part from the non-oily part of the water used in the MLM soils cleaning process, or which was taken into the process with the waste material.

THE MLM LIQUID MEMBRANE

MLM (Membrane-Like-Material) is a new chemical class of Liquid Membranes, quite unlike those described in the literature. It is an inclusion type of Liquid Membrane, so called because it includes the target species during its initial formation, from which the included material is recovered, following a further separation step. The MLM appears as sludge, with the target species trapped in it. While it remains within the water phase, it is very stable, with the target specie firmly held. However, it does not form a compound with the target and it promptly dissociates at the air to water interface. The extraction of oily

compounds using MLM-forming solvents, cannot be compared with similar extractions using repeated solvent washes, especially when the solvents are selected to be the same for each method. In an MLM based extraction, the solvent itself is counted as an oily compound and is removed with the target species. In solvent extraction, the solvent residue may be many times larger than the volume or mass of the target species; it usually is not counted as an oily compound, and must then be extracted in a further step. In the case of soils, this solvent residue can amount to 30 to 60% of the soil by weight and the most frequently cited method of removing it is the application of heat. To compare the two methods on the same basis, the final removal of solvents for both methods must be considered. When this is done, the comparison becomes moot, since the nature of the comparison has then been changed to comparing the extraction of solvent using MLM, to the extraction of the same solvent using Heat.

Figure 1 - 8 show an experiment that was performed as an MLM demonstration for the Valdez operation. The MLM stripping was compared with conventional solvent extraction, in the presence of water. As can be seen, the conventional method has no effect, but the MLM method has completely removed the oil from the sand. The original proposal consisted of two stripping stages, one an in situ spray-on method for the beach, and the other a water-oil separation for the residues.

This process demonstration compares a Naptha Solvent Extraction, with MLM Oil to Water Surface Chemistry exchange. The sand sample was beach sand that was dried and soaked with Peruvian Crude Oil, to simulate beach sand.





Figure 2
Split Sample

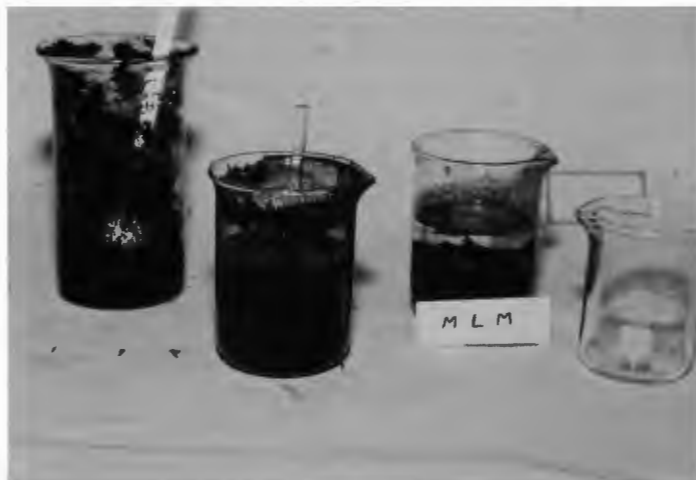


Figure 5
Naptha Side - Stirred



Figure 3
Naptha - Left. MLM - Right



Figure 6
MLM Side at 10 Seconds of Stirring



Figure 4
Water Added to Both

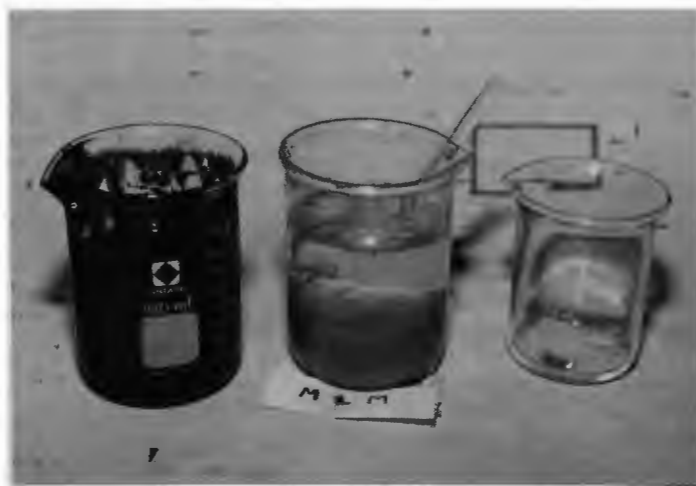


Figure 7
Water Wash is Completed at 3 Minutes

The spectrum of target materials and associated applications for the MLM extraction process, is related to the solubility of the solvent selected and thus is very wide when the solvent is properly chosen. It is fortunate that the best solvents for the formation of MLM are likewise the best solvents for oily compounds that are the most trouble-

some. On the basis of the criteria described, the actual oily residues must be divided by the solvation ratio used immediately prior to MLM extraction. Since these values can be as high as 40 to 1, oily residues can be very low indeed. The MLM Process might therefore be described more as a method of extracting a solvent rather than as a solvent ex-

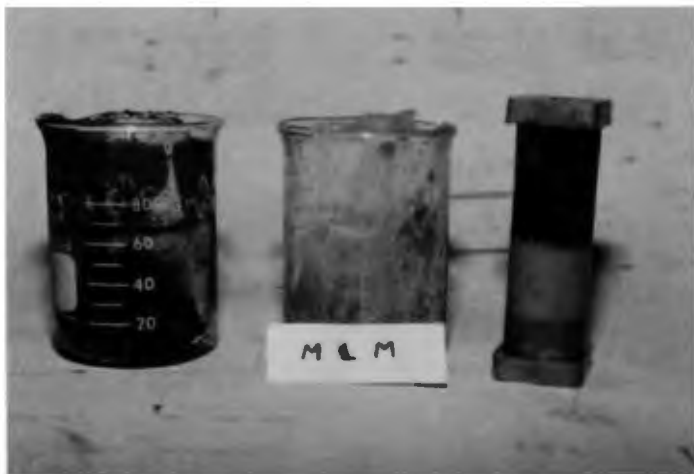


Figure 8
MLM Cleaned, Sample Taken. Naptha Side Has Been Drained

MLM SOLIDS PROCESSING

The MLM Process was discovered in 1981 during work on a process that used kerosene as the agent in a surfactant based water exchange process. The purpose of the work was to develop a process suitable for the extraction of tar sand. The process under development was found to be only 60% effective and had to be supplemented with soils washing and water cleaning techniques to make it usable. The use of surfactants at or near the Critical Micelle Concentration (CMC) was the attractive feature of this older technology. Working at or near the CMC leads to surfactant values near 200 mg/L instead of the 2% or 20,000 mg/L and up for other methods. It was necessary to develop a Sand Washing technique, derived from our then current water treatment program. This resulted in three unit processes needed to make this system work.

The challenge was thus established by these difficulties, to find other ways to exchange oil for water at a solid interface, once we knew that it was possible. It was found that certain solvents, in the presence of a component found in Athabasca Bitumen, would form a film at an interface between a solution of the solvent and water. This film was remarkably stable in the water phase, but obviously had one side active in water. The other side was adjacent to the oily phase and initial experiments showed that the film was not only stable in the oil phase, but also that the film would dissolve until the area of the film equalled the area of the interface. Other experiments showed that the film thickness was not of molecular dimensions, but was thick enough to be manipulated and had palpable tensile strength, considering its origin. A condensation effect was observed that released oily compounds captured by the film, into the oil phase. If the area of the surface was suddenly reduced, then wrinkles and folds would occur in the skin, that slowly dissolved, leaving a new layer of MLM that occupied the reduced surface area. It was found that this material could be literally cut out of the surface and lifted away into the water phase, where it could be manipulated, measured and handled "like" a membrane. A new layer of MLM would form in the cut out area, and over perhaps 30 min, the region would be completely healed.

It was postulated that since the water side seemed to be so stable, that perhaps the MLM could be formed adjacent to an oil-coated particle, with the water side facing into the particle. It turned out that conditions could be established to ensure the formation of the MLM in the proper manner to effect removal of the oily compound. The compound, with the solvent, and the bitumen extract in contact with the particle, was then lifted off and used to form the MLM, with the introduction of water. Thus it became evident that the heretofore impractical separations of oily materials from surfaces would be possible.

The spreading rates were determined, using very simple sand substrate experiments. They were approximately two orders of magnitude

greater than in surfactant based systems. The method used in these experiments was to oil-wet a known surface area of sand, typically 2000 ft² and then to effect the separation, while determining the time for the separate process to occur. This time was the spreading rate of the MLM throughout the sand mass. It was noted that the MLM formed a front that was remarkably well defined. In a 4 in deep sand bed in a separatory funnel, the interface front moved through the sand with a fully oil-wet to fully water-wet exchange occurring in only 0.125 in; moreover, this front was flat, with no fingering.

The zone in which the exchange of oil and water was taking place had a turbulence that could be clearly seen. Since the relatively heavy solvent was being displaced upward by the lighter water, it was postulated that the driving force was the weight of the solid particle falling through the MLM after it was coated with water. Later work showed that cylindrical vessels could be used and also that the range of operation extended from large excess liquid amounts to almost dry, provided that the starting condition for the water exchange step was properly determined.

Experimental results showed that the conditions of the soil and oily contaminant, at the start of the MLM formation step, were important, with the heavier molecular weight materials being harder to remove. Once it was learned that the solvent used must penetrate all the way to the actual solid surface, so that the MLM can form there, these difficulties were circumvented. If the solvent does not reach the solid surface, the MLM, if it formed as a layer, could be oriented the wrong way or would form as an amorphous mass and be ineffective. If the MLM formed in this manner, then the last molecular layer of oily material would not be available to effect the formation of the MLM. If the MLM formed an amorphous mass, then the layering, essential to effect clean separation, would not be present. The starting conditions are the bench-level determinations of the best concentration of solvent and oily compound that will permit the exchange step to go to completion. These conditions vary principally with the concentration of oily material present and the molecular weight of the target species.

The greater the molecular weight of the compound to be captured, the more solvent must be present at the solid interface for the MLM to form. A typical concentration of material for which this process was originally developed, was 150,000 to 200,000 mg/L, of oily material, with molecular weights all the way up to the heaviest components of heavy tars and bitumens, for which we expected to see residues of under 20 mg/L of solvent plus oil, with a final solvation ratio, at the end of the counter flow extractor, of as much as 40 to 1.

CONVENTIONAL SOILS WASHING

We found during the early development work that surfactants could act as an interferant in the MLM water exchange step. The puzzle was solved when our glassware was divided into two parts. The first was cleaned in conventional detergent cleaners, rinsed and dried. The other was then cleaned using solvent extraction, followed by acid cleaning. The extra steps in the cleaning process eliminated the interference effects. This finding lead to attempts to model the surfactant operation, and to re-investigate the question as to why the original surfactant-based technology that we started with was only 60% effective in establishing water-wet surface area.

The model that was proposed was that the oil-soluble tails of the surfactant molecules would enter the residue oil layer, leaving the water-soluble heads to form a layer that would then be above the oil layer. This process inhibits all further oil removal, since neither the solvents nor the surfactants can subsequently approach the oil layer underneath, due to the presence of this water layer. We believe that this effect is real and that it represents a limit to the effectiveness of all soil washing processes that use surfactants. It might be noted that this same limit also applies to enhanced oil recovery. The surfactant wash will certainly increase the oily material recovery somewhat, but it can never approach the performance of a replacement system where the oil is physically replaced with water.

THE MLM PROCESS FLOW DIAGRAM

A simplified flow diagram is shown in Figure 1. This process flow diagram is based on the detailed Mass Flow Process Diagram that has been prepared for API Separator Waste. The actual flow diagram was prepared from testing at bench-scale level on waste samples from a refinery site. This particular site had material characteristics that varied from 5% to 95% spent catalyst, which is an inherently water-wet material, and which makes solvent extraction very difficult.

The operation of the MLM Soils Washing System, is described below.

A conveyor, such as a screw conveyor, feeds a constant stream of input material into the receiving hopper of the MLM Solids Treatment Unit, prior to the first mixer stage.

The material is then passed to a second mixer stage, where conventional solvent extraction of most of the oil is performed. The solvent extraction step is divided into two stages to allow two different solvents to be used as a process option. A non-halogenated solvent is used in the first stage and a halogenated solvent, suitable to form MLM, is used in the second. Only one solvent extraction step is shown in Figure 9.

After solvent extraction in the third mixer stage, the oil-coated, solid particles are then coated with solvent, plus the MLM Extract. Thus, small amounts of contaminant materials on the soil have been largely substituted with larger amounts of a solvent. The solvent extraction process ensures that sufficient time has elapsed to allow the two oil phase components of the MLM to penetrated all the way to the solid surface. If the target contaminant is present at only the mg/L level, then the composition of the solvent and MLM extract alone are adjusted to ensure that MLM forms in the correct orientation and strength, once the water part is added. Upon the completion of the solvent extraction to the degree required, the solid material is pumped to the fourth mixer, where water is added and the mixture is stirred to ensure complete coverage of all of the material with MLM.

The MLM-coated material is then passed to mixer number five, where the MLM residue is removed using a water flush. The water films around each soil particle will not permit either oily material or solvent to re-

attach to the soil particle. Flushing must be sufficient in this stage to effectively remove all of the MLM, and any solvent that may have been used. Solvent residues are believed to be primarily from the interstitial areas, where solvent resides after washing. The cleaned soil is then sent to a dewatering unit, after which it exits the system and is ready for disposal.

Meanwhile, the collected water from the oily rinse stage and the MLM-flushing stage is returned to the MLM water treatment unit, where all of the oily fraction is collected, also using MLM; the oil containment leaves the unit as a solvent-bearing sludge. This sludge is then taken away for further treatment in a solvent recovery system.

The solvent recovery unit can be a Wet Still, where the condensation occurs in a counterflow water stream. Solvent recovery must take into account the vapor pressures of the site contaminants that are expected, to ensure that any with lower boiling points than the solvent selected will be recovered separately.

EARLY CLAY TESTS

The MLM process was developed to recover Tar and Bitumen at effectively 100% recovery, leaving a water-wet residue. A definitive test was made to determine the final residue of the solvent on the water-wet sand and from a starting condition of 130,000 mg/L, the solvent plus oil residue was determined by GC methods to be less than 20 mg/L. Several dozen samples of various waste materials and tar and oil sands were tested for separation efficiency. In all cases, separation was essentially complete. For a deposit of light oil in Bakersfield, California, which is in a clay formation, complete separation was achieved, even though the sample consisted of 40% bentonite, with the oil bound on the clay. No other potentially commercial process has been found to process this material.

The results on clay-bound oil proved to be important in that the process was shown to be effective in removing oily compounds from soil, and few soils have 40% bentonite. In the U.S. EPA SBIR Project, dioxin was shown to be reduced by an order of magnitude for each extraction. However, it is likely that the extraction was more effective than this,

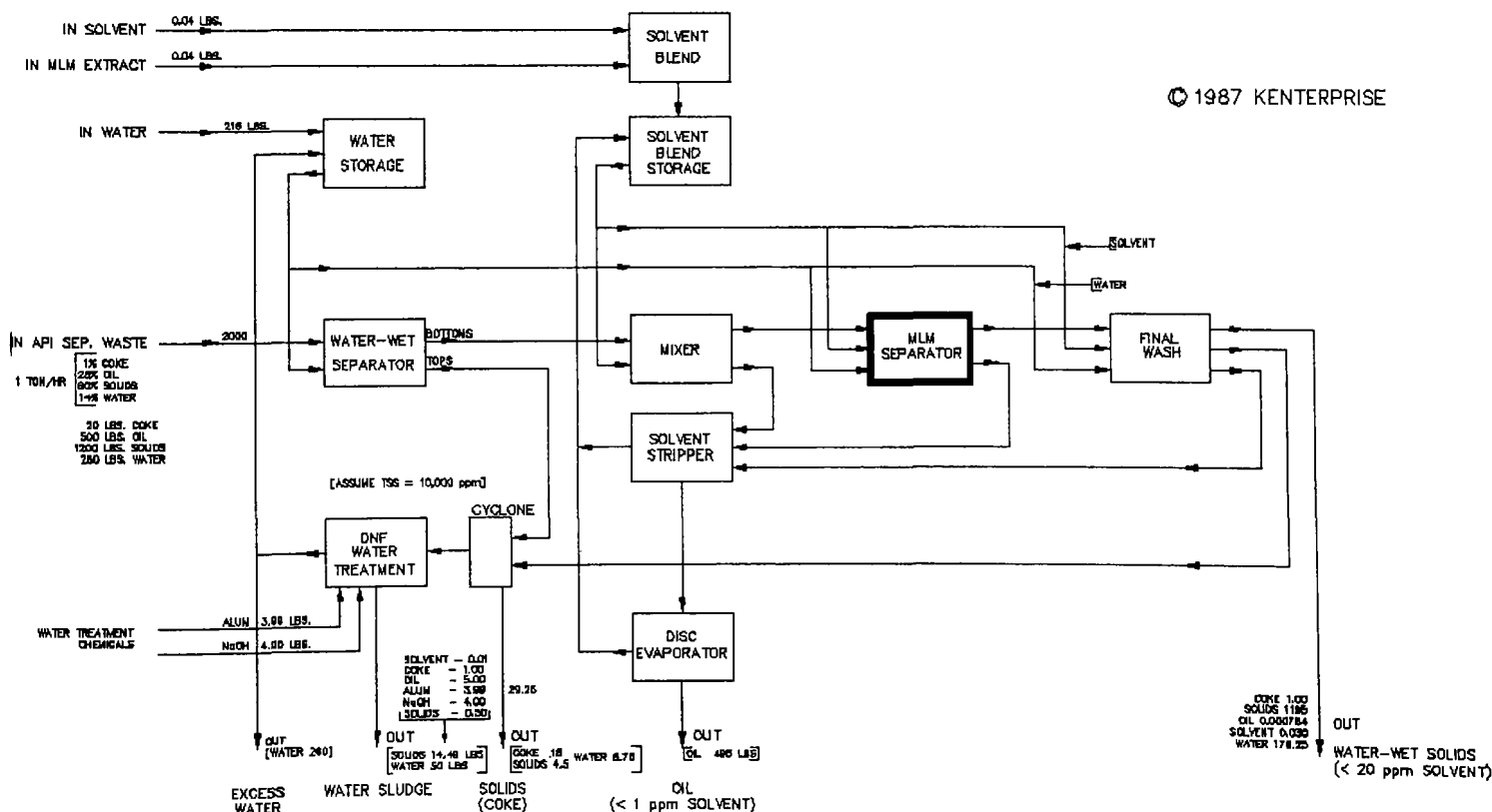


Figure 9

since the MLM concentrate could not be analyzed by the U.S. EPA method. The MLM apparently binds the dioxin within its temporary structure to an extent that defeats the GC analytical process. All of the other parts of the sample were successfully measured, so that the dioxin removal could be inferred, but it could not be measured.

In comparing removal efficiencies in clay-type soils relative to oily wastes and other media, it should be pointed out that the two cases cited compare a dioxin sample at 10 ppm starting concentration with an oily waste at 190,000 mg/L. The samples were, in fact, sandy material at 0.020 to 0.030 in in diameter for the dioxin case and bentonite clay for the oily waste case, with the particle size extending down into the low micron size range. Thus, the comparison takes the highest oily content, on the finest material and compares it with the lowest oily content on the most coarse material. This comparison shows a broad effective performance range for MLM, regarding the soil type and particle size.

An additional example of the potential application of this process is the treatment of API Separator waste which is refinery residue that can consist of large amounts of spent catalyst, sand, rust and other wastes. A preliminary study, undertaken as a prerequisite to the project, consisted of 10 different waste types including Tank Bottoms and Drilling Mud residues which were processed in a demonstration. All of the samples were cleaned, yielding a solid residue that showed no signs of oil in a solvent extraction step done after heat drying of the water-wet solids.

THE MLM SOLIDS PROCESSING

A typical selection of equipment includes a five-pass Ribbon Mixer, consisting of identical stages, with the material lifted from one stage to the next. Our requirements are that all of the mixers have a water blanket, with the solvent contained all the time. Available mixers are able to meet these needs and one or more stages can be modified to effect the MLM formation.

THE MLM PROCESS STEPS

In these discussions, "water-wet" means that the water is in direct adherent contact with the surface and is a Surface Chemistry condition. Likewise, "oil-wet" means the direct contact of the oil with the surface. Each condition implies the absence of an underlying layer of the opposite species. It is not possible to change from one condition to the other without intervention. The MLM process provides the intervention necessary to move the surface conditions from oil-wet to water-wet, after which it is not possible to again oil-wet the solid surfaces without a further intervention, such as heat far above the boiling point of water.

The process consists of the steps discussed below. Water Wash is used first to separate the non-oily material from the mixture, if the water-wet material is in the form of fines and if it is not contaminated. An example of that kind of material is spent catalyst in API separator waste. If the contamination level is in the low ppm range, so that the fines are likely to carry the contaminant out with the wash, this step may not be used. An example of the latter is a very small amount of a material such as PCB in the presence of a large amount of fine clay, where it would be preferable to wet the fines with solvent, rather than to try to separate them in a water wash.

For spent Catalysts in API waste, the fines have been found to be water-wet and constituting as much as 99% of the total material present. In this case, the oily material is attached to large particles and its density is likely to be well over 1.0, so that the relatively small amount of heavy oily material separates well from the large amount of non-oily material.

MLM will form around large lumps of water-wet fines and prevent the solvent from penetrating into the mass. Thus, for wastes from API Separators, the spent catalyst must first be removed with a water wash and the fines will not carry out contaminants because they are not contaminated.

In many fine soil wastes, the water wash cannot be used, since the fines are contaminated and will carry out the contaminant if a water wash is used. The occurrence of soils with water-wet fines also has been experienced. The sequence of steps therefore, needs to be established on a site-specific basis using bench-scale tests.

Solvent Extraction

A countercurrent solvent extraction is employed next to remove the bulk of the oily material from the oil-wet portion of the waste and to solvent-wet any dry material that is present, using a solvent selected to form MLM. If the oily part of the resulting mixture is in the high ppm concentration range, such as in an oil sludge, a solvent may be selected to optimize the solvent extraction step and not be chosen necessarily for the MLM formation, which would then be done in the next step.

Second Extraction

A halogenated solvent, such as methylene chloride, or a suitable compound already present at the site in large quantities, or p-xylene, together with a small amount of an extract of Athabasca or other Bitumen, are then used in a counter-current solvent extraction. When the oil and solvent concentration reaches the level where MLM oil-to-water exchange is possible, as determined from bench testing, water is added. This point is determined in the laboratory, where the solvent color showing the residual contaminant density and the dwell time for full penetration of the solvent, are used to determine the initial conditions for the water exchange to take place. The MLM, as it is being formed, then strips and isolates the oily compounds, from the surface, replacing them with a film of water.

As the mixing proceeds, the oil-to-water exchange process irreversibly coats all of the material with water, even if it was originally dry and had no oil on it, as would be found in a typical Superfund Site where some uncontaminated material is mixed in with the oily fraction of the contaminated material. The solvent is recovered and the contaminant appears as a concentrate. The extract of Athabasca Bitumen is not recovered and goes with the contaminant, since its cost does not justify recovery.

Water Wash

A water wash is employed to flush away all of the MLM that remains with the waste after it has been weakened by further exposure to solvent, if necessary. This material is collected by the water treatment system and recovered for disposal. The cleaned material is water-wet and, after being de-watered, can be returned to the site or disposed of in a landfill.

The bulk of the oily residue will be carried in the solvent used for the preliminary extraction. If this oil is a usable oil, the solvent selection for the first extraction might be kerosene, naptha or some other solvent that will not interfere with the subsequent use of the residue, in which case, the solvent need not be recovered.

The use of a halogenated compound for the solvent extraction step will make it difficult for a refinery to accept the oil for processing, since chlorine is not compatible with the catalysts used in the refining process. p-Xylene is acceptable, however and, in addition, will perform about as well as methylene chloride. Its main drawback is that is very difficult to handle in the pure state since it can convert large amounts of pumping turbulence energy into electrostatic energy resulting in an extreme fire hazard. Methylchloride also must be used alone and not in the presence of the other two isomers, since only one of the three isomers will form MLM, while the other two inhibit the formation of MLM, even in the presence of p-xylene.

Problem Contaminants

If the oil is dioxin- or PCB-contaminated, the recoverable oil is almost certainly not commercially usable. The solvent selection will then be optimized for best Target Material extraction, i.e., for best MLM formation. Some of the oily material will appear in the solvent that will form the MLM for the waste involved; the rest will appear in the MLM sludge. This solvent will be selected from methylene chloride, p-xylene, tetrachloroethane 1,1,1 or any other halogenated solvent. Work is proceeding to find other non-halogenated solvents.

The solvents are always used either under a water blanket or in a closed container. The selection of a solvent must take into account the vapor loss from leaks in the solvent recovery system, with a much smaller amount of a solvent leaving the process with the solid residue.

We are very conscious of the need to select the solvent so as to be neither phototropically active nor present a health hazard. The MLM-extract from Bitumen is a high molecular weight material that is used in low mg/L quantities in the MLM forming solvent. It is retained with the oily material from which it can be extracted if necessary, but this is very unlikely since it is relatively insoluble.

MLM WATER TREATMENT

Considerable portions of the MLM and free oils are likely to show up in the wastewater stream. Also, a large amount of water is often present with the oily waste material and is carried into the MLM process with it. Conventional water treatment for the resulting wastewater is difficult and expensive.

An MLM-based water treatment system for broad spectrum oily materials is under development with a Phase II and Phase III SBIR project for industrial laundry and other industrial wastes. This process is an adaptation of the MLM process for solids to allow the formation of large amounts of MLM, in the presence of salts such as sodium chloride, or calcium chloride and to form a floc. Adding air to this mixture allows standard flotation techniques to be used for the separation of oily materials.

Pilot plant tests have shown that chlorinated solvents, such as perchloroethylene, were reduced to concentrations near non-detectable in water; additionally, the heavy metal content of the industrial laundry waste was reduced to less than local municipal discharge limits in a single pass. The heavy metal reduction was not expected until it was realized that the oily contaminants were particles that included the bulk of the heavy metals and these were removed en masse from the waste water, without solid and oil separation.

The MLM Water Treatment Unit is rated at 20 gpm, but the hydraulic limit is well over this, depending on the contamination level. The capacity of the water treatment system is approximately in balance with the solids processing system at the nominal flow ratings. The water soluble components will not be extracted by the MLM Water Treatment system, but will be treated in a following stage using a different method.

Wastewater containing oily contaminants is pumped to a static mixer where a foam consisting of CaCl_2 , water, solvent and MLM Extract is created. The resulting mixture is fed to a second static mixer, to which a metered quantity of air is added. The resulting mixture is then passed to a separation tank where the oily fraction is floated off and the clear water, with its dissolved components, is fed to an outlet pump. The water level in the tank is controlled by an automatic control valve on the discharge side of pump, and water flow rate is controlled by an automatic control valve on the discharge side of the drive pump.

The MLM water treatment unit will handle water containing over 20% oil and will reduce the oil concentration into the range of 1 to 10 mg/L, leaving water soluble materials in place.

ADVANTAGES OF THE MLM TECHNOLOGY

The goal was to design an Oil Production process that was environmentally and economically sound. To meet both economic and environmental needs, the process yield must be high. The most important contribution that the MLM Process and related technology offers, is that it allows the development of a realizable remediation process at reasonable cost. The major cost of an oily waste remediation is not the process cost, but is the handling cost of the materials. Excavation and return of contaminated soil is expensive, but not nearly so great as reburying or incinerating a hazardous material.

The MLM Process is based on a new principle, not previously known or used. It provides an enhancement to the separation and treatment option that has not heretofore been available. Working at the molecular level, it introduces an impermeable barrier to the return of the contaminant that makes separation easy for all wastes that are oil soluble. The separation step is a potentially low-cost extraction which is a complete separation of soils and organic materials.

The MLM Process at it's presently developed stage will remove any material that is soluble in the solvents selected, including the solvents themselves.

WASTES AMENABLE TO THE MLM PROCESS

Oil wastes encountered in oil production, refining and transport will be particularly amenable to treatment by the MLM soil washing process as demonstrated by laboratory tests. It is expected that the MLM process will also be effective in the treatment of halogenated and polycyclic organic materials. Soils which are present together with contaminated material can be either removed or processed through the MLM water exchange step, without performance penalty.

SUMMARY OF MLM RESULTS TO DATE

A process evaluation procedure was developed for the rapid determination of yields greater than 99.9%. A mass balance was performed on each sample tested to determine, by weight, the amount of solvent residue lost on the sand or soil. An upper limit of 50 ppm of solvent plus oil on a solid phase, was established, above which the sample would be rejected and further process development would be performed. This criterion was selected primarily as a commercial yield limit and it was recognized that it was far better than the then best mining practice. A second test was established using a colorimeter with the reference cell filled with clean solvent and the test cell filled with known amounts of oil plus solvent. The upper limit of 50 ppm of residual oil was used for the screening tests, but this value was never reached. Selected samples were tested for solvent plus oil residue at an independent laboratory. The results were as follows:

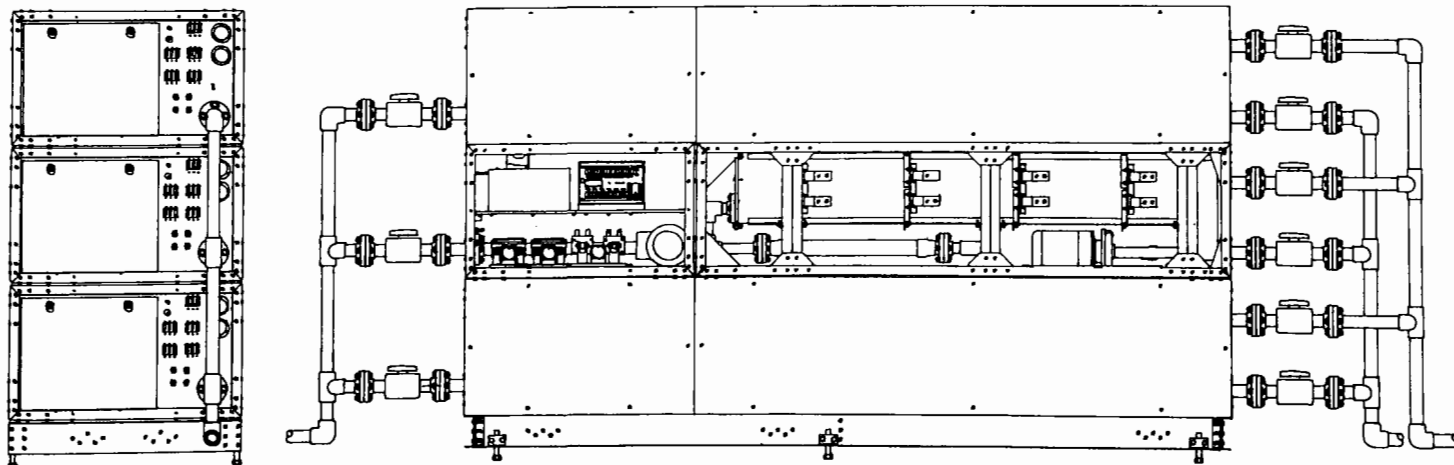


Figure 10
MLM Water treatment Unit

- No oily material was found that could not be processed to better than 99.9 % removal after process adjustment.
- The sample size varied from 10 to 1800 g. Two groups of solvents were used, one for preliminary stripping and the other for MLM stripping of the oil plus the first solvent residue. Many solvents were tried, both Halogens and non-halogens; with the exception of p-xylene, no non-halogenated solvent would work.
- Solvents which would not form MLM were always found to be removed to the oily side and none of them appeared as interferences, so that oils could always be extracted without halogen residue with an appropriate choice of solvent.
- Some of the materials tested are shown below. Sample 3 (Athabasca Tar Sand), which was the most intensely studied of the oil group, was also tested to see if sea water could be used instead of fresh water; as it turned out, sea water could be used. This result then led to tests on Sample 12, the Ohio Brine, which demonstrated the existence of the very strong partitioning effect between water-soluble salts and other dissolved materials and non-soluble, or partly soluble materials such as oils and solvents. The test also led to the approach which was successful, for our industrial laundry wastewater cleaning project, with the Phase II Project, for the SBIR Program of the U.S. EPA.

CONCLUSIONS

The MLM technology represents an innovative soil washing/contaminant recovery process which can achieve significant reduction of various heavy organic materials. The process satisfies the goals of the SITE emerging technology program since its functional characteristics are applicable to a wide variety of wastes in a variety of soils. The process also has the potential of being an effective resource recovery technology which will substantially reduce the amount and

Contaminated Materials Tested

OILS

No.	Source	Type	%Oil	% ppmRemoval
1.	Athabasca	Tar Sand	14%	140,000,999.9 +
2.	Athabasca	Tar Sand	10%	100,000,999.9 +
3.	Athabasca	Tar Sand (oxidized)	8%	80,000,999.9 +
3.	Peru, S.A.	Heavy Oil	14%	140,000,999.998
4.	Columbia, S.A.	Heavy Oil	13%	130,000,999.9 +
5.	Utah, U.S.	Tar Sand	8%	80,000,999.9 +
6.	New Mexico	Tar Sand	8%	80,000,999.9 +
7.	Alabama	Tar Sand	6%	60,000,999.9 +
8.	California	Light Oil	19%	190,000,999.9 +
API WASTES				
9.	Montreal	API Waste	25%	250,000,999.9 +
10.	Calgary Can.	API Waste	20%	200,000,999.9 +
DIOXIN				
11.	Weston	sample dioxin	—	1090.0
BRINES				
12.	Ohio	Brine	6%	60,000,999.9 +

costs of environmental control requirements because of the uniquely high efficiency of stripping oily and heavy organic materials from soils.

The process can be used effectively as a concentration step yielding cleaned water-wet soils and low volume concentrated wastes which could be further processed by other means such as incineration. The process operating parameters in ambient conditions offer the advantage of low cost simple and reliable operating systems which should enhance operational acceptability.

Bioremediation of Pesticides and Chlorinated Phenolic Herbicides - Above Ground and In Situ - Case Studies

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ABSTRACT

Remediation of hazardous waste sites requires the integration of science, technology and engineering to cost-effectively cleanup complex contaminants. Bioremediation, long recognized as an effective technology for treating petroleum hydrocarbons, is also effective treating more complex compounds such as pesticides and chlorinated phenolic herbicides. This paper will discuss the application of bioremediation technology to more complex waste sites, the various bioremediation technologies and actual case histories of complex site cleanups of soil and groundwater using bioremediation in above ground and in situ processes.

INTRODUCTION

Hazardous waste disposal represents one of the major environmental problems in the world today. Numerous methods and techniques have been proposed and tried for treating and disposing chemical wastes and their by-products to render them harmless to man and his environment. In spite of all the effort and money spent, no single technology has evolved which is economically and technically satisfactory for all waste constituents and matrices. One of the most promising technologies for this enormous problem, however, is the application of biotechnology.

Biodegradation, the microbial transformation of organic compounds, has long been recognized as an effective process for the removal of toxic chemicals from the environment. Biodegradation offers a relatively inexpensive yet highly efficient method of removing toxic chemicals from contaminated soils and groundwater.

Bioremediation, the controlled use of biodegradation to remove toxic chemicals from soil and groundwater, is an effective and efficient remedial technology for many complex sites, utilized alone or in combination with other physical and chemical treatment strategies. The purpose of this paper is to address some of the principles of biological degradation of toxic chemicals and to demonstrate through actual field experiences the effectiveness of bioremediation of contaminated sites.

DESCRIPTION OF BIOTREATABLE WASTE

Biological processes have been used for many years to remediate petroleum hydrocarbons such as gasoline, diesel, crude oil and creosote. More difficult compounds, such as pesticides and their derivatives (i.e. phenoxyacetate herbicides, carbamates, and organophosphates); chlorinated solvents (i.e., methylene chloride, trichloroethylene (TCE) and vinyl chloride); and halogenated aromatic hydrocarbons (i.e., penta chlorophenol, chlorinated benzenes and even some PCBs also can be biodegraded successfully. Microbiological processes can also potentially be used to transform and recover metals such as lead, cadmium, mercury and chromium (Table 1).

The biochemical pathways for many contaminants found at hazardous waste sites have been extensively studied in a range of microorganisms^{1,2}. The complexity of the environment and the complexity of organic material substances often preclude easily predictable biodegradation results in hazardous waste sites. However,

Table 1
Examples of Superfund Wastes and Hazardous Constituents
Which Can be Treated by the Solid-Phase Processes

Waste Description	Common Hazardous Constituents	Biological	Carbon Adsorption	Washing Extraction
Spent halogenated solvents and compounds from the manufacture of chlorinated aliphatic hydrocarbons	1,1,2-Trichloroethylene (TCE)	X	X	
	Chloroform	X	X	
	1,1,1-Trichloroethane (TCA)	X*	X	
	Tetrachloroethene (PCE)	X*	X	
	1,2-Trans-Dichloroethylene (DCE)	X	X	
	Methylene Chloride	X	X	
	1,1-Dichloroethane		X	
	1,1-Dichloroethene	X	X	
	Vinylchloride	X	X	
	Carbon tetrachloride		X	
	1,2-Dichloroethane (EDC)	X	X	
	1,1,2-Trichloroethane	X*	X	
	1,1,2,2-Tetrachloroethane	X*	X	
	Cis-1,2-Dichloroethylene	X	X	
	Trichlorofluoromethane		X	
Wastes from the use and manufacture of chlorinated phenols, benzenes and their pesticide derivatives	Chloroethane	X		
	Bis(2-chloroethyl)ether	X	X	
	Dibromochloromethane		X	
	Chlorobenzene	X	X	
	Pentachlorophenol (PCP)	X	X	X
	Dichlorobenzene	X	X	
	Hexachlorobenzene (HCB)	X*	X	
	2,4-D, Salts & Esters	X	X	X
	2,4,5-T	X	X	
	Trichlorobenzene	X	X	
	Trichlorophenol	X	X	X
	Hexachlorocyclohexene	X*	X	
	Dichlorophenol	X	X	X
	Cyclohexane	X	X	
	Chlorophenol	X	X	X
Spent non-halogenated solvents	Toluene	X	X	
	Benzene	X	X	
	Phenol	X	X	X
	Ethylbenzene	X	X	
	Xylene (O,M,P)	X	X	X
	Methyl ethyl ketone	X	X	X
	Acetone	X	X	X
	Methyl isobutyl ketone	X	X	X
	Cresols	X	X	X
	Ethyl Ether	X	X	X
	Methanol (alcohols)	X	X	X
	Lead	X**		X
	Cadmium	X**		X
	Arsenic	X**		X
	Zinc			X
Metal plating and cleaning wastes	Chromium	X**		X
	Copper			X
	Nickle			X
	Barium	X**		X
	Selenium	X**		
	Mercury	X**		
	Cyanide	X**		X
	Azide	X**		
Petrochemical products and wastes, straight and branched chain-alkanes, gasoline, diesel, crude oil, creosote and refinery waste	Naphthalene	X	X	X
	Phenanthrene	X		X
	Benzo(a)pyrene	X		X
	Anthracene	X		X
	Bis(2-ethylhexyl)phthalate	X		X
	Styrene	X		X
	Benzo(j,k)fluorene	X		X
	Pyrene	X		X
	Fluorene	X		X
	di-n-butyl phthalate	X		X
	Acenaphthene	X		X
	Tetrahydrofuran	X		X
	Chrysene	X		X
	Diethyl phthalate	X		X
	Benzo(a)anthracene	X		X
	Acenaphthylene	X		X
	Dibenzofuran	X		X

*Anaerobically only

**Biologically transformed in laboratory systems

accumulated data and an understanding of microbial biochemistry make it possible to generalize to some extent the relative rates of biodegradation of compounds found at the site. Treatability studies are conducted to establish degradation potential rates for specific site contaminants.

An understanding of the metabolic pathway(s) is required in order to control and manipulate the environment to bring about optimum bioremediation at complex sites. The controlled biodestruction of complex hazardous materials by natural microorganisms is not an accident of nature but the systematic interaction of scientific knowledge (ecology, physiology, genetic, chemistry and hydrogeology) with sound engineering principles to maximize the desired metabolic reactions in environmental cleanups.

Biological processes can be used to remediate water, soil, sludge, sediment and other types of materials contaminated with organic and inorganic constituents. A prerequisite to the development of effective bioremediation processes for the aforementioned types of media is the design of materials handling and engineering systems which ensure that the contaminated material is processed into a form which is amenable to bioremediation. Clays can be particularly difficult to treat because of material handling problems and the tendency of the clay to keep contaminants away from the microbial cultures. This latter problem, one of limited bioavailability, is one of the more challenging problems to overcome from an engineering standpoint.

BIOLOGICAL TREATMENT TECHNOLOGIES

Biological treatment technologies for contaminated soils and groundwater fall into four main categories: (1) solid-phase biotreatment (landfarming); (2) slurry-phase biotreatment; (3) insitu biotreatment; and (4) combined technologies with chemical or physical treatment. The selection of a specific treatment process is a function of the physical/chemical nature of the contaminant, the contaminant concentrations, the waste matrix and economic considerations (i.e., overall cost, treatment time-frame, etc.).

Solid-Phase Biotreatment

Solid-phase biotreatment relies on principles applied in agriculture in the biocycling of natural compounds. The conditions for biodegradation are optimized by aerating the soil with regular tilling and by the addition of nutrients and water. Naturally indigenous microbial populations are diverse and often contain the appropriate microorganisms for degradation of many site contaminants found in the contaminated soils.

The rates of bioremediation of contaminated soils are enhanced by optimizing oxygen levels, moisture content, available nutrients such as nitrogen and phosphorous, pH and contact between the appropriate microorganisms and the contaminants. This technique has been successfully used for years in the managed disposal of oily sludge and other petroleum refinery wastes through a process called landfarming. Solid-phase biotreatment of contaminated soils is probably the most widely used and cost-effective biotreatment technology applied today. Typically, the process, illustrated in Figure 1, is used for petroleum and creosote-contaminated soils. Typical costs for this type of treatment are \$40-\$90/yd³ but are highly dependent on conditions at the

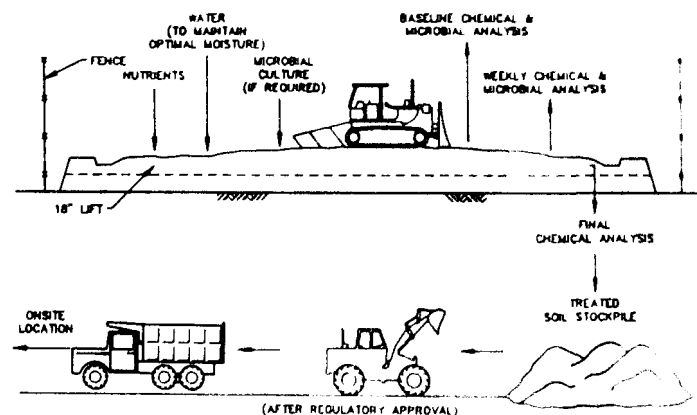


Figure 1

Typical Solid-Phase Bioremediation Diagram

site and materials handling costs. These costs compare favorably with disposal costs that typically range between \$250-\$300/yd³ for Class I disposal. Recent federal regulation (RCRA, Land Ban) may even prohibit disposal of some wastes due to fugitive emissions and leaching of organics and metals, thus requiring treatment prior to disposal.

Generally, solid-phase bioremediation can be conducted without extensive engineering of a treatment unit. As shown on Figure 1, contaminated soils are spread over an area of the site and treated using landfarming techniques. When leachate collection is required, because the waste is highly leachable and/or there is groundwater near the surface, leachate collection systems using liners, trenches and/or wells can be employed.

An example of a highly controlled solid-phase bioremediation system was engineered and constructed by ECOVA to control volatiles and leachate. The System consisted of a treatment bed which was lined with a 80-mm high-density liner with heat welded seams on top of which was placed clean sand. The sand provided protection for the liner and proper drainage for contaminated water as it leached from contaminated soils placed on the treatment bed. Lateral perforated drainage pipe was placed on top of the synthetic liner in the sand bed for collection of soil leachate. The lined soil treatment bed was completely enclosed with a modified plastic film greenhouse. An overhead spray irrigation system contained within the greenhouse provided moisture control and a means of distributing nutrients and microbial inocula (as needed) to the soil treatment bed.

Contaminated leachate that drained from the soil was transported by the drain pipes and collected in a gravity-flow lined sump. Leachate was then pumped from the collection sump to an on-site bioreactor for treatment. Treated leachate was used as a source of microbial inocula and reapplied to the soil treatment bed through the overhead irrigation system, after adjusting for optimum nutrients and environmental parameters.

Volatile organic compounds which were released from the soil during processing were controlled by an air management system, which was attached to the soil treatment facility enclosure. As the volatile compounds were released from the soil, they were drawn through the structure to the air management system.

Biodegradable volatile organic compounds can be treated in a vapor phase bioreactor. Non-biodegradable volatile organic compounds can be removed from the effluent gas stream by adsorption on activated carbon. The design of choice will depend on the nature, concentration and volume of the air emissions, regulatory controls and cost-effectiveness.

Soil heap bioremediation is a modification of solid-phase treatment used when available space (area) is limited. In soil heap bioremediation, contaminated soil is excavated and stockpiled into a heap on a lined treatment area to prevent further contamination. Microbial inoculum (as needed) and nutrients are applied to the surface of the stockpile and allowed to percolate down through the soil. The pile can be covered and an air emissions recovery system installed as described above. A leachate collection system is used to collect the fluid, which is recycled. An internal piping system may be installed to blow air upwards through the soil and thus accelerate the biodegradation process through the addition of oxygen. During operation, pH and moisture content are maintained within ranges conducive to optimum microbial activity. Typical costs are similar to conventional solid-phase treatment.

Composting processes are another modification of solid-phase treatment in which the system is operated at higher temperature due to increased biological activity. This technology would be used for highly contaminated soils, treatment of poorly textured soils and in areas where temperature is critical to the sustained treatment process. Contaminated soils are mixed with suitable bulking agents, such as straw, bark or wood chips, and piled in mounds. The bulking agent improves soil texture for aeration and drainage. The system is optimized for pH, moisture and nutrients using irrigation techniques and can be enclosed to contain volatile emissions. Care must be taken for leaching control, for volatile emissions control and that the bulking agent does not interfere with the biodegradation of the contaminants (preferential carbon source).

Slurry-Phase Soil Bioremediation

The biotreatment of organic waste in bioreactors has been an effective treatment system for wastewater, groundwater and other waste types. Several commercially available bioreactor treatment systems have been used for hazardous wastewater treatment³. These systems will not be described here except to emphasize the need to optimize the advantages of the system from both microbiological and operational perspectives regardless of the choice of system. Some of the advantages of using a bioreactor include:

- Greater process management and control
- Increased contact between microorganisms and contaminants (less heterogeneity)
- Use of specific cultures or inoculum
- Decreased acclimation times and faster biodegradation rates

Slurry-phase bioremediation is a process where contaminated soils are treated as an aqueous slurry in large, mobile bioreactor tanks. This system maintains intimate mixing and contact of microorganisms with the hazardous compounds and creates the appropriate environmental conditions for optimizing microbial biodegradation of target contaminants. One disadvantage is the additional excavation and material handling of the contaminated material that is often required. The slurry retention time may be varied, as required, and the bioreactor has the potential to operate in batch or continuous modes. Treated soils are dewatered and the water containing high populations of acclimated microorganisms is recycled. This process greatly reduces the acclimation and treatment times for subsequent batches. The general schematic of slurry-phase treatment is shown on Figure 2.

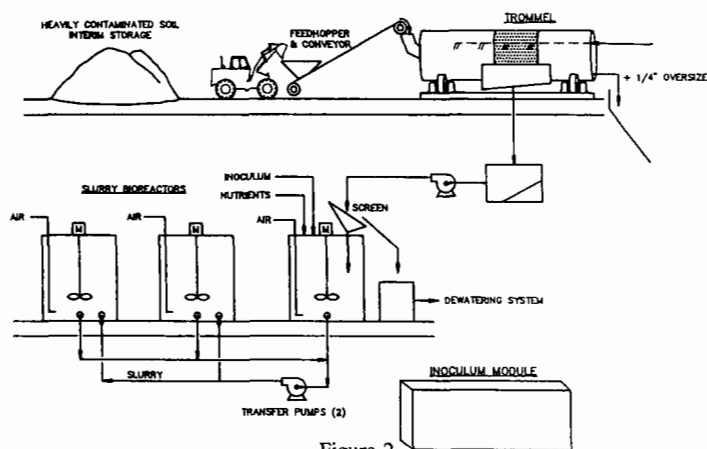


Figure 2
Typical Slurry-Phase Bioremediation Diagram

The first step in the treatment process is to create the aqueous soil slurry. During this initial step, all stones and rubble greater than 0.25 in. in diameter are physically separated from the soil, and the soil is mixed with water to obtain the appropriate slurry density. The water used to make the slurry may be contaminated ground water, surface water or another source of water. A typical soil slurry contains approximately 40% solids by weight; the actual percent solids is determined in the laboratory based on the concentration of contaminants, the rate of biodegradation and the physical nature of the soils. The soil is mechanically agitated in a reactor vessel to keep the solids suspended and the appropriate environmental conditions for enhancing biodegradation maintained. Inorganic and organic nutrients, oxygen and acid or alkali for pH control may be added to maintain optimal conditions. Microorganisms may be added initially to seed the bioreactor or added continuously to maintain the correct concentration of biomass necessary for rapid biodegradation. The residence time in the bioreactor varies with the soil matrix, physical/chemical nature of the contaminant (including concentration) and the biodegradability of the contaminants. Once biodegradation of the contaminants is completed, the soil slurry is dewatered.

Depending on the nature and concentration of the contaminants, and the local regulations, volatile emissions may be released to the atmosphere or treated to prevent emission. Because the soil is treated

in a contained process, a remediation system can be designed for soils contaminated with a complex mixture of hazardous compounds. The design of the slurry-phase bioremediation process can be modified to treat soils that are contaminated with biodegradable semi-volatile and volatile compounds, as well as some heavy metals.

The cost of treatment using slurry-phase bioremediation is higher than other biotreatments per unit cost but is substantially lower than incineration or direct disposal. Costs are influenced by materials handling, retention times, equipment needs, volume of waste and reactor designs. Slurry-phase reactors can be as simple as lined ponds or lagoons engineered for slurry-soil treatment. Costs for slurry-phase treatment typically range from \$75-\$150/yd³.

In Situ Bioremediation

In situ bioremediation is the biological treatment of contaminated soils and groundwater without excavation, usually where contamination is deep in the subsurface or under buildings, roadways, etc. In situ treatment involves the controlled management and manipulation of microbial processes in the subsurface. This process requires an understanding of both microbiological processes relative to biodegradation of the target contaminants and the soil physical and chemical environmental effects on the microbial processes. Typically, these systems utilize aerobic processes and involve the addition of oxygen as air, oxygen gas

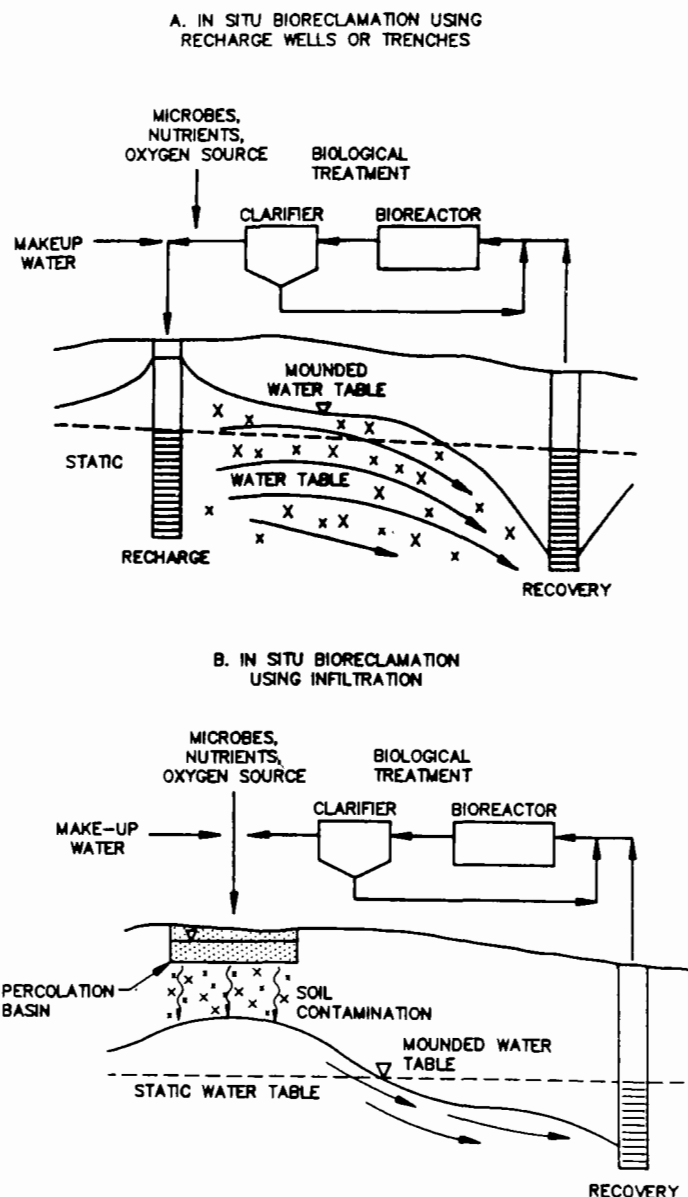


Figure 3
Typical In Situ Bioremediation Diagrams

or hydrogen peroxide and small amounts of inorganic nitrogen and phosphorous. Recent evidence has shown anaerobic processes may be effective in the biotreatment of, at least, BTX (gasoline) type contamination.

The in situ bioremediation system usually is accompanied by a surface bioreactor for treatment of the recovered groundwater which can then be reinjected to enhance the subsurface active microflora. The design and engineering of any system site is highly dependent on types of contaminants, permeability of the soils, regulatory constraints, contamination of vadose zone, etc. Therefore, a design is highly dependent upon the site and costs vary greatly. Two adaptations of in situ bioremediation are schematically shown in Figure 3.

Biological degradation of subsurface contaminants can be accomplished through delivery of an oxygenated nutrient solution to the zone of contamination to stimulate natural microbial activity. Areas of contaminated soils above the water table can be treated by artificially raising the groundwater table. Water is cycled through the subsurface using a series of recovery and recharge trenches or wells. Figure 3 schematically depicts an in situ bioreclamation system using recovery and recharge wells. Water recharge (using recovered groundwater and supplemental makeup water) causes groundwater mounding in the water table where the bulk of the contaminants are located. The water is recovered in a downgradient trench or well and is pumped to a surface bioreactor where it is treated to remove residual contaminants, amended with nutrients and oxygen, and reintroduced into the subsurface. Water may be oxygenated by sparging with air or pure oxygen or by adding hydrogen peroxide. The system can be cycled by reversing the role of the recharge and discharge wells to target zones if contamination is located above the existing water table.

CASE HISTORIES

In Situ Bioremediation of Chlorinated Phenolic Herbicides

Shallow groundwater contamination was detected beneath a herbicide formulation facility in 1981. The aquifer consisted of 35 ft of glacial outwash deposits; 25 ft of silty sand and clay overlaying 10 ft of coarse sand and gravel which rested on shale bedrock. The major contaminants were identified as chlorinated phenols, primarily 4-chloro-2-methylphenol (4C2MP). A pump and treat system (consisting of 11 extraction wells feeding two activated carbon units) was installed in 1983. Effluent from the system was returned to the aquifer via eight injection wells. To achieve a more rapid reduction in contaminant levels, an in situ program was evaluated in 1987.

Aerobic laboratory culture techniques were used to assess 4C2MP biodegradation potential in the site groundwater. High 4C2MP biodegradation potentials were observed in groundwater samples obtained from three site wells (Table 2):

Table 2
4C2MP Concentrations in Aerobic Cultures

Well	C ₀	C ₇	C ₁₄	% Removed
I-4	X = 1133	X = 1133	X = <41	>96
P-4	X = 3400	X = 3800	X = 1380	60
P-8	X = 710	X = 710	X = <41	>94

X = Average 4C2MP concentration (3 replicates).

C₀ = Initial Concentration.

C₇ = Final Control Concentration (7 days).

C₁₄ = Final Test Concentration (7 days).

High 4C2MP biodegradation potentials were observed with no nutrient adjustment. This study showed that only aeration was needed to reduce 4C2MP concentrations in the groundwater.

In 1988, the number of recovery wells was increased to 19 and two additional injection wells were installed. Airlift pumps were placed in

the recovery wells, thereby increasing the oxygen concentration in the injected effluent. Initial results are promising:

- Significant reduction in off-site contaminant plume size was effected by gradient control of the recovery system.
- Decreased dissolved oxygen concentrations were initially measured in the injection wells; this suggested that phenolic degrading microbial populations had been established adjacent to the injection wells.
- In the initial 3 mo of operation, the total phenol plume exhibited a 25 to 35% reduction in size; after 6 mo a 50% reduction was observed.

Bioremediation of Pesticide-Contaminated Soil and Groundwater - North Dakota

ECOVA Corporation was responsible for the cleanup of soil, surface water and groundwater at a site in North Dakota after it had been contaminated during a fire at a pesticide storage facility. Water used to put out the fire carried large amounts of insecticides and herbicides into the soil beneath the warehouse facility and into a nearby creek which carried contaminants downstream. The principal contaminants were 2,4-dichlorophenoxyacetic acid (2,4-D) and 4-chloro-2-methylphenoxy-acetic acid (MCPA), with lesser amounts of trifluralin, alachlor, carbofuran and others.

The remediation program involved extensive material handling, soil and material segregation and the use of several bioremediation techniques. The remediation techniques included solid) and slurry-phase biological treatment of soil, above-ground biological treatment of water and in situ biodegradation. Activities during this project included the following:

- Decontamination of over 12,000 yd³ of soil, containing from 10 to 2,000 mg/kg 2,4-and other pesticides, in slurry-phase and solid-phase bioremediation systems.
- Surface and in situ bioremediation along with surface granular activated carbon (GAC) treatment of over 5,000,000 gal of groundwater to a 100 ug/L cleanup criterion established by the overseeing regulatory agencies. Operation of the GAC groundwater treatment units was conducted in temperatures as low as -20°F.
- Separation of approximately 650 yd³ of riprap from the soils, followed by decontamination and placement in municipal sewage lagoons.
- Construction of a sandblasting containment facility to decontaminate 200 yd³ of concrete.

Initial feasibility studies were designed to establish the effectiveness of biological treatment of pesticide-contaminated soils and groundwater and to identify the treatment conditions needed to maximize biodegradation of the compounds present at the site. Three treatment systems were studied: water treatment and both solid- and slurry-phase treatment of soils.

Contaminated water from the site which contained 100 mg/L 2,4-D was biologically treated to below 1 mg/L within 4 days in the laboratory. Laboratory studies on soils showed moderately contaminated soils could be treated in a solid-phase bioremediation system to meet regulatory criteria (total MCPA and 2,4-D=10 mg/kg-l). Two site soil samples were incubated as soil slurries to determine biotreatability. One soil was a highly-contaminated sample from the center of the burn site (14,000 mg/kg-l 2,4-D) and the other was a moderately contaminated sample from the edge of the burn site (400 mg/kg-l 2,4-D).

The inoculum used was strain JMP-134. At 4-day intervals, 0.5 mL of a washed suspension containing approximately 10⁸ cells/mL was added to each inoculated slurry. Nutrients (nitrogen and phosphorus) were added at the beginning of the incubation.

When moderately contaminated soil was treated in a soil-slurry bioreactor, the contaminant concentrations declined on average from 390 to 15 mg/kg over 16 days.

In the highly-contaminated soil, the 2,4-D concentrations declined from 13,200 to 2,610 mg/kg in nutrient amended soil and to 2,220 mg/kg in soil which had been inoculated and nutrient-amended. The results showed that even highly contaminated soil could be rapidly treated in a slurry-phase reactor. Further, soil with contaminant concentrations

near the expected average for the burn site area (200 mg/kg of 2,4-D) could be treated to achieve the regulatory criteria in approximately 2 wk. The systems became nutrient limited after initial growth and nutrient additions produced the lowest final contaminant concentrations, particularly evident in the highly contaminated soil. Inoculation with 2,4-D degrading bacteria had no effect on the rate of biodegradation.

Using the treatability data, solid-phase biological treatment techniques were implemented to remediate 10,000 yd³ of soil contaminated with the complex mixture of herbicides and insecticides as illustrated in Figure 4. To treat this soil, ECOVA designed and constructed a soil treatment area approximately 5 ac in size. The treatment area was constructed with an engineered clay liner 12 in. thick and a drainage system to control water movement both inside and outside the facility.

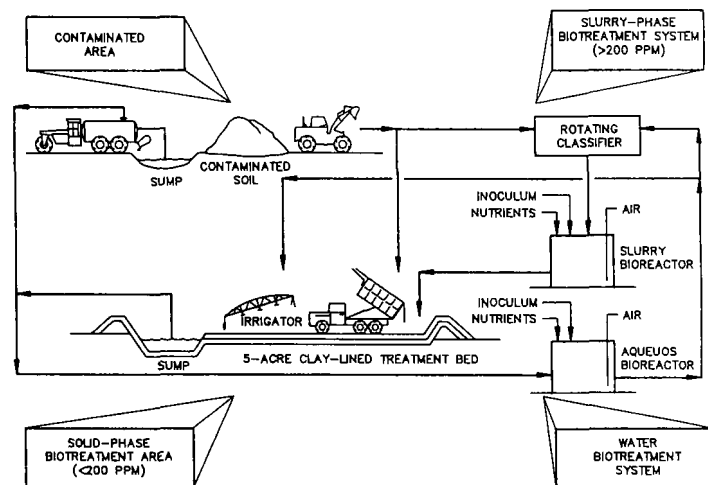


Figure 4
Integrated Bioremediation Treatment Approach

Following construction of the solid-phase treatment facility, 10,000 yd³ of soil were removed from the burn site and contaminated creek. The soil was spread on the treatment bed to an average depth of 15 in. During the 3 mo of field operations, soil conditions were optimized for biological activity by daily tilling and by maintaining the soil moisture content between 8 and 15% by weight. The combined 2,4-D and MCPA concentrations decreased from 86 to 5 mg/kg during the 3 mo of operation of the solid-phase treatment facility (Table 3). In addition, over 1,000,000 gal of contaminated water were treated biologically. The water was treated in on-site bioreactors and then either discharged or applied to the solid-phase bioremediation facility to maintain moisture content.

Table 3
2,4-D and MCPA Concentrations During Field Operations

Day	2,4-D Conc.		MCPA Conc.		Total Concentration
	Mean	S.D.	Mean	S.D.	
	mg/kg				
0	41.8	63.5	44.2	31.5	86.0
7	17.8	16.7	32.3	24.5	50.1
25	4.6	5.1	23.0	12.5	27.6
33	4.0	4.9	16.0	15.2	20.0
55	2.5	2.4	<5.0*	--	7.5
77	4.0	3.5	1.2**0.6		5.2

* Not detected in all samples, detection limit of 5.0 mg/kg.

** Maximum value, since only 7 of 24 analyzed samples had detectable MCPA at a detection limit of 1 mg/kg. For samples with no detectable MCPA, a value of 1.0 mg/kg was used for calculations.

Slurry-phase soil bioremediation techniques were used to treat more than 750 yd³ of soil contaminated with up to 1,500 mg/kg 2,4-D and MCPA. Three slurry bioreactors capable of treating 26,000 gal of fluid were mobilized to the site along with equipment to slurry the soil and optimize the biodegradation process. Material was withdrawn from a stockpile of highly contaminated soil and added to a trommel unit that slurried the soil and separated out stones and rubble greater than 1/4 in. in diameter. The slurry was then pumped into 26,000 gal bioreactors.

Each reactor was capable of holding approximately 60 yd³ of soil. Temperature, pH and dissolved oxygen were optimized to increase the rate of degradation.

Biodegradation of pesticides in the soil slurry reduced 2,4-D and MCPA levels from 800 mg/kg (400 mg/kg in the slurry) to less than 10 mg/kg in 13 days (Table 4). The estimated 2,4-D half-life was 2.1 days over this period, again similar to that observed in the treatability study with moderately contaminated soil. Upon completion of the biological treatment, the slurry was spread onto the solid-phase treatment facility.

Table 4
2,4-D and MCPA Concentration During Operation of the Soil/Slurry Bioreactor

Day	2,4-D Conc. (mg/kg)	MCPA Conc. (mg/kg)
0	204	186
2	104	177
4	10	246
6	5	51
13	3	ND

ND = Not Detectable. Detection Limit = 15 mg/kg.

Groundwater treatment continued during the winter months of 1988-89. A hydrogeological assessment revealed subsurface groundwater contamination in three areas: (1) the burn site, (2) a subsurface location 1,800 ft downstream of the burn site and (3) the impoundment (an area blocked off to contain the run-off water from the fire). The contaminant level at the burn site has been reduced so that only monitoring is necessary. At the latter two areas, long-term recovery systems were designed and built to recover and treat over 5,000,000 gal of groundwater by carbon filtration and in situ biodegradation which reduced the treatment time by half.

An upgradient injection gallery was established to flush treated water and nutrients, as required, through the contaminated plume. Downgradient recovery well and trenches recover treated groundwater. During treatment, the groundwater was monitored to guard against off-site migration.

Additional groundwater treatment was accomplished by using automated GAC treatment units. These units, consisting of sand filters, GAC filters and automated control systems, successfully treated groundwater at the site through sub-zero temperatures.

This case history demonstrates that microbiological processes can be used to develop cost-effective, onsite remediation systems for hazardous waste sites.

The initial laboratory treatability studies showed that both water and soil at the site were amenable to bioremediation. These studies also provided reasonable estimates of degradation rates in the three treatment systems used at the site: above-ground water treatment, solid-phase treatment of moderately contaminated soil and slurry-phase treatment of highly contaminated soil.

When the project was complete, over 12,000 yd³ of soil, riprap and concrete and 6,000,000 gal of water had been decontaminated for less than half the cost of off-site disposal. The site has been restored to its pre-contaminated state and can be redeveloped by the owner.

Solid-Phase Bioremediation of Contaminated Soil - California

A former manufacturing facility producing heavy equipment for over 65 yr had soil contaminated with volatile organic compounds and hydrocarbons. Motor oil, diesel fuel and cleaning fluids had been stored at the site during its operation. During demolition of the plant, soils in two areas of the plant were found to be contaminated. These contaminated soils (approximately 16,000 yd³ were excavated and stockpiled for remedial action. ECOVA's objective was to biotreat the

stockpiled soils using solid-phase bioremediation to reduce contaminant concentrations to a target level that would allow disposal of the treated soil in a Class III landfill (100 mg/kg TPH).

Preliminary chemical evaluation (35 samples) detected TPH concentrations ranging from detection limits (10mg/kg) to 16,000 mg/kg with an average concentration of 1,275 mg/kg. Aerobic microorganisms were relatively abundant ranging from 10^7 to 10^8 cells/g (wet). Bench-scale biotreatability evaluations indicated that biodegradation of the petroleum contamination could be stimulated relatively rapidly; by the fourth week of treatment, the TPH concentration was reduced to below 100 mg/kg (Fig. 5). This biodegradation occurred with the addition of nutrients (nitrogen and phosphorous) and aeration of the soils. Inoculation with microorganisms which degrade diesel fuel constituents was not necessary.

Hydrocarbon Contaminated Soil Lab Biotreatability

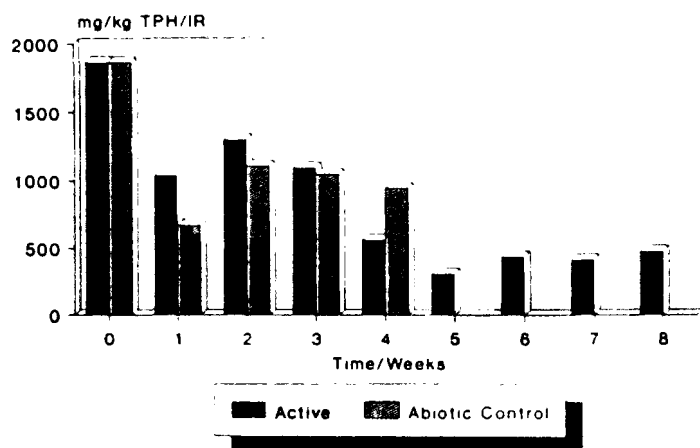


Figure 5
Bench-Scale Evaluations

For ECOVA's solid-phase bioremediation of the site, the contaminated soils were spread over the treatment area. Due to the limited treatment area, the contaminated soils required treatment in two lifts (30 in.). Over-sized material and debris (concrete, etc.) were removed from the treatment zone during spreading. Because little rainfall was expected, no liner was installed. Treatment operations consisted of daily operation of the upper lift (18 in.) with the soil stabilizer (Fig. 6).

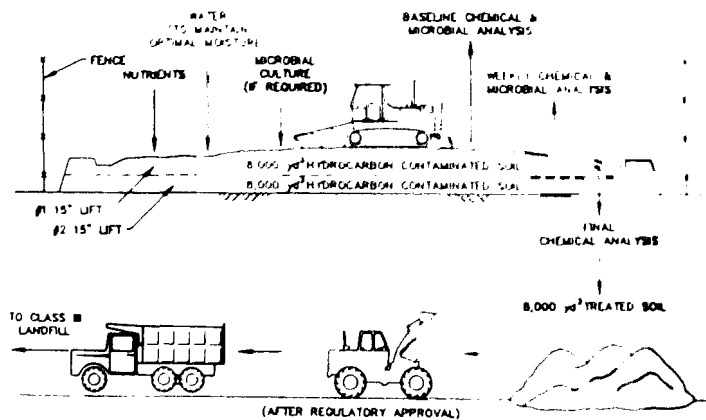


Figure 6
Process Flow Diagram

Moisture and nutrients (N & P) were added using ECOVA's terragator which tills the soil and adds nutrients in a single pass. A nutrient mixture developed in ECOVA's laboratory was applied at a rate determined in the laboratory and monitored periodically during operation.

Remediation monitoring included soil sampling for TPH from 35 separate cells, air monitoring samples for volatile contaminants, microbial enumeration and nutrient (NH_4) concentration.

Two applications of nutrients were required during treatment (Fig. 7) to maintain optimum microbial activity but not overload the system with nutrients. The microbial population increased rapidly and stayed at a high level throughout the remediation process (Fig. 8). Treatment of the second lift was completed within 4 wk to target concentration.

Ammonia Concentration During Bioreclamation of Contaminated Soil

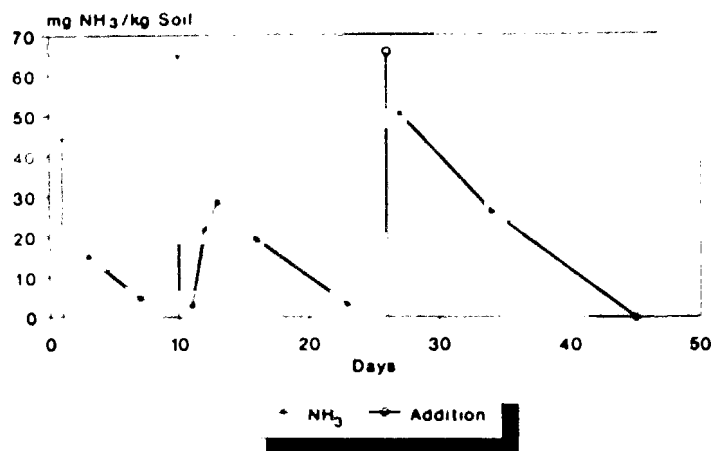


Figure 7
Nutrient Applications

Enumeration of Microorganisms Solid-Phase Field Remediation

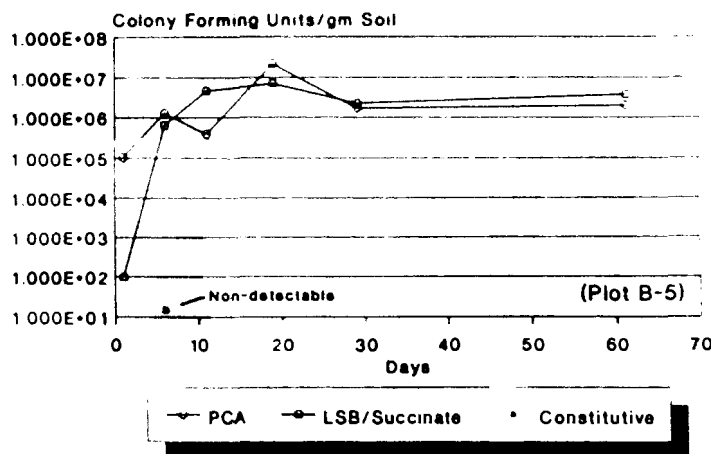


Figure 8
Microbial Population

This case study exemplifies the utility of biological technology in the rapid treatment of petroleum contaminated soils. The cost of treatment was \$65.00 yd³.

CONCLUSION

Bioremediation is a technically feasible and cost-effective treatment for a wide range of wastes. Effective design and implementation of bioremediation systems relies on a detailed understanding of the physical/chemical nature of the contaminants and the site soils and groundwater. Much of this information can be obtained by conducting carefully designed bench- and pilot-scale treatability studies. Selection of the most effective process, whether it be solid-phase, slurry-phase or in situ systems, depends upon analysis of this type of information by experienced professional scientists, microbiologists, chemists,

hydrogeologists and engineers. The case studies presented here are but a few of the examples of successful applications of bioremediation systems to a wide array of hazardous wastes.

REFERENCES

1. Gibson, D.T., *Microbial Degradation of Organic Compounds*, Marcel Dekker, Inc., New York, NY, 1980.
2. Atlas, R.M., *Petroleum Microbiology*, Macmillan, New York, NY, 1984.
3. Grady, C.P. L., Jr. and Lim, C, *Biological Wastewater Treatment*, Marcel Dekker, Inc., New York, NY, 1980.

Bioremediation Of Hydrocarbon-Contaminated Solids Using Liquid/Solids Contact Reactors

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ABSTRACT

The use of liquid/solids contact reactors (LSCs) for bioremediation is increasing because these treatments offer rapid on-site treatment with low land area requirements and little risk of off-site contamination. LSCs are biological treatment systems operated to maximize mass transfer rates and contact between contaminants and microorganisms capable of degrading the contaminants. The purpose of this paper is to provide an overview of the concepts and current results from using LSCs for the cleanup of soils and sludges contaminated with hydrocarbons. The data show that LSCs can sustain high numbers of microorganisms and rapid respiration rates in comparison to unmanaged soils or simulated land treatment. The results also show that microbiological monitoring of LSC reactors is critical for optimizing performance during treatment. Representative data from laboratory studies and field applications demonstrate the usefulness of LSCs for destruction of hydrocarbons in both oil refinery sludges and wood preserving wastes. Results of pilot- and full-scale testing show that LSCs can achieve contaminant removal rates much greater than those typical of land treatment.

INTRODUCTION

Bioremediation is a proven cleanup technology for soils and sludges contaminated with heavy hydrocarbons such as creosote or oil (1). The use of liquid/solids contact reactors (LSCs) for bioremediation is increasing because it offers rapid on-site treatment, with low land area requirements and little risk of off-site contamination. The purpose of this paper is to provide an overview of the concepts and practical aspects of using LSCs. After a brief discussion of the rationale behind the development of LSC technology and the basic concepts involved, the results of laboratory and field testing of LSCs will be presented. Results of microbiological monitoring will be discussed first, both to demonstrate the increases in numbers and activity which are achievable, and to introduce the critical operational parameters which must be controlled to maximize the effectiveness of LSC treatment. Finally, representative data from laboratory studies and field applications are presented to demonstrate the usefulness of LSCs for destruction of hydrocarbons in different organic wastes.

BASIC CONCEPTS

Rationale for LSCs

Bioremediation has become recognized as an effective and cost-efficient approach for on-site cleanup of a wide variety of hazardous organic wastes¹. Historically, land treatment has been the principal bioremediation method for contaminated solids, and it is still the least expensive and most widely used alternative^{2,3}. However, recent restrictions on land disposal (Federal Register, 40 CFR Part 268), driven by concerns over off-site migration, will require that some form of con-

tained bioremediation be used in many cases, either as an alternative form of treatment or as a pretreatment before land application in many cases. Contained bioremediation alternatives include enclosed land treatment (in lined reaction cells with emission controls if needed), composting and LSCs. Of these alternatives, LSCs are capable of producing the fastest and most effective cleanup in many cases, and field experiences have shown that the technology can be readily implemented and completed at reasonable cost.

Besides the ability to contain wastes and thereby reduce the risk of off-site contamination, LSCs also have the important advantages of rapid reaction rates, low land area requirements and a high degree of flexibility. The rapid reaction rates achievable in LSCs result from the ability to maximize mass transfer rates and provide optimum conditions for microbial activity. Because solids can be treated rapidly in contained reactors, much less area is needed for on-site remediation than during land treatment. Also, bench-scale LSCs can be used in laboratory testing to establish the feasibility of bioremediation more rapidly than simulated land treatment.

The flexibility derives from the fact that the wastes are contained in a relatively homogenous form in an engineered system designed for precise and rapid control of environmental conditions. This flexibility allows for the use of a variety of different biological treatment options as well as the use of biological treatment in conjunction with chemical and physical treatment procedures, such as soil washing or phase separation. The variety of options available for mixing and aeration allows treatment of a wide variety of materials with differing handling characteristics.

Technology description

Liquid/solids contact treatment is analogous to conventional biological suspended growth treatment (e.g., activated sludge). LSCs are designed to relieve the environmental factors commonly limiting microbial growth and activity in soil (principally the availability of carbon sources, inorganic nutrients and oxygen). To achieve this goal of maximizing biological activity, the wastes are suspended in a slurry and are mixed to maximize mass transfer rates and contact between contaminants and the microorganisms capable of degrading those contaminants.

Aerobic treatment in batch systems has been the most common mode of operation, but LSCs are sufficiently flexible to allow anaerobic treatment at a variety of redox potentials, or aerobic/anaerobic cycling. LSCs can be operated in single batches, in sequenced batch reactors or in semi-continuous or continuous feed. LSC treatment can be performed in contained mobile reactors or in lined in situ lagoons (Fig. 1).

A principal goal of the mixing and aeration is to supply sufficient oxygen throughout the slurry matrix to prevent oxygen transfer limitations to activity which generally occurs when oxygen must be supplied by diffusion over even short distances. Mixing can be provided by

aeration alone or by aeration and mechanical mixing. Aeration can be provided by floating or submerged aerators or by compressors and spargers.

Chemicals added to LSC reactors include nutrients and neutralizing agents to relieve any chemical limitations to microbial activity. Other materials, such as surfactants, dispersants and cometabolites (compounds supporting growth and inducing degradation of contaminant compounds) can be added to improve materials handling characteristics or increase substrate availability or degradation.

Since the overall goal of LSC operations is to maximize microbial numbers and activity, microbiological monitoring can be used as an inexpensive monitoring parameter to provide rapid feedback on performance. The next section of this paper gives typical data on microbial numbers and activity as well as examples showing the use of these data to optimize LSC performance.

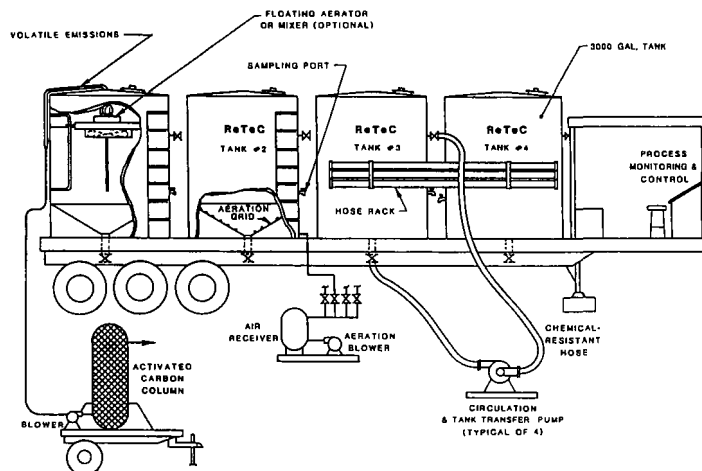
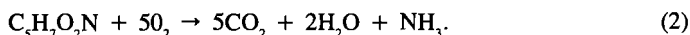
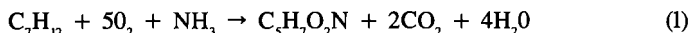


Figure 1
Schematic Diagram of ReTeC's Mobile LSC Reactor,
Showing Various Options for Mixing and Aeration

MICROBIOLOGICAL MONITORING

Microbial numbers

Biodegradation of hydrocarbons can be viewed as proceeding by the following stoichiometry, in which biomass is produced initially (Eq. 1) and then is eventually completely degraded (mineralized) to carbon dioxide and water⁴:



The first phase can occur much more rapidly than the second, so that biomass can increase 3 to 4 orders of magnitude during the initial stages of degradation in batch reactors. Under typical operating conditions, the microbial population densities increase dramatically at the start of LSC treatment and then stabilize and slowly decline (Fig. 2). Additionally, the organisms responsible for PAH biodegradation are capable of rapid increase both in total numbers and in relative abundance. Microbial population densities remain high for a longer time in sludge with higher levels of contamination, reflecting the fact that substrate depletion occurs after most of the readily-degradable material has been used.

As indicated in Figure 2, the lag period commonly observed when hydrocarbons are added to a pristine environment is generally brief during LSC treatment. The lack of an apparent lag period results from the rapid growth rate in LSC reactors and the fact that appropriate acclimated organisms are generally present in these materials, since the sites have a long history of exposure to the contaminants. As a result, microbial inoculation usually is not beneficial⁵, although it can be useful in some cases, such as the cleanup of highly concentrated wastes or extremely recalcitrant compounds⁶.

To some extent, the success of enhanced bioremediation can be gauged by monitoring microbial numbers. Generally, unmanaged soils and sludges have population densities on the order of 10^6 cells/g solids (Table 1). The numbers typically increase to between 10^7 and 10^8 cells/g during land treatment of soils or sludges. Numbers of recoverable cells (which represent 1 to 10% of the total number of cells present) rarely exceed 10^8 cells/g in soil, even when high levels of organic matter are present⁷. This upper limit to population densities during land treatment is probably a result of the diffusion-limited, nutrient- and oxygen-supplying capability in soils. However, during LSC operations, the numbers typically range between 10^8 to 10^9 cells/g when soils are treated, while for sludges, which have relatively high organic carbon contents, microbial populations generally range from 10^9 to nearly 10^{10} cells/g solids. These results reflect the success of LSCs in maximizing microbial growth and demonstrate that LSCs are particularly useful for highly contaminated sludges with high oxygen demands.

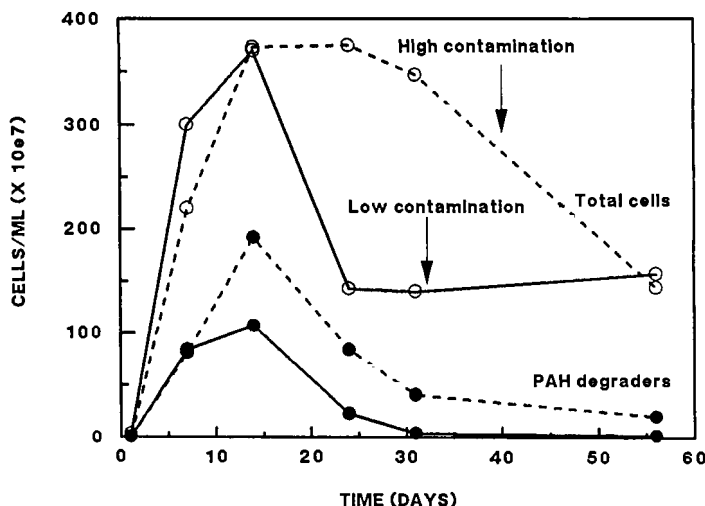


Figure 2

Number of microorganisms in LSC reactors over time during batch operation. Open circles represent total aerobic heterotrophic microorganisms and closed circles show numbers of PAH-degrading microorganisms. Results are shown for creosote-contaminated soils with high or low PAH concentrations.

Respiration

Direct measurements of microbial activity are a more important measure of performance than microbial counts or biomass estimates, because the amount of activity per cell or per gram of biomass can vary widely. For example, oxygen uptake rates (OURs) were measured at various times during operation of the LSCs described in Figure 2. The results (Fig. 3) show that the specific OUR varied over time, so that microbial numbers were not necessarily correlated with activity. This was true whether the specific OUR was expressed as a function of the microbial biomass as measured by plate counts (Fig. 3A, assuming 10^{12} cells/g) or as a function of the volatile suspended solids (Fig. 3B). The pattern seen in the low contamination reactor is the most common, in which the organisms are relatively active initially and specific OUR then declines with time.

Because respiration should be directly correlated with overall biodegradation, OUR measurements in an aerobic reactor are the best measures of performance and the effects of amendments. Equations 1 and 2 suggest that complete biodegradation will require nearly 4 g O_2 /g Carbon (C) mineralized, so that the progress of biodegradation can be estimated by measuring cumulative oxygen uptake as a proportion of the total organic carbon.

For example, the data in Figure 4 are taken from LSCs operated with creosote-contaminated material from three separate sites. The solids were all creosote-contaminated impoundment sludges, similar in physical and chemical characteristics, except that the sites had varying concen-

trations of the wood preservative pentachlorophenol (PCP), which is highly toxic to microorganisms. The ratio of cumulative O₂ uptake: TOC content over one month varied from 1.9 (half the theoretical maximum) in the sludge with low PCP to 0.7 in the sludge with the highest PCP concentration (near 3000 mg/kg). Figure 4 also shows that respiration in the site C material during LSC treatment was approximately four times faster than that measured during simulated land treatment.

Table 1
Microbial Population Densities in Samples from Unmanaged Sites (Time 0 samples before treatment) and in samples taken during steady-state operation of either land treatment demonstrations (LTD) or liquid/solids reactors (LSC) with the same wastes used in laboratory treatability studies.

Site No.	Sample Type	Treatment	Total Aerobic Heterotrophs (CFU/g dry weight x 10 ¹¹)
Creosote			
1	Soil	Time 0	0.3
		LTD	8.9 - 15.3
		LSC	22 - 94
2	Soil	Time 0	0.1 - 4.7
		LTD	2.0 - 9.6
		LSC	22 - 57
3	Sludge	Time 0	0.2 - 0.6
		LSC	440 - 1600
Oil Refinery Wastes			
4	Soil	Time 0	1.4
		LTD	1.1 - 9.7
		LSC	59 - 107
5	Soil	Time 0	0.07
		LTD	0.3 - 0.6
		LSC	5.3 - 8.8
6	Soil	Time 0	0.4
		LSC	3.5 - 10.2
7	Sludge	Time 0	0.4
		LSC	55 - 895
8	Sludge	Time 0	0.8
		LSC	44 - 157
Coal Gasification Wastes			
9	Sludge	Time 0	0.04
		LTD	4.0 - 25
		LSC	380 - 1450
10	Sludge	Time 0	0.09
		LTD	8.4 - 17.3
		LSC	130 - 400

OPTIMIZING PERFORMANCE

Microbiological monitoring can be used to assess the impact of alternate operating practices and to ensure adequate performance during operations. Obviously, any aerobic biological treatment process must be operated to maintain adequate pH (generally from 5.5 to 8.0), dissolved oxygen (in excess of 2 mg/L) and salinity levels. However, there are operating considerations that are unique to LSCs or deserve extended discussion.

Nutrients

Equation 1 suggests that nitrogen (N) availability can be an important factor controlling biodegradation rates, and that the demand for N during the initial stages of LSC operations can be very high. This N will be recycled eventually (Eq. 2), so that N must be supplied in large amounts initially but in lesser amounts as treatment progresses. To estimate N demand, we can use the microbial numbers presented earlier. A typical cell density during LSC operations may be roughly 10⁹ cells/mL, or approximately 1 g/L dry weight of cells. Since microbial cells are approximately 50% C and have a C:N ratio of roughly 5:1⁷, this means that 100 mg/L of N will be required for the initial rapid population increase.

However, the demand for nitrogen, and other nutrients (especially P), is hard to predict and can represent a major cost in LSC operations. It is therefore generally necessary to empirically determine the nutrient demands. Respiration monitoring can aid in this determination. For example, in the case shown in Figure 5, 100 mg/L of nitrate-N were added to all reactors at start-up, and 50 mg/L were added at the indicated times to simulated LSCs containing varying amounts of solids with a TOC content of 24%. Calculations based on the responses observed at varying solids loadings indicate that the inorganic N required was equivalent to a C:N ratio between 120 and 240:1. Using the lower value as the supply rate resulted in substantial cost savings over the commonly-assumed target C:N ratios of between 10:1 and 50:1⁸.

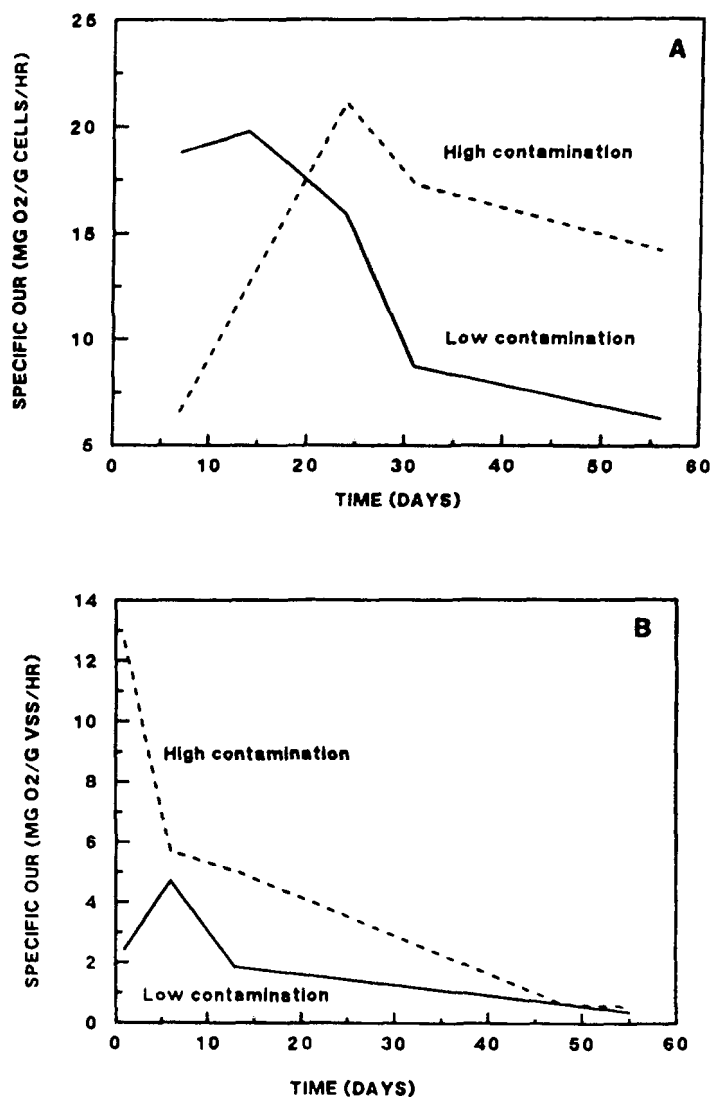


Figure 3
Specific oxygen uptake in low- or high-contamination soils during batch LSC operation. Total uptake is normalized to the total cell numbers (A) or the volatile suspended solids (B).

Solids loading

It is economically desirable to operate a LSC with as high a solids content as possible. The ability to sustain a reasonable suspension sets an upper limit on the loading at between 30 and 40% solids (dry weight basis). However, there may be toxicity problems which require a lower solids content, or the ability to achieve adequate mixing and aeration may be reduced at the higher loading rates. Figure 5 presents evidence for this type of inhibition at higher loading rates. Thus, respiration increased on a per unit reactor volume basis as the solids loading

increased from 5 to 20% dry weight of solids. However, it is apparent from the data that the relative respiration rate ($\text{g O}_2/\text{g solids}$) decreased as the solids content increased, suggesting some inhibition resulting from either less effective mixing and oxygen transfer or from toxicity of the contaminants.

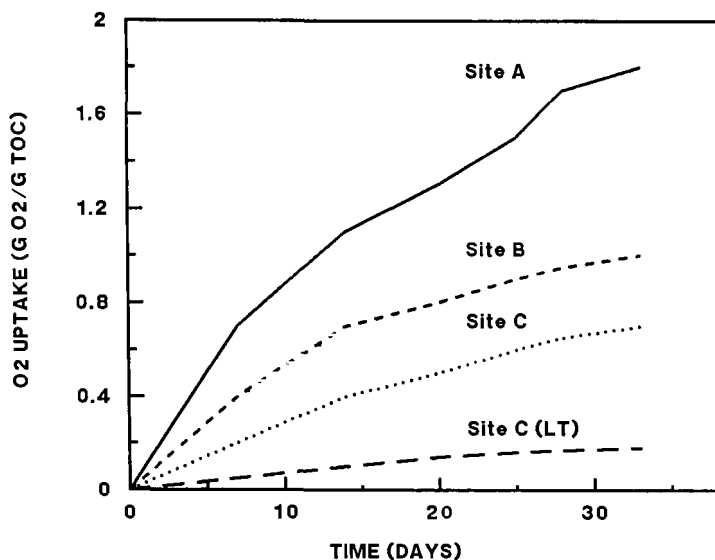


Figure 4
Oxygen uptake per gram total organic carbon in three PCP and creosote-contaminated sludges during LSC treatment. PCP concentrations increase from sites A through C. Uptake during simulated land treatment of the site C sludge is shown for comparison.

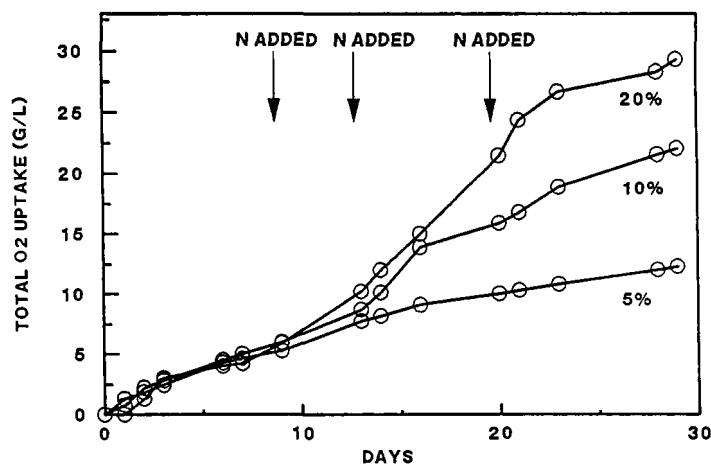


Figure 5
Oxygen uptake during LSC treatment of creosote-contaminated sludge at three loading rates (5, 10 or 20% dry weight of solids). Arrows show times of supplemental nitrate additions.

Mixing

One of the more surprising findings has been that high-energy mechanical mixing does not necessarily improve performance. Typical mixing energy requirements needed to keep solids in suspension range from approximately 0.1 to 1 hp/1000 gal depending on the solids content and the physical characteristics of the solids. Higher mixing energies are not only more expensive, but they also can be detrimental. For example, Figure 6 shows data from two reactors containing the same sludge but operated either with or without mechanical mixing (in addition to identical mixing through aeration). The faster respiration in the unmixed LSC reactor was not due to nutrient availability, since

nutrients were added until no response was observed. However, the increased respiration rate was associated with visibly larger average floc size in the mixed reactor. It therefore appears that mechanical mixing can impair LSC performance in some cases by promoting agglomeration of oily materials and therefore reducing the surface area available for dissolution and microbial colonization.

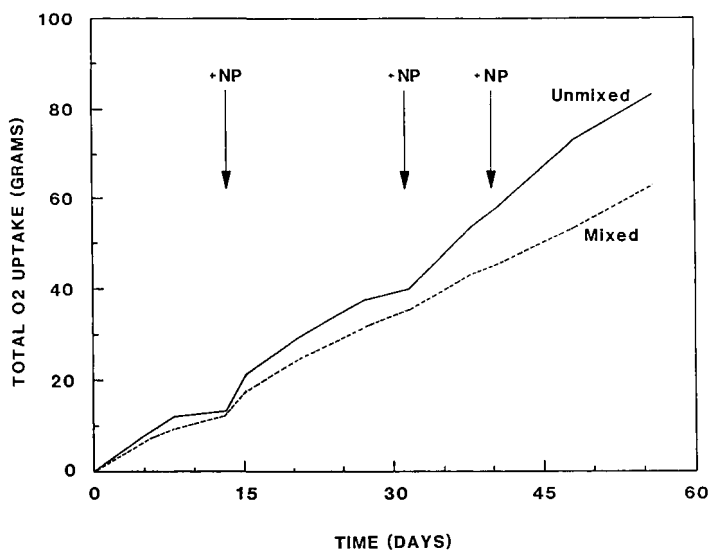


Figure 6
Cumulative oxygen uptake during LSC treatment of oil refinery sludge in reactors with aeration only or aeration plus mechanical mixing. Arrows indicate times of supplemental nutrient (N and P) additions.

CONTAMINANT REMOVAL

LSCs have been used predominantly in two types of situations: (1) wood preserving wastes, especially impoundment sludges and the surrounding soils contaminated with creosote oil and PCP; and (2) oil refinery wastes, principally sludges from storage and treatment lagoons. In both these cases, the wastes have high concentrations of oil and grease and relatively high levels of higher molecular⁹weight hydrocarbons, including the potentially carcinogenic PAHs.

This section presents examples of the degree of contaminant destruction achievable in LSCs used for bioremediation of these wastes.

Wood preserving wastes

LSCs have been used by ReTeC for the remediation of creosote- and PCP-contaminated soils and sludges in at least 10 full- or pilot-scale field treatment systems. Significant reductions in both solids mass and contaminant concentrations have been achieved. Successful cleanup resulting in closure has been achieved in full-scale remediation efforts.

Table 2 presents typical data on the solids and mass loss of total PAHs during LSC treatment of sludge contaminated with creosote at two solids loadings. The results show that very little of the material is in the aqueous phase, since the solubility of the compounds is low and degradation of the compounds in the aqueous phase is rapid. Almost 30% of the solids were lost in both cases. This loss can reduce the costs for eventual disposal or further treatment, if either is necessary. Also, the solids mass loss must be known to calculate the true amount of contaminant destruction during treatment. The analytical results indicate that approximately 90% of the total PAHs were degraded over 55 days of operation.

It is also important to note that there are differences in the degradability of different compounds. Representative data on the loss of various PAHs is shown in Figure 7. As typically observed, biodegradation of the 2- to 4-ring PAHs was much more rapid than degradation of the more carcinogenic 5- and 6-ring compounds, although all compounds were degraded to some extent. The differences in degradability reflect

the lower solubilities and greater inherent resistance to degradative enzymes of the 5- and 6-ring PAHs⁹. However, the removal rates observed during LSC treatment were substantially faster than those typical of land treatment^{10,11}.

Table 2
Concentrations and total masses of solids and total PAHs before and after 8 weeks of simulated LSC reactor operations with two samples from a wood-preserving site contaminated with amounts of creosote oil.

Reactor	Initial			Final			Loss	
	Mass (g)	PAH Conc. (mg/kg)	PAH Mass (g)	Mass (g)	PAH Conc. (mg/kg)	PAH Mass (g)	Mass (%)	PAH (%)
Low Contamination								
#1: 10% Solids								
Solids	87.4	56,953	5.0	74.6	6,906	0.52	14.4	90
Liquid	-	-	-	1000	6.6	0.007	-	-
#2: 25% Solids								
Solids	274.4	56,953	15.6	197.1	7,386	1.46	28.2	91
Liquid	-	-	-	1000	12.4	0.012	-	-
High Contamination								
#3: 5% Solids								
Solids	191.3	125,251	11.4	63.5	57,201	3.63	20.4	68
Liquid	-	-	-	1000	6.5	0.007	-	-
#4: 25% Solids								
Solids	138.2	125,251	17.3	100.5	97,744	9.82	27.3	43
Liquid	-	-	-	1000	9.3	0.010	-	-

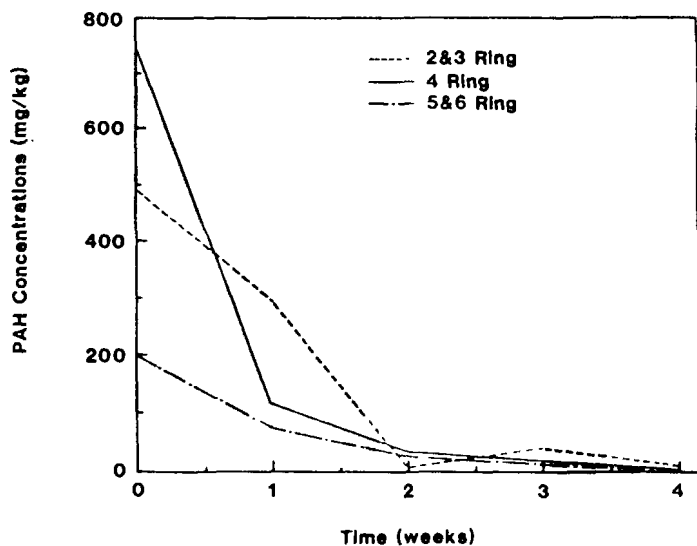


Figure 7
PAH concentrations by ring number during LSC treatment of creosote-contaminated sandy soil.

LSCs have been used for the successful full-scale treatment of wood preserving wastes in aerated on-site lagoons. In one representative case, 100 yd³ of impoundment sludge containing PCP and creosote were fed into an on-site sequenced-batch LSC weekly. Closure criteria were based on the concentrations of PCP and the combined concentration of the PAHs phenanthrene and anthracene. These criteria were exceeded during operations, with an average reduction of PCP concentrations from 2600 to 32 mg/L and an average reduction in the target PAH concentrations from 1200 to 86 mg/L.

Oil refinery wastes

Oil sludges have extremely high oxygen demands, with much of the

organic material consisting of relatively degradable compounds. Thus, it is not surprising that these wastes are excellent candidates for treatment in LSCs. Oxygen uptake measurements show that, on a unit reactor volume basis, treatment of oil refining wastes produces extremely high rates of metabolic activity (Fig. 8). The oxygen uptake rates were almost twice those of creosote sludges, which have somewhat lower TOC contents and a higher proportion of resistant organic compounds, and 10 times faster than contaminated soils.

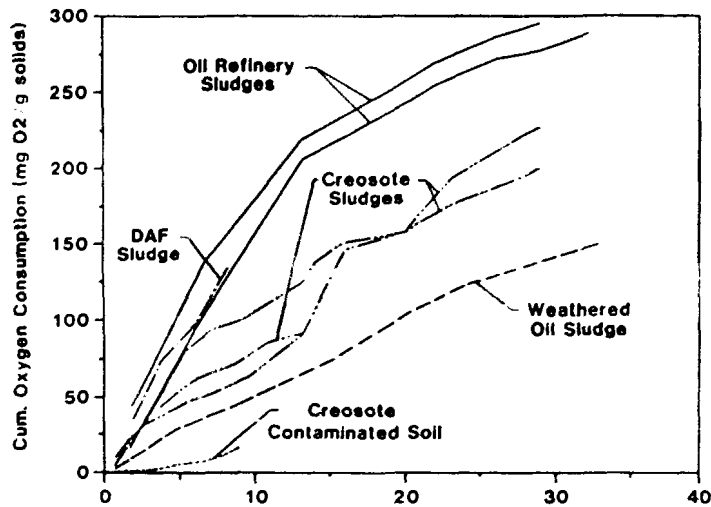


Figure 8
Cumulative oxygen uptake (normalized to mass of solids) during bench-scale LSC treatment of a variety of contaminated solids.

In addition to several laboratory-scale treatability tests of oil sludges in LSCs, ReTeC has performed several pilot-scale demonstrations of LSCs for biological treatment of oil refining sludges. Removal rates for oil and grease have been rapid in comparison to land treatment data, but results have varied widely, principally because the sludges differ in the proportions of readily-degradable and recalcitrant hydrocarbons. Typical land treatment half-lives for similar sludges range from 6 to 15 mo (C/C12, 13D/D). Assuming first-order kinetics for our studies, half-lives for oil and grease generally ranged from 2 to 4 wk for lagoon sludges and 6 to 14 wk for more recalcitrant stockpiled sludges in sludge ponds and pits (Fig. 9).

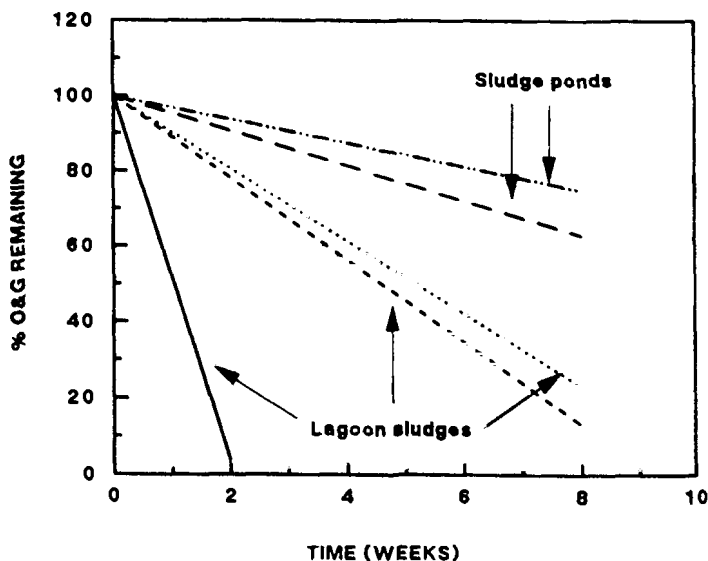


Figure 9
Oil and grease losses during LSC treatment of oil Sludges from wastewater lagoons or from sludge storage pond.

Losses of PAHs were also relatively rapid, again varying depending on the nature of the waste and loading rate. In one study, the losses of carcinogenic PAHs (principally the 5- and 6-ring PAHs) ranged from 30 to 80% over 2 mo, while virtually all of the non-carcinogenic PAHs were degraded (Fig. 10). The total PAH reductions ranged from 70 to 95%, again well in excess of typical losses during land treatment of oil sludges over a similar time period¹⁴.

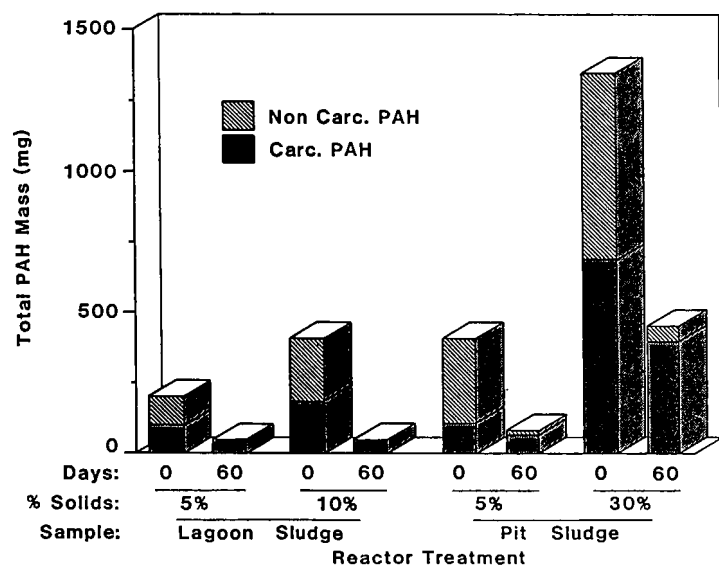


Figure 10

Total concentrations of carcinogenic and noncarcinogenic PAH compounds before and after 60 days of LSC treatment of oil sludges at differing solids loading rates.

CONCLUSION

LSC technology represents a method for rapid biological treatment of contaminated solids in a contained reactor. The technology has proven highly effective for oil refinery sludges and wood preserving wastes.

LSCs are operated to maximize microbial activities by encouraging rapid mass transfer and maximum contact between contaminants and microorganisms capable of degrading the contaminants. Microbiological monitoring demonstrates that the technology effectively enhances microbial numbers and activity and provides the rapid feedback needed to optimize performance. Pilot- and full-scale applications have shown that LSCs can provide highly effective on-site bioremediation, with contaminant removal rates much greater than those typical of land treatment.

REFERENCES

- Bartha, R., Biotechnology of petroleum pollutant biodegradation, *Microbial Ecology*, 12 1986, 155-172.
- Loehr, R.C. and Malina, J.F., *Land Treatment - A Hazardous Waste Management Alternative*, Water Resources Symposium Number Thirteen, Center for Research in Water Resources, Bureau of Engineering, The University of Texas at Austin, Austin, TX, 1986.
- Atlas, R.M., Stimulated petroleum biodegradation, *Critical Reviews in Microbiology*, 5, 1977, 371-386.
- McCarty, P.L., Stoichiometry of biological reactions, *Progress in Water Technology*, 7, 1975, 157-172.
- Atlas, R.M. Microbial degradation of petroleum hydrocarbons: an environmental perspective, *Microbiology Review*, 45, 1981, 180-209.
- Deutsch, D.J., Waste treatment boosted by bacterial additions, *Chemical Engineer*, 86 (9), 1979, 100-102.
- Alexander, M., *Introduction to Soil Microbiology*, 2nd ed., John Wiley and Sons, New York, NY, 1977.
- American Petroleum Institute, *Manual on disposal of refinery wastes*, API, New York, Chap 7, 1980, 1-3.
- Gibson, D.T., Biodegradation of Aromatic Petroleum Hydrocarbons, in *Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms*, ed. D. Wolfe, Pergamon Press, New York, NY, 36-46.
- McGinnis, G.D., Borazzani, H., McFarland, L.K., Pope, D.F. and Strobel, D.A., *Characterization and Laboratory Soil Treatability Studies for Creosote and Pentachlorophenol Sludges and Contaminated Soil*, EPA/600/52-88/055, U.S. EPA, Washington, DC, Jan., 1989.
- Sims, R.C. and Overcash, M.R., Fate of polynuclear aromatic compounds in soil-plant systems, *Residue Reviews*, 88, 1983, 1-68.
- Kincannon, C.B., *Oil Waste Disposal by Soil Cultivation Process*, U.S. EPA Publication No. R2-72-110, U.S. EPA, Washington, DC, 1972.
- Loehr, R.C., Martin, J.H., Neuhauser, E.F., Norton, R.A., and Malecki, M.R., *Land Treatment of an Oily Waste - Degradation, Immobilization, and Bioaccumulation*, U.S. EPA Rept. No. 600 FLQ 2/85, 009, Feb., 1985.
- American Petroleum Institute, *The Land Treatability of Appendix VIII Constituents Present in Petroleum Industry Wastes*, API, Washington, DC, 1984.

Oxygen Sources for In Situ Bioremediation

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INTRODUCTION

It is well recognized that microorganisms play prominent roles in the transformation and degradation of organic chemicals. Microbial communities in nature exhibit a truly impressive biochemical versatility in the number and kinds of synthetic organic compounds that they are able to metabolize^{1,2}. Microbial metabolism is virtually the only natural transformation of organic contaminants that can result in complete mineralization.

However, there are limits to the metabolic versatility of microorganisms. Many substrates, even those that are known to be highly biodegradable, are often transformed so slowly in nature that they cause some degradation of environmental quality. This resistance to biodegradation is primarily a function of: (a) the existing environmental conditions; (b) the structure of the particular contaminant; and (c) the physiology of the requisite microorganisms^{3,4}. Of these, the environmental limitations are the most common and the most easily rectified.

In order to grow, microorganisms need a suitable physical and chemical environment. The nature of the limiting environmental factor(s) can be classified as general environmental quality or metabolically dependent. In the first case, extremes of temperature, pH, salinity and contaminant concentrations will markedly influence the rates of microbial growth and substrate utilization. In the second case, microorganisms must have the basic requirements for growth and metabolism. Like all other forms of life, microorganisms are primarily composed of C, H, O, N, P and S, although a variety of other elements are also found in trace amounts. These substances must already be present or be supplied in the proper form and ratios for the requisite microorganisms to proliferate and degrade organic substrates.

In most cases, the organic pollutants themselves are able to supply the carbon and energy required to support heterotrophic microbial growth. However, the introduction of carbonaceous materials to soils and groundwater aquifers can cause an imbalance in the natural biodegradation processes, limiting the microbial transformation of the organic pollutant. For example, when labile carbon is introduced to an aerobic aquifer, the microorganisms consume oxygen along with the carbon substrate. An anaerobic aquifer can be expected whenever the rate of aerobic respiration exceeds the rate of oxygen input to the site. To sustain aerobic microbial growth, oxygen, therefore, must be supplied to the subsurface microorganisms.

IMPORTANCE OF OXYGEN

The importance of oxygen supply to in situ biodegradation was well documented recently in a study of a wood treating site in Conroe, Texas⁵. A downgradient portion of the contaminant plume was characterized by low levels of organic pollutants and dissolved oxygen, while inorganic contaminants (i.e., chloride), which were associated with the organic wastes, remained at elevated concentrations. The authors suggested that oxygen was consumed during the aerobic metabolism of the organic contaminants by the indigenous microorganisms. Hydrocarbons persisted in areas of the plume where oxygen levels were insufficient to support aerobic biological activity.

Artificially increasing the oxygenation of subsurface environments will dramatically increase the growth of heterotrophic bacteria. In a study of petroleum hydrocarbon degradation, sand columns were used to determine the effect of oxygen supply on bacterial growth and degradation of gasoline.

Several columns were prepared under identical conditions using 50 ml of wet sand sieved to 40 to 60 mesh. A total of 50 ml of gasoline was added to each column and allowed to drain through. An average of 4.3 mL of gasoline was retained in the column. The columns were then washed with 2 L of nutrients made up in groundwater. Different levels of oxygen were supplied to the columns by using air, oxygen and/or hydrogen peroxide dissolved in groundwater. The columns were kept at design oxygen levels for 2 wk. At the completion of the experiments, the columns were drained and analyzed for gasoline content, total organic carbon (TOC), total bacteria and gasoline utilizing bacteria.

Bacterial counts in the interior of the column showed a very strong dependence on the oxygen level:

Table 1
Dependence Of Bacterial Growth On Available Oxygen
Bacteria, Colony Forming Units (CFU) / gram dry soil

Available Oxygen (mg/l, ar)	Heterotrophic Bacteria (x 10 ⁶)	Gasoline Utilizing Bacteria (x 10 ⁶)
8	0.05	0.0001
40	5.5	0.7
112	75	27
200	207	31
Correlation w/D.O.	0.979	0.933

As can be seen from the data, the bacterial counts increased dramatically with increasing available oxygen. Gasoline-utilizing bacteria are even more sensitive to oxygen levels than are general heterotrophic bacteria.

The biodegradation of gasoline in the columns also was affected by the oxygenation:

Table 2
Dependence of Gasoline Degradation on Oxygen Levels

Available Oxygen	Gasoline Bio-degraded	Gasoline Flushed Out	Total Gasoline Removed
<u>ppm (Ave.)</u>	<u>grams</u>	<u>grams</u>	<u>grams</u>
8	.388	.71	1.098
40	.508	.77	1.278
112	.773	.59	1.363
200	1.272	.49	1.762
Corr. w D.O.	.994	-.93	.974

Two conclusions can be drawn from these data. First, the more oxygen that was supplied, the more gasoline was biodegraded. Second, the rate of biodegradation under highly oxygenated conditions was greater than the rate of physical removal/dissolution.

These sand column studies demonstrate that bacterial growth and metabolism are very dependent on oxygenation. As a result, an important part of the biological treatment of organic contaminants is oxygen supply.

METHODS OF OXYGEN SUPPLY

There are basically two approaches to oxygen supply—physical and chemical. Physical oxygen supply involves forcing air and/or pure oxygen into the contaminated matrix. Chemical oxygen supply involves the addition of substances which can be converted to oxygen (such as hydrogen peroxide)⁶ or substances which can act as terminal electron acceptors directly (such as nitrate)^{7,8}. All of these methods have been used to treat contaminated soils and aquifers. This paper will review five methods of oxygen supply: air sparging; injection of aerated/oxygenated water; venting; injection of hydrogen peroxide; and injection of nitrate.

The choice of an oxygenation method depends on several factors. Basically, one wants to achieve maximum efficiency in oxygenation. The principle is to balance oxygen supply with oxygen demand. The factors that must be considered in achieving this balance of supply and demand are:

- Contaminant load and location
- Oxygen mass transfer, (lb per unit time) supplied by each method
- Ease of transport/utilization

CONTAMINANT LOAD

The first factor to consider in choosing an oxygen source is the contaminant load and location. Contaminant location is important because vent systems require unsaturated environments and will, therefore, be excluded in treating contaminants below the water table. Contaminant load, on the other hand, impacts all means of oxygen supply in that it determines oxygen demand. What drives contaminant load is the phase distribution.

Petroleum hydrocarbons exist in the subsurface as three condensed phases: mobile free product (phase separated); residually saturated soil (adsorbed phase); and contaminated groundwater (dissolved phase). The distribution of hydrocarbons into these different phases, while a result of dynamic transport, is ultimately a function of their physical and chemical properties and the hydrogeological and geochemical characteristics of the formation. One must examine the phase distribution by two means: (1) by the areal extent of contamination or the volume of the subsurface impacted by a phase and (2) by the severity

of contamination or the amount of the contaminant within a phase, measured as either total weight or concentration. The following table gives a representative phase distribution for a gasoline spill in sand and gravel:

Table 3
Phase Distribution of Gasoline in Sand and Gravel

Phase	Extent of Contamination			Mass Distribution	
	Impacted Sediments			of Hydrocarbons	
	Volume, cu. yd.	% of Total	lb.	Conc. ppm	% of Total
Free phase ¹	780	5.3	26,800 ¹	---	69.3
Adsorbed (soil)	2,670	18.3	11,500	4,000	29.7
Dissolved (water)	11,120	76.3	390	15	1.0

¹ Actual value recovered from site

There are several generalizations that can be made from the above data concerning the distribution of petroleum hydrocarbons between the different phases. First, groundwater flow is the primary long-term mechanism for dispersion of the contamination once the free phase product layer has achieved flow equilibrium. Thus, the areal extent of dissolved phase hydrocarbon contamination is typically greater than that for other phases. However, the amount of material in the groundwater is small compared to that retained in the soil matrix less than 5%. The residually saturated soil (i.e., adsorbed phase), if untreated, is a continuing source of groundwater contamination.

In looking at the contaminant load, the presence of and the distribution between the different phases is an important factor. Table 4 gives the amounts of contaminants in lb/yd³ of water for the dissolved phase and lb/yd³ of soil for the adsorbed phase contamination. The calculation assumes a dry soil bulk density of 2700 lb/yd³. From these data, it is obvious that contaminated soil drives the contaminant load. One cubic yard of soil contaminated at only 100 ppm contains as much contaminant as 45 yd³ of contaminated water (dissolved phase) contaminated at 100 mg/L. Thus, knowing whether or not there is a high contaminant load, adsorbed phase or a low contaminant load, primarily dissolved phase, is important in choosing an oxygenation method.

Table 4
Comparison of Contaminant Loading Dissolved and Adsorbed Phases

Dissolved Phase at	Water (lb/yd ³)	Adsorbed Phase at	Soil (lb/yd ³)
1 ppm	6x10 ⁻⁵	100 ppm	.27
10 ppm	6x10 ⁻⁴	1,000 ppm	2.70
100 ppm	6x10 ⁻³	10,000 ppm	27.00

OXYGEN MASS TRANSFER

The second factor to consider in choosing an oxygen supply method is oxygen mass transfer. It is easy to calculate the amount of oxygen supplied by the different methods. The more oxygen supplied per unit time, the greater the contaminant load that can be treated.

Air Sparging

Air sparging, one of the simpler techniques of oxygen supply, provides oxygen by diffusing air/oxygen into a well bore. This supply process is accomplished by supplying air (or oxygen) to a porous stone,

sintured metal or fitted glass diffuser beneath the water surface. The water in the well bore is saturated with oxygen and diffuses out into the formation. The amount of oxygen supplied is a function, therefore, of the rate of water flow by the well bore. The rate of water flow, in turn, is a function of the hydraulic conductivity, the groundwater gradient and the surface area of the formation affected by the well bore. The matrix in Table 5 shows the amount of oxygen an air sparger provides per well per day for different hydraulic conductivities and gradients. The table assumes a 30-ft saturated thickness and that the lateral influence of the well is 3 ft.

Table 5
Oxygen Supplied
By Sparging, Single Well (lb/day)

Hydraulic Conductivity	Hydraulic Gradient (ft / ft)					
	(high)		(medium)		(low)	
	0.1		0.01		0.001	
gals / day / ft ²	(air)	(oxygen)	(air)	(oxygen)	(air)	(oxygen)
10 ⁴ (gravel)	6	30	0.6	03.	0.06	0.3
10 ² (medium sand)	0.06	0.3	6x10 ⁻³	3x10 ⁻²	6x10 ⁻⁴	3x10 ⁻³
10 ⁻¹ (silt)	6x10 ⁻⁵	3x10 ⁻⁴	6x10 ⁻⁶	3x10 ⁻⁵	6x10 ⁻⁷	3x10 ⁻⁶

As can be seen, air sparging supplies a limited source of oxygen. Sparging pure oxygen instead of air will increase the amount of dissolved oxygen supplied by a factor of five so that the maximum oxygen delivered would be 30 lb. oxygen per day instead of 6 lb/day.

Saturated Water

A second system is to pump air/oxygen saturated water into a contaminated aquifer. The amount of oxygen supplied is a function of injection rate (Table 6).

Table 6
Oxygen Supplied
By Aerated/Oxygenated Water Injection
Single Well (lb/day)

Injection Rate, (gpm)	Oxygen Supplied (lb/day)	
	aerated water (10 mg/L D.O.)	oxygenated water (50 mg/L D.O.)
1	0.12	0.60
10	1.2	6.0
100	12.0	60.0

Air Vent Systems

Air vent systems are an efficient means of supplying oxygen through unsaturated contaminated soils. This technique is used to treat vadose zone contamination or to treat excavated soil piles. Air can be added by either injection or by withdrawal. In vadose zone treatment, the common method is vacuum withdrawal. This method has the added advantage of physically removing volatile contaminants in addition to supplying oxygen. The amount of oxygen supplied is a simple function of the air flow rates. The following table uses a 20% oxygen content for air to calculate air supply

Table 7
Oxygen Supplied
By Venting System (Unsaturated Soils)
Single Well

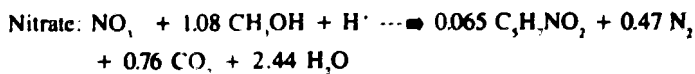
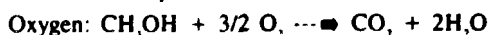
(scfm)	(lbs/day)
1	23
5	117
10	233
20	467
50	1170
100	2330

Chemical Supply

Finally, there are two chemical carrier systems - hydrogen peroxide and nitrate. While both of these materials are highly soluble, their common use rate is about 1000 mg/L. The number of oxygen equivalents supplied is dependent on the chemistry involved. Hydrogen peroxide is converted through decomposition to oxygen:



Each pound of hydrogen peroxide supplies 0.47 lb of oxygen. Nitrate is, on the other hand, directly utilized as a terminal electron acceptor. Its oxygen equivalents can be calculated by comparing the amount of nitrate required to oxidize a substrate versus the amount of oxygen. Take, for example, the oxidation of methanol:



Based on the above equations, 1 lb of nitrate is equivalent to 0.84 lb oxygen.

The oxygen equivalents supplied by these two chemical carriers are a simple function of injection rate.

Table 8
Oxygen Equivalents Supplied
By Chemical Carriers, Single Well
(at 1000 mg/L)

Injection rate (gpm)	Oxygen Supplied (lb/day)	
	H ₂ O ₂ (0.47 equiv O ₂ /part H ₂ O ₂)	NO ₃ (0.84 equiv O ₂ /part NO ₃)
1.0	6	10
5.0	28	50
10.0	56	100
20.0	112	200
50	280	500

EASE OF TRANSPORT

The third factor in considering an oxygen source is the ease of transport and utilization. This factor involves the mode of application, the maintenance of the system and the rate and/or degree of utilization.

An air sparger system uses a small compressor able to deliver 1 cfm per well. The sparger itself is either a porous stone, a sintured metal diffuser or a fritted glass diffuser. Power consumption is minimal. The transport of the aerated water is limited by the rate of groundwater flow. The most significant operating cost in an air sparger system is maintenance of the compressor and of the diffuser and well screen. Biofouling or inorganic fouling of the diffuser and well screen can be significant and therefore require a high degree of maintenance. Bacterial utilization of the dissolved oxygen is very high.

Injection of aerated/oxygenated water is a relatively simple system. The simplest approach is to use an air stripper absorber to aerate the water. Often in treating a contaminated aquifer, groundwater is recovered and air-stripped to achieve hydraulic control of the contaminant plume. ReInjection of the stripped groundwater can therefore be accomplished at a relatively low cost. The main cost of operation is controlling fouling of the injection system. Transport of the oxygenated water is dependent on the geology (hydraulic conductivity). Bacterial utilization of the injected dissolved oxygen is very good.

Venting systems, while limited to unsaturated soils, are very efficient means of oxygen supply. The primary capital cost is the vacuum pump(s) needed to drive the system. Maintenance of the pumps is fairly simple and power consumption is minimal. The efficiency of the vent system is enhanced by volatile chemical removal from the soil. The largest potential cost with a vent system is treatment of the vapor discharge which can be accomplished by using disposable carbon, regenerable carbon or catalytic oxidation.

A hydrogen peroxide system is generally a low capital cost, easy to maintain system. The use of hydrogen peroxide does have a fairly high operating cost due to the cost of the purchased hydrogen peroxide which is dependent on the volume used. On a per pound of oxygen basis, the cost will range from \$1.50 to \$2.50. The greatest cost factor involved with hydrogen peroxide is how quickly it decomposes. There are two mechanisms of decomposition - biological and metal catalysis. Ideally, one would like minimal metal catalyzed decomposition. However, in some soils containing high levels of iron or manganese, metal catalyzed decomposition can be severe. In such cases, the solubility limit of oxygen in the water is rapidly exceeded and the water phase degased, losing available oxygen and drastically reducing the efficiency of the system.

Finally, nitrate systems are a potential electron acceptor alternative. Operationally, these systems have not been proven. Capital costs for a nitrate system would be fairly low, consisting of a supply tank and metering pump (similar to hydrogen peroxide). Chemical costs for nitrate are \$0.60 to 0.70/lb oxygen equivalent. The issue with nitrate, however, is neither the cost nor the ease of addition, but instead the biochemistry of utilization and the regulatory issues. In a recent test of nitrate utilization, it was found that even with an extremely labile substrate such as sucrose, there was a significant lag phase in the utilization of the nitrate when oxygen was also available at low levels. It would appear that nitrate utilization requires low oxygen requirements. If the biochemistry of nitrate is complicated, the regulatory issues become significant. Nitrate levels in groundwater are regulated at 10 mg/L. If nitrate is not rapidly utilized, injection would have to be tightly controlled and may be precluded or the nitrate would have to be removed.

COST ANALYSIS

To put the above analyses into perspective, the costs and effectiveness for the different oxygenation systems will be compared for a high degree of contamination (significant adsorbed and dissolved phase) and for a low degree of contamination (primarily dissolved phase only).

The analysis for the high degree of contamination assumes an area of contamination of approximately 250 x 100 ft with a loss of approximately 500 gal of a petroleum hydrocarbon fuel in a permeable sand. The example also assumes that the majority of the contaminant is adsorbed phase and is at, or above, the water table. Based on these assumptions, Tables 9 to 11 were constructed to compare the various oxygen systems.

Table 9
Operating Cost Comparison High Degree of Contamination

System	Capital	Operation	Maintenance	Treatment	
				Time	Cost
Air Sparging	\$35,000	\$800/mnth	\$1200/mnth	1716 d	\$150k
Water Injection	\$77,000	\$1200/mnth	\$1000/mnth	1580 d	\$194k
Venting (vpr ctrl)	\$88,500	\$1500/mnth	\$1000/mnth	132 d	\$101k
Hydrogen Peroxide	\$60,000	\$10000/mnth	\$1500/mnth	330 d	\$187k
Nitrate Injection	\$120,000	\$6500/mnth	\$1000/mnth	335 d	\$210k

Several things should be noted in this table. First, the nitrate capital costs are high because of a projected need for tight off-site control of nitrate due to groundwater regulation of nitrate levels. Second, the vent system includes a vapor phase control system - a catalytic oxidizer which costs approximately \$60,000. If vapor phase controls are not necessary, then the capital and total cost would be reduced significantly for the vent system.

Table 9 gives the gross operating and capital costs for the different oxygen systems. It does not, however, take into account the effectiveness of treatment. The different systems will not equally treat all phases of contamination. For example a vent system is ineffective in treating contaminated groundwater and in treating adsorbed phase contamination below the water table unless the water table drops naturally or is artificially lowered. An air sparging system is ineffective in treating vadose zone contamination unless the water table rises. The following table takes into account these factors and other efficiency factors and estimates a cost-effectiveness for the different systems.

Table 10
Cost-Effectiveness Comparison
High Degree of Contamination

System	Flow	Site		System	Treatment	Contaminant
	Rate	Oxygen (lb/day)	Treated (%)	Utilization Efficiency (%)	Time (days)	Treatment Cost (\$/lb)
Air Sparging	15 wells @ 2cfm	6	41	1 (sparg) 70 (D.O.)	1716	90.3
Water Inject	70 gpm	8	85	50	1580	100.2
Venting	160 cfm	4000	72	5	132	13.4
Peroxide	70 gpm	190	95	15	330	65.1
Nitrate	70 gpm (120 gpm recovery)	211	85	13	335	77.2

As can be seen from Table 10, there is a wide variance in both cost-effectiveness and in treatment-effectiveness. In terms of cost performance, the order is:

venting ➡ ➡ peroxide ➡ nitrate ➡ air sparger ➡ water injection

In terms of treatment effectiveness, the order is:

peroxide ➡ nitrate = water injection ➡ venting ➡ ➡ air sparging

While venting is a very cost-effective method, it is limited to treating the vadose zone. Consequently, its treatment-effectiveness is limited.

The above analysis is given for a situation with extensive contamination. If the degree of contamination is changed so that the soil contamination is minimal, the analyses would change. Assuming that there is no soil contamination above the water table and that the soil levels are <100 ppm, the performance of the different systems would be as follows assuming all other factors, such as capital, operating and maintenance costs, etc., remain constant

Table 11
Cost/Performance
Low Degree of Contamination
(Dissolved Phase Only)

System	Oxygen Delivered O ₂ (lb/day)	Time of (days)	Cost of Treated (\$/lb)
Air Sparging	6	180	117
Water Injection	8	330	314
Venting	Not Applicable	---	---
Peroxide	190	180	134
Nitrate	211	240	166

Where the degree of contamination is less, simpler systems such as air sparging become more cost-effective. Where the contamination is only in the dissolved phase, an air sparger system is often the best choice.

The choice of an oxygen supply is dependent on the contaminant load, the mass transfer and the ease of transport/utilization. Depending on the degree of contamination, different systems will be most effective.

CASE HISTORIES

To examine the performance of different oxygenation systems, three case histories will be discussed. All three case histories deal with gasoline contamination. In the first case history, the oxygenation system was an air sparger network. In the second case history, hydrogen peroxide was used. In the third case history, a vent system was used. Each case history will discuss the degree of contamination, the installation and operation of the oxygenation system and the results attained.

Case History 1: Air Sparging Network

In this case history, the contamination problem occurred when an undetermined amount of gasoline leaked from a below ground storage tank. The area of the loss is underlain by approximately 6 to 7 ft of

red-brown, heavy silt loam which, in turn, is underlain by a fractured red-brown shale and siltstone. Depth to groundwater is 20 to 25 ft below grade within the bedrock system. Impact from the loss included a dissolved phase hydrocarbon plume that extended approximately 250 ft in a north-south direction and 350 ft in an east-west direction with concentrations ranging from 10 mg/L to 15 mg/L for gasoline-type hydrocarbons. Ten domestic water supply wells were impacted in addition to organic vapors within nearby residential basements. Free-floating phase hydrocarbons were absent.

The remedial system designed and implemented at this site included contamination plume and water table manipulation via pumping, dissolved organic removal of the pumped water by air stripping, and accelerated in situ bioremediation of adsorbed and dissolved phases by the physical addition of oxygen and nutrients (Fig. 1). The physical addition of these components to the original loss area was accomplished through the re-infiltration of treated oxygen and nutrient-rich groundwater into an infiltration gallery located in the former tank pit. An air sparging system, consisting of mechanical air compressors, air lines and down well diffusers, provided needed oxygen to peripheral areas of the plume outside the infiltration gallery.

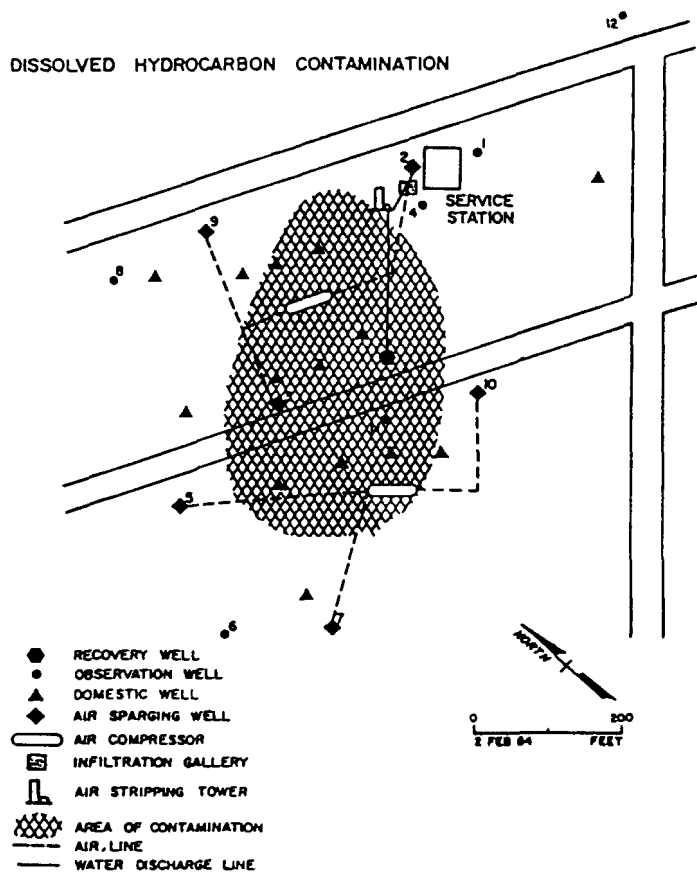


Figure 1
Schematic of Bioreclamation System

The air sparging system effectively to partially effectively delivered needed oxygen to the peripheral areas. Major limitations focused on the maximum quantity of oxygen that could be induced into the groundwater system (10 mg/L) at the sparging point and the fouling and plugging of the sparging points by the development of thick biologic growths. These conditions interfered with optimum oxygen transfer to the fractured bedrock system and required frequent mechanical cleaning.

The first 11 mo of operations showed a general 50 to 85 % reduction in organic contaminants, despite the non-optimum conditions of the air sparging system (Fig. 2). At 85% reduction, the treatment stabilized indicating that the air sparging was a limited system. The residual contamination was adsorbed phase trapped in the fractures of the bedrock system.

A comprehensive program to accelerate oxygen transfer rates was subsequently incorporated at the site in an effort to reduce the project restoration time-frame. The program involved the delivery of increased quantities of oxygen to the groundwater system via the trickle feed and disassociation of dilute quantities of hydrogen peroxide (100 mg/L). This case history demonstrates that air sparging is ineffective in treating adsorbed phase hydrocarbons. It also indicates that maintenance of the air sparging system is significant and therefore is not a desirable application for long-term programs.

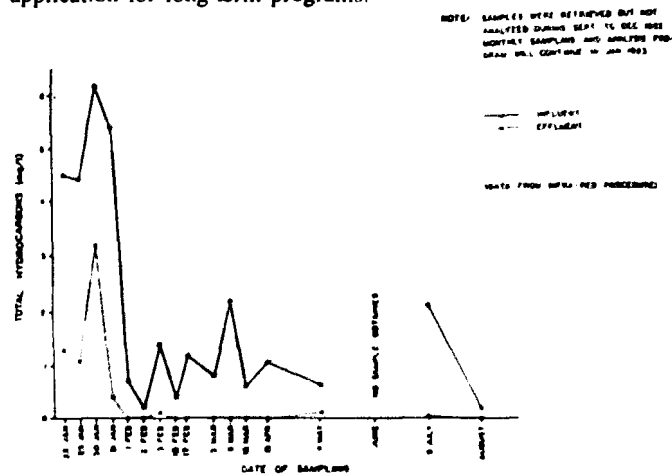


Figure 2
Total Hydrocarbon Concentrations for Air Stripping Tower

Case History 2: Hydrogen Peroxide

This case study involves petroleum leakage over a period of time from underground storage tanks, pumps and lines at a service station. The area in which the loss occurred has complex geology with a varied hydrocarbon phase distribution within the water table in both the 7- to 10-ft thick variable fill overburden and in the underlying fractured limestone bedrock. The subsurface hydrocarbon contamination was not only limited to the property on which the loss occurs, but also migrated with natural groundwater flow across a busy intersection to a commercial building (Fig. 3).

Three general areas of interest were addressed by the remedial program (Fig. 3): Area A was a lightly contaminated area with most of the subsurface hydrocarbons being found in the fill material; Area B was the location of the underground storage tanks and included significant contamination in both the fill and the bedrock; and Area C was the commercial building basement which had been impacted by phase-separated hydrocarbons.

The general remediation program designed for this site involved the in situ bioremediation of impacted groundwater and sediments through the addition of aerated water supplied with nutrients and hydrogen peroxide. Remedial response was strongly correlated to the product distribution and the geology. A 95% reduction in dissolved hydrocarbon levels was achieved in 5 mo of operation in Area A (Fig. 4). Response in Area B was the least dramatic and most variable, with the greatest reduction of dissolved levels (40 to 50%) achieved in a few months representing treatment of the adsorbed phase in the more permeable fill. Following this initial response, the remedial response slowed representing treatment of contamination in the bedrock. Area C achieved an 85% reduction in hydrocarbon contamination in approximately 6 mo.

Hydrogen peroxide was added to the groundwater system at both the infiltration gallery and former air sparging wells. The most recent results show overall hydrocarbon concentration levels to have declined in the core area with only five of the original 10 home owner wells still contaminated.

Case History 3: Soil Venting

In this case study, a pre-closure site investigation of a former service station facility in Massachusetts revealed low levels of both dissolved

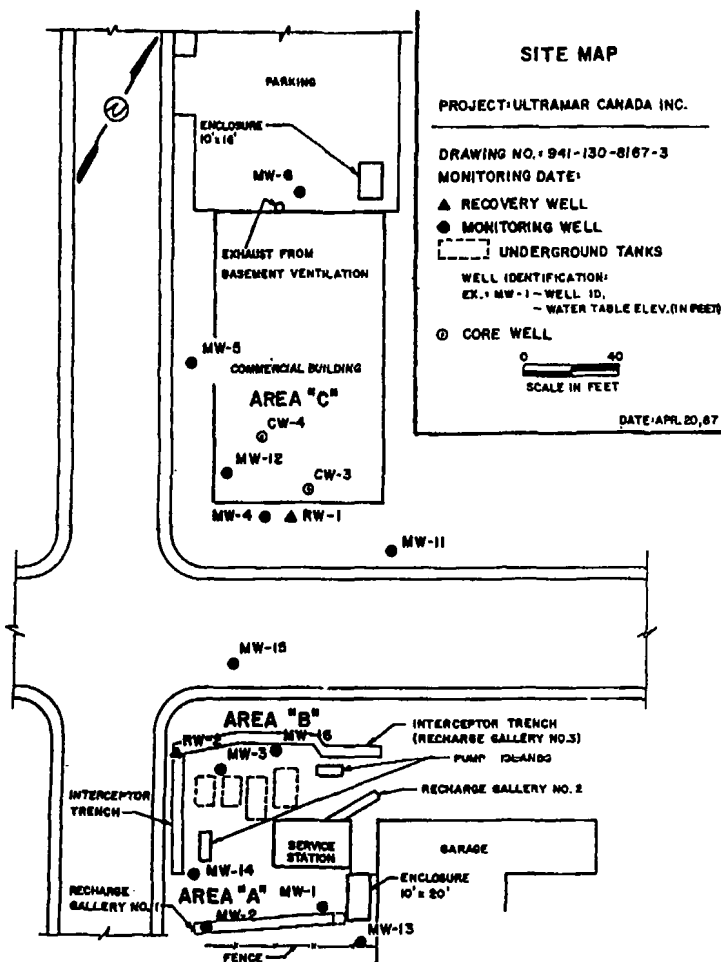


Figure 3
Site Map

and adsorbed phase gasoline contamination associated with the underground storage tanks. The highest concentration of adsorbed phase hydrocarbon contamination was found to be present at a depth of 9 to 11 ft in soils that are in a zone of seasonal groundwater fluctuation.

A soil venting system was installed at the site to address the adsorbed phase hydrocarbons above the water table. The system designed for the site included six soil vapor extraction points, two of which were placed within the former underground storage tank locations. The points were

Table 12
Air Sample Result Sheet

DATE	OXYGEN ppm	CARBON DIOXIDE ppm	METHANE ppm	BENZENE ppm	TOLUENE ppm	ETHYL BENZENE ppm	XYLENE ppm	TPH ppm	WATER ppm
02/07/89	210000	11000	740	1.20	0.44	0.22	2.00	560	15000
02/08/89	210000	10000	750	0.00	0.52	0.22	1.80	88	15000
02/09/89	210000	10000	420	0.00	0.00	0.00	0.00	0	15000
02/13/89	210000	2900	55	0.00	0.00	0.00	0.00	51	15000
02/14/89	210000	2800	230	1.40	0.00	0.00	0.68	240	15000
02/27/89	210000	1700	170	0.36	2.50	4.20	3.90	130	15000
03/09/89	210000	1300	100	0.36	0.29	0.00	0.00	190	15000
04/12/89	210000	1300	0	0.00	0.00	0.00	0.00	46	15000
04/25/89	210000	1400	0	0.00	0.00	0.00	0.00	21	15000

All samples taken from effluent of soil vent blower

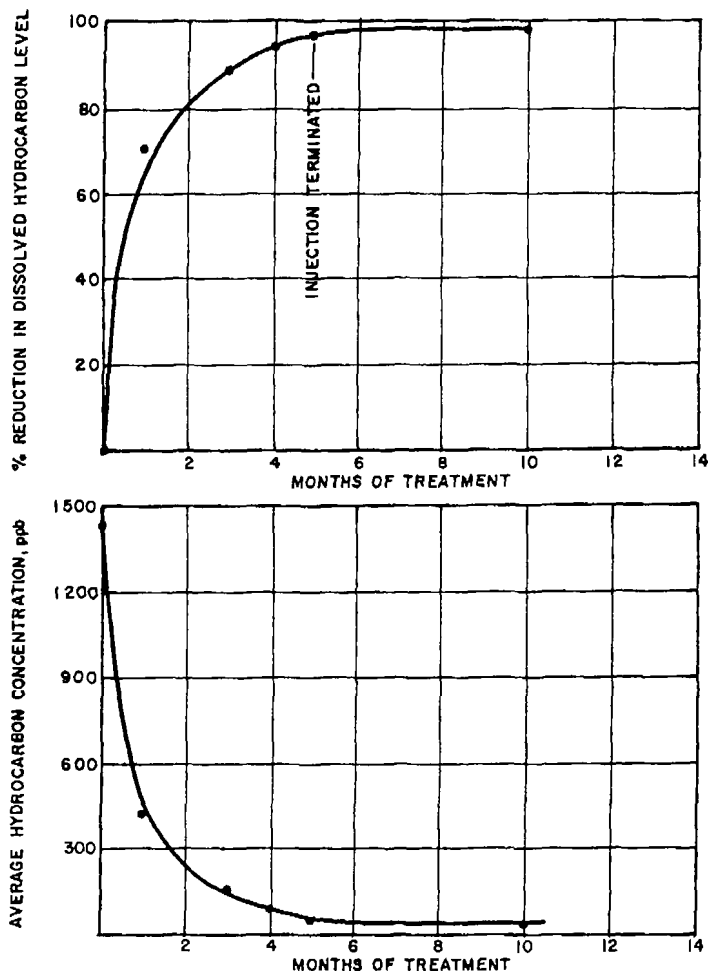


Figure 4
Bioreclamation Results Area "A" (MW-1,2,13,14)

constructed of 2-in. diameter schedule 40 PVC with 0.020-in. slot well screen extending over the contaminated zone and placed using a 30-ft radius of influence. Granular activated carbon for adsorption of volatile organic carbons from the soil vapor was utilized for the soil vent blower effluent.

Effluent air sample results of the system's operation over an approximately 1.5-mo period during the dry late winter and early spring are presented in Tables 12 and 13. Up to 122 scfm of soil vapor were drawn through the system during the period. Figure 5 shows CO₂ production rates basically parallel vapor phase concentration of methane and total petroleum hydrocarbons in the effluent soil vapor. This observation

Table 13
Air Sample Result Sheet

DATE	WATER VAPOR prop	MOL WEIGHT lbs. per lb. mole	VELOCITY HEAD in. water	STACK TEMP F	BARO PRESS in. merc	STATIC PRESS in. water	STACK VELOC ft/sec	FLOW RATE cubic ft/min	HYDROCARBONS REMOVAL RATE		
									lbs per day	lbs to date	approx equiv gallons
02/07/89	0.015	28.88	0.15	55	30.02	0.00	21.4	113.8	8.2	8.2	1.3
02/08/89	0.015	28.84	0.11	55	29.99	0.00	18.4	97.4	7.0	15.2	2.4
02/09/89	0.015	28.84	0.15	55	30.05	0.10	21.4	113.8	3.1	18.3	2.9
02/13/89	0.015	28.74	0.15	55	30.52	0.00	21.3	115.0	3.1	30.7	4.9
02/14/89	0.015	28.74	0.15	55	30.20	0.00	21.4	114.4	3.1	33.8	5.4
02/27/89	0.015	28.68	0.10	55	29.67	0.00	17.7	92.7	2.5	76.6	12.2
03/09/89	0.015	28.76	0.10	55	30.44	0.00	17.4	93.7	4.6	103.7	16.5
04/12/89	0.015	28.75	0.17	55	30.37	0.08	22.7	122.1	1.5	229.8	36.5

All samples taken from effluent of soil vent blower

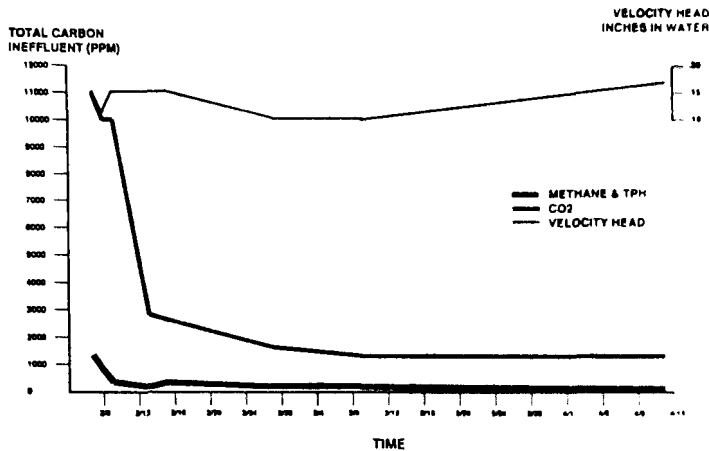


Figure 5
Gas Production Rate

demonstrates that significant biodegradation occurs even with highly volatile compounds.

Normal CO_2 content of air is 0.04%; the 11% CO_2 observed initially represents a 275-fold increase in CO_2 . This response demonstrates that bacteria can readily use oxygen provided by a vent system.

REFERENCES

1. Alexander, M., "Biodegradation of Chemicals of Environmental Concern." *SCIENCE*, 211 pp. 32-138, 1981.
2. Kobayaski, H. and Rittmann, B.E., "Microbial Removal of Hazardous Organic Compounds." *Environ. Sci. Tech.* 16, pp 170a-183a, 1982.
3. Alexander, M., "Biodegradation: Problems of Molecular Recalcitrance and Microbial Fallibility." *Adv. Appl. Microbiol.* 7 pp 35-80, 1965.
4. Alexander, M., "Nonbiodegradable and Other Recalcitrant Molecules." *Biotech. Bioeng.* 15, pp 611-647, 1973.
5. Wilson, J.T., McNabb, J.F., Cochran, J.W., Wang, T.H., Tomson, M.B. and Bedient, P.B., "Influence of Microbial Adaption on the Fate of Organic Pollutants in Ground Water." *Env. Toxicol. Chem.* 4, pp 743-750, 1985.
6. Brown, R.A., Norris, R.D. and Raymond, R.L., "Oxygen Transport in Contaminated Aquifers." *Proc of the NWWA/API Conf on Petroleum Hydrocarbons and Organic Chemicals in Ground Water-Prevention, Detection and Restoration*. Houston, TX, Nov., 1984.
7. Leprince, Y. Richard, "Use of Biotechnics in Water Treatment: Feasibility and Performance of Biological Treatment of Nitrates." *Aqua Sci. Tech. Rev.*, pp. 455-62, 1982.
8. Andreoli, R. Reynolds, M. Bartilucci, R. Forgione, "Nitrogen Removal in a Subsurface Disposal System." *Water Sci Tech.* 13 (2), pp. 967-76, 1981.

Remedial Options and System Characteristics of an Inactive Land Treatment Facility

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ABSTRACT

Regulatory restrictions on land disposal of certain wastes have prompted closure of land treatment systems. Remaining soils are often highly contaminated. This paper compares some system characteristics measured in soils at an intensely-loaded petroleum waste treatment system when it was operating and when loading ceased. Results indicate that microbial activity decreases rapidly as usable substrate becomes limiting, leaving high concentrations of inassimilable waste in the soil. Remedial options are discussed for soils of former land treatment systems.

INTRODUCTION

The technology of hazardous waste land treatment is evolving rapidly in the face of regulatory restrictions and concerns about long-term liability and environmental damage. Systems presently are designed with double-walled liners to protect against the migration of hazardous leachate, atmospheric emissions collection and air delivery systems, providing oxygen to maintain aerobic soil conditions. The treatment pad and associated appurtenances are constructed at the remediation site. When the project is completed, the system is disassembled. These systems are more carefully engineered than old landfarms, which essentially took advantage of the natural soil assimilative capacity for organics. The kinetics of waste degradation and degree of success varied tremendously among different systems. The differences arose from geographic location and from management practices. These systems usually were operated with minimal environmental controls and containment. Most systems were designed to control rainwater run-on and potentially contaminated run-off. The U.S. EPA mandated a monitoring program for land treatment facilities that included installation of lysimeters for soil pore liquid monitoring, groundwater monitoring wells and soil core monitoring¹.

Given the number and history of use of industrial waste land treatment systems few reported episodes of environmental contamination have occurred. Streebin, et al.² have documented that metals are generally immobilized in the top 25 cm of soil at land treatment sites. They found, however, trace quantities of polynuclear aromatics migrating into the unsaturated zone and high levels of TOC and COD in soil pore water. The American Petroleum Institute³ reports that polynuclear aromatic hydrocarbons have sufficiently high organic carbon partition coefficients and, as such, will be strongly adsorbed in soil and immobilized in land treatment systems.

Remedial use of land treatment created many systems which are now being closed. Other factors also are responsible. The 1984 Hazardous and Solid Waste Amendments to the RCRA mandate a land ban on disposal of specific waste streams. Two-thirds of listed wastes are now regulated; the remainder are scheduled for regulation by May 8, 1990.

For some areas of the country such as southern California, tightening air quality restrictions and land use pressures have contributed to the closures.

Soils of treatment systems require remediation or disposal when waste incorporation ceases. A moderate, continuous waste application rate is needed for maximum stabilized performance of land treatment systems⁴. When applications cease, micro-biological activity declines.

The petroleum industry historically has operated land treatment systems for selected waste streams economically at moderate loading rates. Petroleum waste materials are generally easily biodegraded by an acclimated consortia of microorganisms. This paper reports a 3-year monitoring study of an intensely-loaded petroleum waste land treatment facility. System performance was evaluated by monitoring operational variables such as waste loading rate and frequency, soil physical variables and microbiological parameters such as carbon dioxide evolution and microbial population density. Additionally, aspects of the structure and function of the microbial ecosystem were inferred from the monitoring results. Waste additions were more or less continuous until November, 1987, when operations ceased completely.

METHODS AND MATERIALS

Representative soil samples were obtained from the land treatment facility in pre-sterilized sampling jars. Samples used for analysis were selected from a composite of soils from a particular section. This sample compositing was done to reduce spatial variations introduced from waste loading practices, a significant source of variability even in systems that practice uniform waste application and incorporation⁴.

Total Viable Count

Soil samples were mixed with sterilized, distilled water and gently swirled and sonicated under low power to break up the oily agglomerates. Growth media compositions for enumeration of microorganisms were chosen on the basis of ability to select for petroleum-degraders⁵. Brain-heart infusion agar was chosen as a base to which amendments were added, described elsewhere⁵. Enumeration of bacteria, fungi and actinomycetes was accomplished by plating 10-mL drops of successively diluted suspensions on hardened agar. The procedure, developed by Harris and Sommers⁶, is a modified most probable number determination. The number of organisms determined is a function of the entire dilution series rather than the most dilute member of the series.

Respiration

Degradative activity of the microorganisms was measured as carbon dioxide evolution in 250-mL biometer flasks (Bellco Biotechnology). Carbon dioxide is absorbed in alkali and is analyzed titrimetrically

following precipitation with BaCl_2 . Details of the procedure can be found elsewhere⁵.

RESULTS AND DISCUSSION

The land treatment system received no waste loading after November, 1987. The fortuitous closure allowed comparison of measurements of system parameters during continuous waste loading and after loading ceased.

Microbial Numbers and Activity

Active treatment system soils harbor a diverse assemblage of microorganisms. Figure 1 shows seasonal fluctuations of microbial numbers for one section. Millions of organisms per gram of soil are recorded from all seasons with peak numbers occurring in the hot summer months. Bacteria, fungi, yeast and actinomycete groups were culturable from the treatment soils. Statistical analysis of the ecological relationships of the microbial groups have been presented⁶.

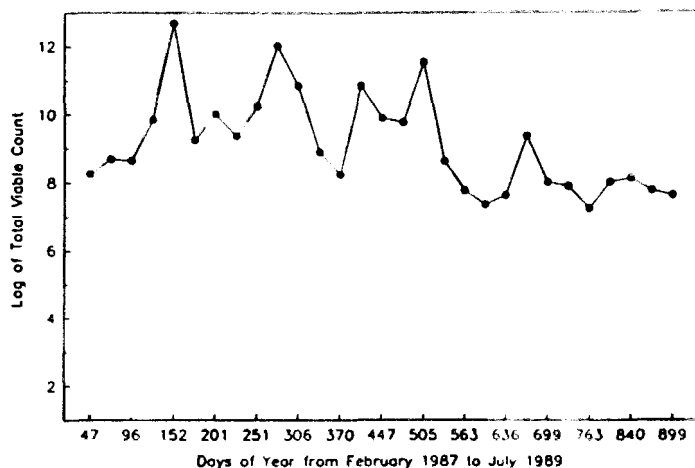


Figure 1
Total Viable Count Measured in Landfarm Section A from February 1987 to July 1989

Substantial densities of microorganisms are present in the treatment soils of the closed facility. However, fewer kinds of colonies were observed. The lower diversity of microorganisms suggests more restricted resource partitioning. Organisms currently inhabiting the treatment soils are viable, but presumably substrate-limited.

Respiratory activity, as measured by microbial CO_2 evolution, is influenced by time of year, general environmental conditions and the presence of a continuous supply of usable substrate. Figure 2 shows respiration values in $\text{mg CO}_2/\text{g soil/day}$ for one section of the landfarm from February, 1987 to August, 1989. The values indicate high levels of microbial activity and substrate decomposition until about July, 1988. Proper environmental, biochemical and physical conditions were maintained in this period. Loading ceased in November, 1987. In late summer of that year, approximately 400 tons of waste were applied to each section. This substantial waste loading enabled degradative activity to continue for approximately 6 mo. The rate of degradation began to decline in late summer of 1988 and eventually leveled off at low, constant activity.

Degradation Kinetics

Steady-state concentrations of 15 to 30% oil in soil by weight is an assimilable loading when environmental conditions are not stressful and a reasonable portion of the waste is usable substrate. Martin *et al.*⁷ showed that for representative land treatment units, activity in the system was a function of the waste half-life and the weight percentage of oil added with each application. Larger molecular-weight, more recalcitrant, less soluble organics will biodegrade slowly or cometabolically.

Polynuclear aromatics, heteronuclear species or poly-substituted molecules will degrade by different pathways than simple hydrocarbons.

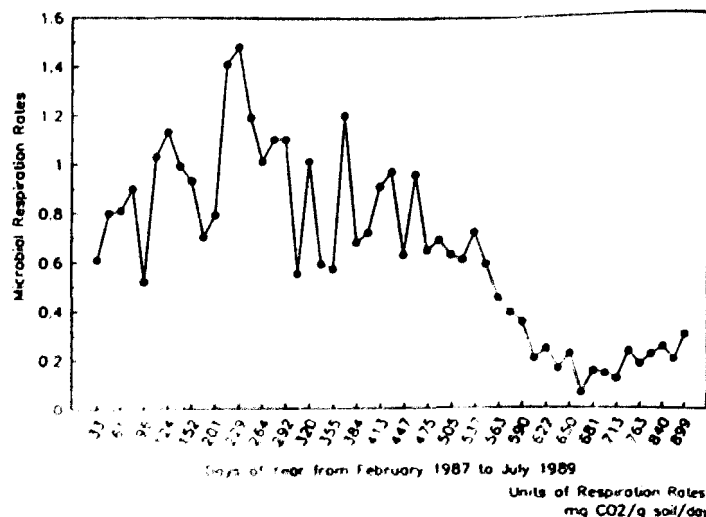


Figure 2
Microbial Respiration Rates Measured in Landfarm Section A from February 1987 to July 1989

The degradation kinetics of these groups may differ from the overall performance of the system.

Cometabolic substrate decomposition of a particular group may be first-order (or some other order) with respect to the energy-yielding substrate. Diauxic relationships, whereby one substrate is preferred over another until that substrate becomes limiting, are also likely. Thus, while overall system performance may be driven by an excess of usable substrate, degradation kinetics for specific groups are likely more complex. System performance is best described by a multiple-substrate kinetic model. However, rate coefficients describing breakdown of individual waste components are presently unknown. The rapid breakdown of some of these groups is contingent on the supply of readily assimilable substrate for maintenance of a stable microbial community. This is the driving force for total system respiration.

Continuous applications of differing quantities and quality of petroleum waste makes predictions of waste degradation kinetics difficult in functioning systems. Martin *et al.*⁷ demonstrated the dependence of the predicted stabilized weight percentage of oil in soil on waste half-life. For a facility located in a moderate climate that can operate with a waste application frequency of weekly for 52 weeks per year (0.35% oil in soil per application), the predicted weight percentages correspond with the following half-lives: $t_{1/2} = 60$ days, 5.7%, $t_{1/2} = 125$ days, 12.2%, $t_{1/2} = 146$ days, 14.2%, $t_{1/2} = 304$ days, 30%. Maintenance of a reasonable waste degradation half-life is essential. Buildup of recalcitrant organics will occur regardless of how a system is operated, but the process may be slowed by repeated, modest waste applications.

Cessation of waste loading caused profound changes in system dynamics. Respiration rates fell to low levels, remaining constant under varying seasonal conditions (Figure 2). The decline in respiration rates to present levels occurred as usable substrate presumably became limiting.

Table 1 shows a comparison of the length of time to reduce oil concentrations to nominal levels. A concentration of 15% oil in soil by weight (150,000 parts per million) was chosen as representative of present conditions in the facility. The cleanup level chosen was 100 ppm (0.01% oil in soil), current regulatory levels for petroleum hydrocarbons in soil. The kinetic coefficients were estimated from CO_2 evolution data corresponding to conditions of intense activity (1.0 $\text{mg CO}_2/\text{g soil/day}$) and closure conditions (0.10 $\text{mg CO}_2/\text{g soil/day}$). The results of the two calculations are presented; time to reach the targeted cleanup level using zero-order and first-order kinetic equations. A ten-carbon alkane was chosen as a representative waste molecule for calculation of the moles of oil per gram of soil, although the actual weight of material present in the facility is likely heavier. The calculations presented in Table 1 are likely extreme estimates. The time predicted by first-order

kinetics for natural remediation of the soils indicates the process is not a practical alternative. The calculation assumes equilibrium conditions; time to reduce a one-time application of 15% oil in soil is predicted. However, the zero-order prediction is too simplistic; some materials in the treatment soils have more complicated cometabolic (probably first order for growth-supporting substrate) biochemical pathways. The calculation assumes all substrate is completely assimilable by the microbes. The indication is that the treatment soils will require remediation. The community of microorganisms adapted for life in intensely-loaded land treatment facilities require supplies of readily usable substrate to maintain adequate degradation activity.

Table 1
Comparison of Times to Reduce Oil in Soil Concentrations

Initial Concentration = 150 mg oil/g soil (15% by weight) = 1.056×10^{-3} moles oil/g soil	
Final Concentration = 0.10 mg oil/g soil (0.01%) = 7.042×10^{-6} moles oil/g soil	
<u>Zero-order Kinetics</u>	<u>First-order Kinetics</u>
(1) Operating System	(1) Operating System
evolution rate = 1.0 mg CO ₂ /g soil/day	evolution rate = 1.0 mg CO ₂ /g soil/day
t = 500 days	t = 3650 days
(2) Closed System	(2) Closed System
evolution rate = 0.1 mg CO ₂ /g soil/day	evolution rate = 0.1 mg CO ₂ /g soil/day
t = 5000 days	t = 36,500 days

Remedial Options

The preceding discussion show that options and remedial strategies are necessary for soils of closed land treatment facilities. The high concentrations of polynuclear aromatics limits the applicability of several developing strategies for reuse of hydrocarbon-contaminated soils. Contaminated soils have been used in asphalt production, although limits are set on hydrocarbon concentrations and clay content of the soils. Fixation of soil hydrocarbons with chelating agents and polymer material or batch chemical oxidation with subsequent reuse of the soil as fill material have been used at sites with petroleum or gasoline contamination. Again, it is unlikely that either process would be adequate for the high concentrations of heavier molecular weight hydrocarbons in the former treatment soils. Concerns about long-term stability of soils with chemically-fixed hydrocarbons have also been raised.

The concentrations of petroleum waste in the treatment soils mandates that off-site disposal be in a Class I landfill. Costs for disposal and transportation for 18,000 cubic yards of soil (conservatively estimated for a 9 acre landfarm of 1 foot depth) could cost between \$300 to \$400 per cubic yard or 5.4 to 7.2 million dollars. Additionally, the generator would maintain liability for the landfilled waste.

An aggressive in-situ remedial program re-stimulating the dormant natural petroleum-degrading organisms should be investigated. Bench-scale studies can determine an appropriate substrate addition to stimu-

late natural biodegradation and cometabolism of the larger-molecular weight organics. The compound chosen would provide the driving force for breakdown of the remaining waste materials. The substrate may be a petroleum hydrocarbon or some other compound. Monitoring oxygen, nutrients and soil water content would assure the correct environmental conditions. A surfactant carefully applied may facilitate the solubilization of the more recalcitrant molecules. Insoluble or sparingly soluble organics are readily adsorbed and act to bind soil particles together, creating anaerobic zones.

Solubilization in pore or hygroscopic water promotes microorganism-substrate contact. Microbial augmentation may be attempted, although the natural petroleum-degrading organisms are highly adaptable and ubiquitous. The oil in soil concentrations could be reduced to levels where other remedial options could be utilized. Without substrate additions, it is unlikely that biological remediation would be successful.

CONCLUSIONS

Soil characteristics of the closed treatment facility dictate that effective options be developed for management of the highly contaminated soils. Biodegradation decreases to an unacceptably low level, in part as a result of a high percentage of remaining high-molecular weight, recalcitrant organics and a minimal supply of growth-supporting substrate. Contaminated soils allowed to lie fallow for long periods restrict land usage and increase the chance for undesirable environmental impact. Soil remedial options currently in widespread use for gasoline or waste oil contamination may have limited applicability because of the nature and concentration of the petroleum residuals. An effective in-situ remedial program would include development of a suitable cometabolic substrate addition with maintenance of environmental conditions conducive for biodegradation. Applications of such an approach would include remediation of contaminated soils at former coal gasification plants and abandoned oil fields slated for redevelopment.

REFERENCES

1. Morrison, A., Land Treatment of Hazardous Waste, *Civil Engineering*, May 1983, pp. 33-38.
2. Streebin, L.E., J.M. Robertson, A.B. Callender, L. Doty and K. Bagawandoss, Closure Evaluation for Petroleum Residue Land Treatment, *EPA Rept. No. 600/S2-84-162*, U.S. EPA, Ada, Oklahoma, December 1984.
3. American Petroleum Institute, *The Land Treatability of Appendix VIII Constituents Present in Petroleum Industry Wastes*, API Publication 4379, 1984.
4. Loehr, R.C., J.H. Martin and E.F. Neuhauser, Spatial Variation of Characteristics in the Zone of Incorporation at an Industrial Waste Land Treatment Site, *Hazardous and Industrial Solid Waste Testing: Fourth Symposium*, ASTM STP 886, American Society for Testing and Materials, pp. 285-297, 1986.
5. Marshall, T.R., *Biodegradation of Petroleum Wastes in Soil: The Microbial Ecosystem and Optimization of a Treatment Process*, Ph.D. Thesis, University of Southern California, 203 pp., 1988.
6. Harris, R.F. and L.E. Sommers, Plate-dilution Frequency Technique for Assay of Microbial Ecology, *Applied Microbiology*, 16 (2), pp. 330-334, 1968.
7. Martin, J.P., R.C. Sims and J. Matthews, Review and Evaluation of Current Design and Management Practices for Land Treatment Units Receiving Petroleum Wastes, *Hazardous Wastes and Hazardous Materials*, 3 (3), pp. 261-280.

Case Study of the Bench-Scale Solvent Extraction Treatability Testing of Contaminated Soils and Sludges from the Arrowhead Refinery Superfund Site, Minnesota

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ABSTRACT

Solvent extraction is a separation process that has emerged as an effective hazardous waste treatment technology. It has been successfully applied to industrial wastewaters, soils and sludges contaminated with hydrocarbons, petroleum products and heavy organic compounds.

Solvent extraction is being considered as an alternative treatment technology at the Arrowhead Refinery Superfund Site in Hermantown, Minnesota, the location of a former waste oil recycling facility. Highly acidic, metal-laden sludge bottoms and oil-saturated clay filter cake were disposed of in a 2-ac lagoon. The peat layer underlying the lagoon and the surrounding soils are contaminated with oil, metals and numerous organic compounds.

Under subcontract to CH2M HILL, Resources Conservation Company (RCC) conducted bench-scale tests on sludge peat and soil wastes from the Arrowhead Refinery site using its Basic Extractive Solvent Technology (B.E.S.T.®). The results of the bench-scale test and the applicability of the process to the wastes at the site are discussed.

INTRODUCTION

The Arrowhead Refinery Site occupies approximately 10 ac in north-east Minnesota near Duluth. According to Minnesota Pollution Control Agency (MPCA), milk cans were retinned at the site before 1945. From

1945 to February, 1977, the site was used as a waste oil recycling facility.

The waste oil was treated with sulfuric acid to deemulsify the oil/water mixture. Wastewater from the process was recovered and discharged to the wastewater ditch. The waste oil was then filtered through a clay/sand filter. The sludge from the deemulsification process and the filter cake were disposed of in an uncontained 2-ac lagoon in a wetland on the site. The filter cake also was used as fill in the process area adjacent to the lagoon (Figs 1 and 2).

Site Characterization

The U.S. EPA and MPCA investigated the environmental effects of on-site waste disposal from 1979 through 1984. The results of their investigations indicated that a variety of organic and inorganic contaminants are present at the site in the subsurface soil, sediment, surface water, groundwater and sludge lagoon. The two major contaminant sources defined in the remedial investigation were the contaminated soils in the process area and the sludge and filter cake disposed of in the lagoon (Fig. 3).

The surface soils consist of gravelly sand, silt, and fill material that were deposited during site operations. Much of the soil is visibly stained and saturated with waste oil. The lagoon contains a viscous, black oily liquid sludge and a black filter cake that consists of an oily clay and



Figure 1
Arrowhead Refinery Sludge Lagoon



Figure 2
Arrowhead Refinery Wastewater Ditch

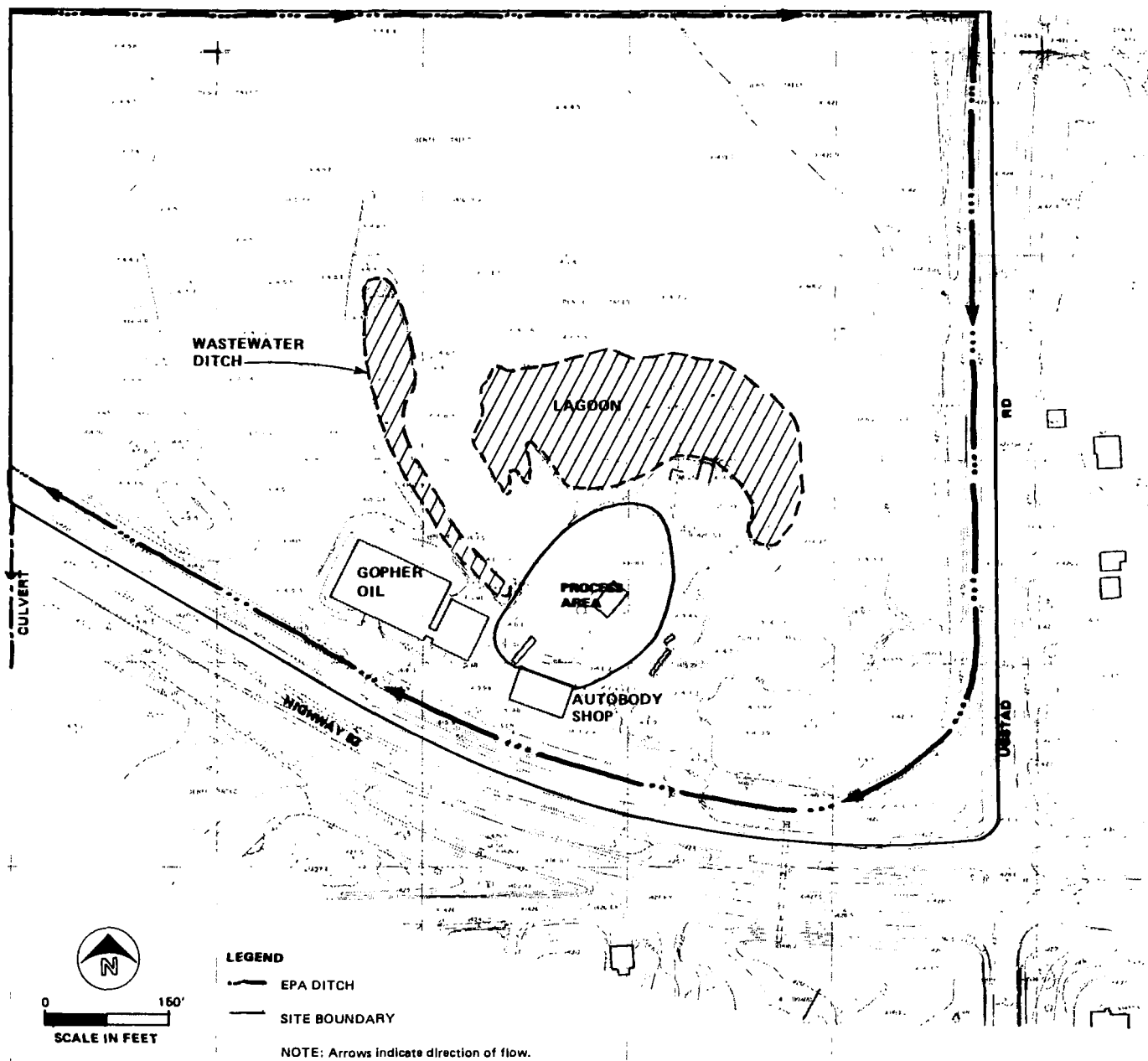


Figure 3
Site Plot Plan

a silty sand and gravel fill layer. The entire lagoon is underlain by a peat layer that appears to be persistent throughout the site and is also highly contaminated. Contaminants detected at the site included polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds, lead, zinc and small quantities of PCBs.

As documented in its ROD for the site, the U.S. EPA's selected remedial action was thermal treatment of site wastes. The U.S. EPA and MPCA are both interested in the application of alternative technologies that might achieve similar levels of treatment more economically than thermal treatment. As a result, the U.S. EPA agreed to fund a treatability study of the refinery wastes using a solvent extraction treatment process.

CH2M HILL had previously performed a remedial investigation and feasibility study of the site for the U.S. EPA. Under contract to the U.S. EPA, CH2M HILL subcontracted the treatability tests to Resources Conservation Company (RCC).

SOLVENT EXTRACTION

Background

Solvent extraction technology has been used for many years as solvent leaching to recover valuable minerals from ores, to remove unwanted materials from coal processing operations and to de-oil quench waters in refinery processing operations. More recently solvent extraction has been used to treat sediments and soils contaminated with PCBs, wastes generated by chemical manufacturers and oily hazardous and toxic wastes.

Organic solvent extraction is particularly suited for treatment of oily wastes, because the wastes can be separated into product oil, solids and water fractions. Solvent extraction can effectively extract the oil fraction of a waste, including PCBs. The remaining solids can sometimes be disposed of as non-hazardous wastes and the water discharged to a wastewater treatment plant.

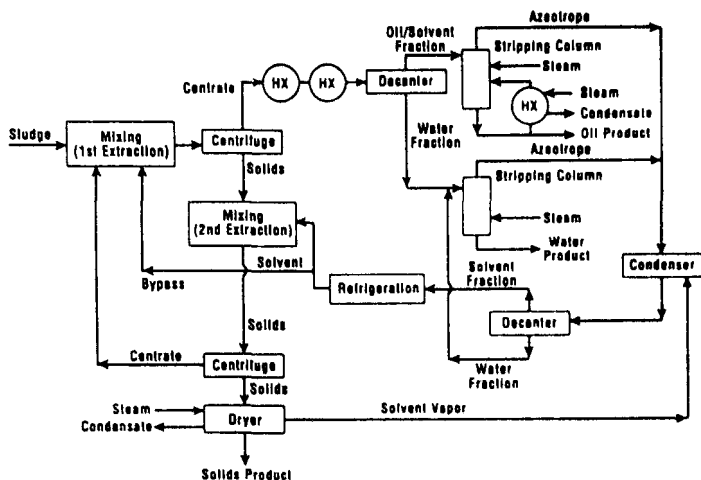


Figure 4
B.E.S.T. Process Flow Diagram

The successful application of solvent extraction depends on solvent selection, process configuration, the nature of the waste and the contaminants, and the economic value of the recoverable compounds. Solvent extraction can be an especially viable treatment alternative where: (1) valuable products can be recovered from the waste; (2) the process can yield non-hazardous residual solids; or (3) inordinate wastewater disposal or air emissions problems are not encountered.

B.E.S.T.®

RCC is the owner of the B.E.S.T.® solvent extraction technology, a patented process that takes advantage of the peculiar solubility behavior of certain aliphatic amines. Triethylamine (TEA) has chemical and physical properties that make it a good candidate for use in solvent extraction.

At temperatures below 65°F, TEA is completely miscible with water and is a good solvent for a variety of organic compounds such as PCBs,

PAHs, and petroleum products. The soluble organic and water components of a waste can be separated from the solids component using TEA.

When TEA is heated, the solubility of water in TEA decreases to less than 2%, separating the water fraction from the soluble organic fraction. The TEA is then removed to yield an organic fraction. The B.E.S.T. process separates the waste into three waste products: (1) a solid with soluble organic contaminants removed, (2) a wastewater that may require treatment before discharge and (3) an oil product that can be recycled for energy recovery or incinerated (Fig. 4).

TEA is a basic compound that reacts with acids in the waste yielding ammonium salts. Excessive reaction of the basic solvent with an acidic waste will result in the loss of expensive solvent. To minimize solvent loss, the B.E.S.T. process includes the addition of caustic to increase the pH of the waste above 11. The high pH has the side benefit of precipitating low concentrations of metals into the product solids and thereby potentially decreasing the leachability of metals in the EPA toxicity test.

To evaluate the ability of the process to treat a given waste, RCC conducts bench-scale treatability tests at its laboratory facility. In the treatability tests, 1-kg batches of waste are subjected to the same unit processes as a full-scale operation. The performance of the process is evaluated at each step of the process, and samples of the products and process intermediates are analyzed to determine if the wastes are being treated effectively.

Treatability Testing

Samples of the contaminated soil, sludge and peat wastes were sent to RCC, and bench-scale treatability tests were conducted in May, 1989. Samples of the raw waste and the treated waste products were analyzed through the U.S. EPA's Contract Laboratory Program. RCC reported its final results to the U.S. EPA in August. The final project report is scheduled to be submitted by CH2M HILL in September for the U.S. EPA and MPCA review. The results of the treatability study and the conclusions of the report will be available after the review of the project report by EPA and MPCA. The results of the study are scheduled to be reported in November.

Bioremediation Using Adapted Bacterial Cultures

Topic 1: Examination of Site Data and Discussion of Microbial Physiology With Regard to Site Remediation

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INTRODUCTION

The number of organic compounds introduced into the environment by humans has increased dramatically in recent years.¹ As a consequence of this xenobiotic (i.e., man-made) introduction, the fate of these compounds, such as pesticides, polycyclic aromatic hydrocarbons and domestic wastes, in the environment is a very important issue. Of particular concern is disappearance, persistence, and/or partial transformation of such compounds and its potential hazardous effect. While many are readily biodegradable, others have proven to be recalcitrant and persistent in soil and water. In recent years, a great deal of research has been done on the biochemistry and genetics of xenobiotic-degrading microorganisms. Both the newer literature on biotechnology and the older literature on industrial microbiology describe important commercial processes in which microbial microorganism cultures play an important role^{2,3}.

This discussion of microbial processes of importance to scientists and engineers involved in an active remediation program on refinery sludges/solids is presented as an overview of the subject only. The primary focus is bacterial processes due to the considerable volumes of information available. However, fungal and actinomycete contributions to soil biotransformation processes/productivity are of equal importance and will be presented within the context of the discussion. Although some bacteria and fungi can cause adverse effects, most species are benign, and many are involved in processes of direct benefit to man. Most of the adverse effects are subject to control and a relatively limited number of species are pathogenic. Life on earth depends on their activity, playing an important role in the biotransformation and mineralization of organic compounds, such as the transforming of free nitrogen molecules in the air for use by plants.

MICROBIAL FORMS

Microbe/Surface Interactions

The evolution of different forms of life has resulted in many large groups which can be divided quite clearly into two categories, plants and animals, showing a variety of well-established characteristics specific to each one. Microorganisms have developed in a different way in which the "plant-animal" relationships are not always well-defined and the criteria for life has to be modified³. The majority of organisms which comprise the major microbial group are of microscopical dimensions, generally with no differentiation of tissue as in higher organisms and living in an interrelated group in nature.

Bacteria include a great variety of unicellular microorganisms of different size and shape, present in almost all natural environments, often in extremely large numbers. Bacteria are usually about 0.2 to 1.5 μm in diameter. The mean diameter is about 1.0 μm . Bacteria have rigid cell walls, as do plants, but some are motile and require organic

nutrients, as animals do.

Bacteria, along with molds, yeasts, viruses, and algae are allocated to the vegetable kingdom. Bacteria have been assigned to the Protophyta division, class Schizomycetes. The class Schizomycetes may be divided into 10 orders. The orders Eubacteriales and Pseudomonadales contain the largest number of species and include most of the bacteria important to man.

Morphology of Bacteria

Bacteria are procaryotic cells, that is they do not have a true nucleus. The procaryotic nucleus has no membrane, does not undergo mitosis, and its hereditary material is contained in a single naked DNA molecule. The procaryotic cell has none of the specialized structures found in eucaryotic cells, such as mitochondria for respiration, an endoplasmatic reticulum as an extension of the cell membrane, lysosomes containing hydrolytic enzymes, and a Golgi apparatus to transport metabolic products⁴. They are usually not photosynthetic microorganisms. On the basis of their shape, bacteria are divided into three conventional groups: cocci, bacilli and spiral forms.

The cocci are spherical or nearly so. They vary in size from 0.5 μm to 1.0 μm in diameter, and their arrangement depends on the order of successive cell division. If this is random, the organisms may occur in clusters and are called staphylococci from the Greek word for grape. When the division takes place in the same plane and the daughter cell adheres to another, chains are formed, called streptococci.

Bacilli, by far the most common, are bacteria shaped like rods or cylinders. They are about 1.0 μm to 10 μm long and 0.3 μm to 1.0 μm wide. The end of the rod appears to be rounded or square, and some tend to form chains. Spiral forms comprise a large variety of cylindrical bacteria which, instead of being straight like bacilli, are convoluted in varying degrees. Vibrios are curved rods, Spirilla are spirals with their bodies relatively rigid, and Spirochetes are also spirals but able to flex and wriggle their bodies.

Filamentous forms of bacteria are also found and these may be several hundred μm long but are usually only about 1 to 2 μm in diameter. The shape of bacteria is determined by its heredity, but some organisms may show morphological changes depending on age and certain environmental conditions.

Structure of a Bacterial Cell

It is generally accepted that all kinds of living cells have some form of outer wall or membrane, cytoplasm, and nuclear material, with each component making its own contribution to the life of the cell. The outer part of the bacterial cell is made up of three definite structures: slime layer or capsule, cell wall, and cytoplasmic membrane.

The slime layer is the outside coating of the bacterial cell. It is a

jellylike layer and may vary in thickness even in different cells of the same culture. When it becomes sufficiently thick and firm to have a form, it is called a capsule. It is usually a polysaccharide (or a polypeptide) and continually produced by the cell as a result of its metabolic activity. Its formation may depend on the presence of carbohydrate in the environment. In many bacteria, this structure is a high-molecular-weight polymer (a long molecule made up of repeating structural units) of a simple hexose sugar, such as glucose (dextran) or levulose (levans). In others, the structure is chemically much more complex, being formed of units of simple sugars (glucose, mannose, and galactose), derived sugars (amino sugars), and sugar acids (gluconic and glucuronic). The slime layer is not an integral part of the cell but a result of its metabolic activity, and consequently it is greatly influenced by the environment⁶. The capsular material confers type specificity on the organism; for example, the type of pneumonia which develops in a host depends on the molecular composition of the capsule.

The chemical composition of the cell wall varies with different bacteria. All bacteria are made up of proteins and complex carbohydrates or polysaccharides, frequently with large amounts of fat or lipids. The structural component of the cell wall is murein. The most commonly studied cell walls most studied are *Staphylococcus aureus*, a complex polymer of N acetylglucosamine (the basic structural unit in chitin from insect exoskeletons). In general, bacteria cell walls appear to be double or triple layered structures. The cell wall limits the volume occupied by the cytoplasm, providing a strong rigid structural component that can support the high osmotic pressure caused by high concentrations of cytoplasmic content in the cell. The cell wall also plays an important role in cell division and a major role in regulating the passage of various materials between the internal and external environment of the organism.

Bacteria can be divided into two large groups on the basis of a differential staining technique called the gram stain. These two groups of bacteria differ mainly in their cell walls: gram-positive and gram-negative cell walls. The gram-positive cell walls consist of 60 to 100 percent murein. Some have a glycerol type of teichoic acid located between the cell membrane and the cell wall. Gram-negative cell walls are chemically more complex, containing about 10 to 20 percent murein. There is a second structure outside of this layer composed of proteins and fatty acids linked to polysaccharides.

The cytoplasmic membrane, located just inside the rigid cell wall, is a semipermeable membrane composed mainly of proteins and lipids acting as part of the osmotic barrier between the external and internal environments of the cell, regulating the permeability of substances entering and leaving the cell. It contains many of the oxidation-reduction enzyme systems concerned with energy metabolism. The cytoplasmic membrane accounts for 8 to 10 percent of the dry weight of the entire cell, and it is chemically composed of a molecule containing a lipoprotein.

The cytoplasmic membrane always initiates division of the cell and, because of its semipermeable nature, plays an important role in controlling the passage of waste products out of the cell without permitting the cell contents to escape. The cytoplasm is the internal environment of the cell. It is a colloidal system containing salts, sugars, proteins, fats, carbohydrates, vitamins, granules, and other materials characteristic of a particular organism. The major component of living cells is water, which accounts for approximately 75 percent of the total mass of the cell. It serves as the medium in which soluble components are diffused, and it serves to hydrate large molecules whose functions depend not only on their chemical composition but on their configuration in space as well. The cytoplasm contains most of the enzymes necessary for metabolic processes of the cell and growth of the organism.

Prokaryotic cells, or cells restricted only to microorganisms, do not possess a true nucleus. The nuclear region is seen as a weakly contrasting area that contains thin fibrillar material of deoxyribonucleic acid (DNA), the genetic material of the cell. Sometimes more than one nuclear region is seen in a single cell, but each of these probably contains only a single DNA molecule.

Various inclusions have been observed in the cytoplasm, such as

granules of starch-like compounds called granulose, flat droplets, pigments, and a polymer of inorganic phosphate called volutin. Under deficient conditions these granules are broken down to provide useful energy and building blocks to the cell. When free from inclusions, the cytoplasm appears homogeneous. The cytoplasm also contains some particles called ribosomes which are part of the protein synthesizing machinery of the cell composed of ribonucleic acid (RNA) and protein. The bacteria nucleus differs from the nucleus in higher organisms because it has no membrane with only one chromosome in the form of a ring.

Many types of bacteria have the ability to move by themselves. Almost all spiral bacteria and many of the bacilli are motile. Cocci are usually nonmotile. The propulsive mechanism of motion is a threadlike appendage called flagellum, arising from within the cytoplasmic membrane, generally several times the length of the cell. Motility can be observed most satisfactorily in young cultures.

A large number of bacteria have short fibers, called pili or fimbriae, attached to their walls. These filamentous appendages, usually shorter than flagella, are composed of protein and have been found only in gram-negative bacteria. Such bacteria have more tendency to stick to each other because pili apparently are used for attachment to the surfaces. Pili can be dissociated into smaller identical subunits called pilin. This accumulated mat is referred to as a glycocalyx.

MICROBIAL FUNCTIONS

Nutritional Requirements

Microorganisms can be classified into three major groups based on the types of material used as energy sources: (1) chemoorganotrophs that use the energy of organic compounds; (2) photoautotrophs that utilize radiant energy; and (3) chemolithotrophs that oxidize inorganic molecules. Most bacteria are chemoorganotrophs.

As do other forms of life, bacteria require water, minerals, vitamins, and sources of carbon and nitrogen for much the same purposes, but in relatively smaller quantities; tap water will often meet their mineral needs. Necessary mineral ions include such trace elements as molybdenum, manganese, and cobalt. Phosphates are frequently added to a media, both as a source of phosphorus for the synthesis of nucleic acids and as a buffer for the media against excessive acidity to neutralize acids. Tables 1 and 2 list the major and minor bio-elements, respectively, their sources, and some of their functions in metabolism.

Table 1
The Ten Major Bio-Elements, Their Sources, and
Some of Their Functions in Microorganisms:
Adapted From *Bacterial Metabolism* (Gottschalk, 1979)

Element	Source	Function in Metabolism
C	organic compounds, CO ₂	main constituents of cell material
O	O ₂ , H ₂ O, organic compounds, CO ₂	
H	H ₂ , H ₂ O, organic compounds	
N	NH ₄ ⁺ , HO-3, N ₂ , organic compounds	
S	SO ₄ ²⁻ , H ₂ S, S ₀ , S ₂ O ₃ ²⁻ , organic sulfur compounds	
		constituent of cysteine, methionine, thiamin pyrophosphate, coenzyme A, biotin, and lipoic acid
P	HPO ₄ ²⁻	constituent of nucleic acids, phospholipids and nucleotides
K	K ⁺	principal inorganic cation in the cell, cofactor of some enzymes
Mg	Mg ²⁺	cofactor of many enzymes (e.g., kinases); present in cell walls, membranes, and phosphate esters
Ca	Ca ²⁺	cofactor of enzymes; present in exoenzymes (amylases, proteases); Ca-dipicolinate is an important component of endospores
Fe	Fe ²⁺ , Fe ³⁺	present in cytochromes, ferredoxins, and other iron-sulfur proteins; cofactor of enzymes (some dehydratases)

The chief vitamin requirement for bacteria is B complex. Biological assay methods based on these requirements for specific vitamins or minerals by specific strains of bacteria have been developed⁷.

The source of carbon in synthetic media is usually glucose but other carbohydrates can be used in a diagnostic test. Because few species form lipases, or enzymes capable of hydrolyzing fats, generally they do not use fats as such. However, many can utilize salts of the lower fatty acids, especially acetic and butyric acids (and other organic acids), required mainly for synthesis of cell protein⁷. For precise study of bacterial physiology, a synthetic medium made from known constituents is preferable.

The energy released by a catalyzed enzyme oxidation of carbon, whether a PAH or glucose, is accumulated in the chemical bonds of the adenosine-5- triphosphate (ATP) when formed from the addition of inorganic phosphate $H_2PO_4^-$ (Pi) to adenosine diphosphate (ADP) in a vital energy process required by all living cells called oxidative phosphorylation. Cellular processes utilize the energy of biological ATP changing back to adenosine-5-diphosphate (ADP) and inorganic phosphate in a reverse reaction (Fig. 1). The formation of phosphate bonds requires energy. The energy stored in ATP is released when the bond connecting the last phosphate is broken. The principle involved when ATP absorbs the energy given off during oxidation and transfers it to the different processes of the cell is called energy coupling and is applied to many metabolic reactions. The energy liberated in these reactions is directed primarily toward biosynthesis of cell materials (Fig. 2).

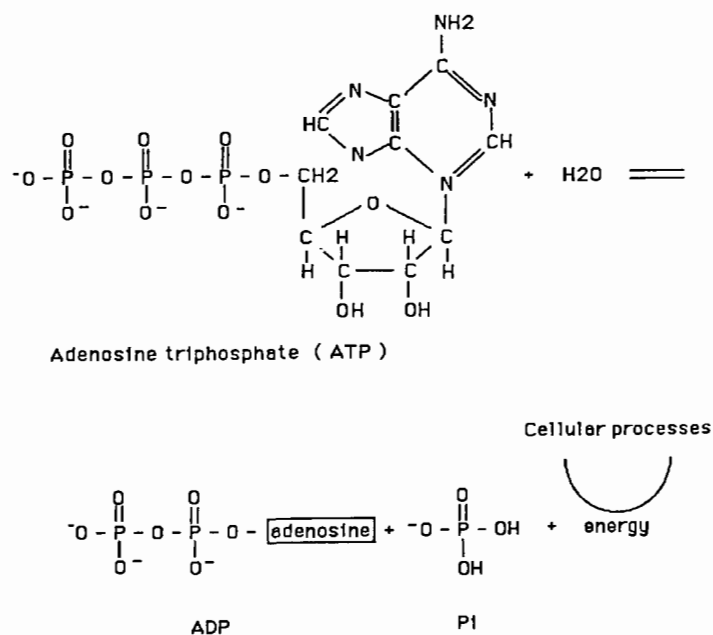


Figure 1
Reverse Reaction Between ATP and ADP

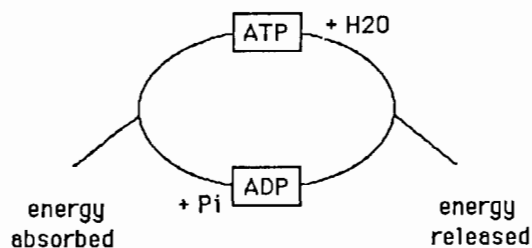


Figure 2
Relation Between Adenosine Triphosphate ATP and Adenosine Diphosphate

Adenosine triphosphate (ATP) consists of a monosaccharide called ribose to which a nitrogen heterocycle, adenine, and a triphosphate group are attached. The triphosphate group has two phosphates bonds. They work as excellent phosphorylating agents and are used as such in a large number of reactions by all organisms, activating the intermediates of cell metabolism to further reactions of condensation, cleavage, and reduction.

The chemical change in the body of living organisms depends on enzymes. The enzymes formed by a bacterial cell determine whether a bacterium can digest a complex material and use it for food. These compounds are biological catalysts that increase the rate of reaction but are not used up in the process. Enzymes are very large protein molecules that bind to the substrate, reacting chemically. Substrate is defined as the compound on which an enzyme exerts its catalytic effect. Inside each microbial cell about 4,000 to 10,000 different chemical reactions take place in order for that to grow and function⁸. Each enzyme has a special region on to which it binds, called an active site, as well as specific activity for the substrate. Certain substances known as inhibitors prevent or slow down the action of enzymes. Competitive inhibitors are molecules similar to those of the substrate. They bind reversibly at the active site, stopping the enzyme from catalyzing the reaction⁸.

Molecules involved in a reaction must have a certain amount of energy, called the activation energy. Enzymes decrease the activation energy barrier of the reaction resulting in more product in a shorter period of time. Some enzymes need an extra non-protein part essential for their functioning, called a cofactor. If the cofactor is an organic molecule it is called a coenzyme.

The utilization of O₂ as an electron acceptor is called respiration and can be measured by the uptake of oxygen gas by the respiring organism. Many respiratory reactions are fundamental for almost all forms of life, including bacteria. If free oxygen enters the reaction, it is called aerobic respiration. Atmospheric oxygen functions as the final hydrogen acceptor in the series of oxidation and reduction reactions and liberates the energy from food in the metabolic process. When O₂ accepts electrons, it is reduced to H₂O. Since enzymes are proteins and exist in living cells, certain environmental conditions, such as temperature, pH, and salt concentration, must be met in order for the enzyme to be active.

One of the most important factors affecting the rate of microbial growth is environmental temperature. There is always a temperature below which growth will not occur because of the deactivation of the enzyme-catalyzed system, as well as a maximum at which heat denaturalization will occur. Between these limits, there is an optimum temperature for bacterial growth, resulting in a very rapid increase in the rate of activation of heat-sensitive cell components, such as enzymes, ribosomes, DNA, and membranes⁴. In general, an increase in temperature produces increased molecular motion which promotes more rapid bacterial growth. Most enzymes experience their optimum activity at a temperature between 20°C and 30°C.

The hydrogen ion concentration (i.e., the acidity or alkalinity) of the solution markedly affects the activity of an enzyme. Some enzymes are active at rather low acid pH values, pH 3 to 4, while others may be active at alkaline pH values as high as 11 or 12. The majority of bacteria (whole cell) prefer a neutral medium neither markedly acid nor alkaline, demonstrating a maximum activity in the range of pH 6 to 8.

Additional concentrations of sodium chloride have been shown to increase bacterial growth by increasing the osmotic pressure up to an optimal point. However, when the concentration is too high, osmotic pressure is raised to a level that inhibits bacterial growth.

Reproduction of Bacteria and Population Growth

Sexual reproduction has been demonstrated in only a few bacteria; they are, for the most part, asexual. Bacteria multiply by an elongation of the cell, followed by a division of the enlarged cell into two cells by a vegetative process called binary fission. Although bacteria can vary in size, they retain their unicellular structure, and the primary definition of bacterial growth is reflected in an increase in the number of individuals. When a bacterial cell grows and divides, the final out-

come is two cells where there was one. Cell division requires the doubling of all cell constituents and their orderly partitioning into two daughter cells. For this process to be completed, therefore, every atom and molecule in the parent cell has to be duplicated and then inserted into its correct place in the developing structure that will eventually become the mature daughter cell.

Under favorable conditions almost all bacteria are able to reproduce very rapidly. Nuclear division is the first step, followed by the division of the cytoplasm into two equal portions separated by an inward growth of the cytoplasmic membrane. A cross wall then divides the cell, providing each daughter cell with a complete cell wall, followed by the final step which separates the sister cells, right after the cell wall is formed. Some bacteria do not separate easily and form chains. When long chains are formed, they appear to be rough or wrinkled because of the resistance to their continued elongation⁶.

Growth of a single cell with an orderly increase in the constituents of the cell is going on all the time, while multiplication is only occurring at the instant of the division⁴. When bacteria are inoculated in a suitable medium and incubated under optimum conditions, the population of bacteria generally increases through several well defined steps (Fig. 3) in a predictable manner.

Reproduction usually does not begin immediately. If conditions are favorable, a period of adaptation to the new environment is required by the organisms to begin their growth. This is called the lag phase and its duration usually varies from an hour to several days depending on the type of bacteria, the age of the culture, and the available nutrients provided in the medium. This period is characterized by the lag in multiplication only since the cells are very active metabolically (Fig. 3).

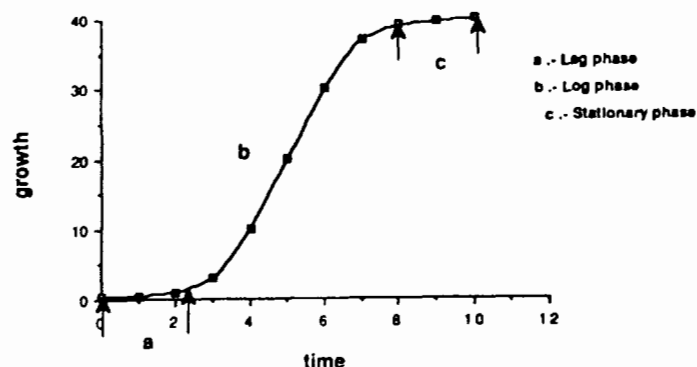


Figure 3

A Common Form of Bacteria Growth Under Favorable Conditions

Following the lag phase is the period of most rapid reproduction in which the typical characteristics of active cells are observed. This is the period of exponential growth. Individual cells grow approximately linearly with time, while the population of cells grow exponentially, doubling at each period of cell division. It is the phase of a constant and rapid generation time, called the log phase.

When rapid growth is halted by exhaustion of nutrients, a deficient supply of oxygen or an accumulation of toxic end product, growth declines to a point where the number of cells remains constant. This is called the stationary phase. During this phase the cells remain in a state of suspended animation. The length of the stationary phase depends upon favorable conditions and the specific microorganism. Unless the cells are transferred into a new environment capable of supporting continued growth, they will eventually die. This death phase in old cultures often becomes exponential in a repeated process until no cells remain.

Kinetics of Bacterial Growth

When the logarithm of the number of cells is plotted versus the time of growth, a straight line results. The rate of exponential growth is usually expressed as the generation time, or doubling time, which is the time it takes for the population to double⁷. Bacterial cells can be

maintained in the logarithmic phase by continually transferring them to a fresh medium of the same constitution. The process can be continued automatically by using a chemostat⁸.

The generation time of an organism can be determined during the log phase. At this period, some cells are just beginning to divide, others are half divided, and still others are finishing division. Each generation results in a doubling of the cell number. With this information, the following can be used to calculate the generation time:

B_0 = number of bacteria at beginning of time interval

B_t = number of bacteria at end of any interval of time (t)

g = generation time, usually expressed in minutes = time, usually expressed in minutes

n = number of generations

$B_t = B_0 \times 2^n$

By taking the logarithms of both sides of the equation, we find

$$\log B_t = \log B_0 + n \log 2$$

Solving for n yields

$$n = \frac{\log B_t - \log B_0}{\log 2}$$

Since by definition

$$g = \frac{t}{n}$$

and

$$n = \frac{t}{g}$$

Substitution generates the following equations:

$$\frac{t}{g} = \frac{\log B_t - \log B_0}{\log 2}$$

then

$$g = \frac{t \log 2}{\log B_t - \log B_0}$$

Generation time depends on the type of organism, concentration of available nutrients, temperature, pH, and oxygen. In general, species multiply rapidly when provided with favorable conditions⁹.

MICROBIAL PROCESSES

The Concept Of Biotransformation/Biodegradation:

Polycyclic Aromatic Hydrocarbon Degradation As A Case Study

Introduction

Microbial metabolism of hydrocarbons has been reported in the literature for several decades. Some of the first investigations date back as early as 1928, when Gray and Thornton¹⁰ first reported soil bacteria capable of decomposing certain aromatic compounds. In 1941, Bushnell and Haas¹¹ documented microbial degradation of certain hydrocarbons. Sisler and Zobell¹², in 1947 used microorganisms of marine origin in their experiments to degrade aromatic hydrocarbons. They studied the utilization of polycyclic aromatic hydrocarbons (PAHs) by mixed cultures of marine bacteria. PAHs were introduced into seawater cultures adsorbed to ignited sand. The amount of PAH metabolized by the bacteria was determined by measuring the amount of carbon dioxide evolved in hydrocarbon oxidation and subtracting carbon dioxide produced by the control cultures. In these experiments, phenanthrene and anthracene were metabolized more rapidly than naphthalene, benz(a)anthracene, and dibenz(a,h)anthracene¹³.

In the present decade, it is well known that hydrocarbons are ubiquitous in the environment and even found in relatively pristine areas. Their sources are of natural as well as anthropogenic origin. Due to

the toxicity, mutagenicity and carcinogenicity that many of them exhibit after undergoing metabolic activation, hydrocarbons in the environment may pose a hazard to the biota and, ultimately, to human health¹³. Major environmental fate/transport mechanisms include:

- evaporation (volatilization)
- photochemical oxidation
- sedimentation
- microbial degradation

Of these, microbial degradation is the area most extensively studied and commercialized as evidenced by the most recent developments in biotechnology and genetic engineering. It is a major mechanism for compound removal from sediments and terrestrial systems. Microbial degradation of aromatic hydrocarbons by bacteria as well as fungi has been documented in numerous publications. The degradation processes are generally inversely proportional to the ring size of the respective PAH molecule. The lower weight PAHs are degraded more rapidly, while molecules with more than three condensed rings generally do not serve as amenable substrates for microbial growth²⁴, hence, the effectiveness of creosote as a wood preservative.

Aromatic and Aliphatic Hydrocarbons

The capacity of microorganisms to grow in a given habitat is determined by their ability to utilize the nutrients in their surroundings¹⁴. Among the energy sources available to be utilized by soil heterotrophic microorganisms are cellulose, hemicellulose, lignin, starch, chitin, sugars, proteins, hydrocarbons and various other compounds¹⁴. Numerous hydrocarbons, or their derivatives, are naturally synthesized within the soil while others are added to the soil from various pollution sources. Their mineralization and formation by the indigenous microflora are a fundamental component in the general carbon cycle¹⁴.

The three major types of microbial metabolism are: fermentation, aerobic respiration and anaerobic respiration^{15,16}. Aerobic respiration plays the most important role in the transformation of PAHs. Very little anaerobic respiration of PAHs has been reported. However, anaerobic biodegradation of PAHs has been observed where suited electron acceptors were supplied¹⁷. Aerobic respiration initially involves the incorporation of molecular oxygen in the hydrocarbon molecules. The hydrocarbons are then converted to more oxidized products. Energy produced during these oxidation processes is partially used in the synthesis of protoplasmic constituents¹⁵.

Definition

Hydrocarbons are compounds containing carbon and hydrogen.

Aliphatic hydrocarbons are straight or branched chain hydrocarbons of various lengths. Aliphatic hydrocarbons are contained naturally in waxes and other constituents of plant tissues as well as in petroleum or petroleum products. Their transformations are therefore of great significance in the terrestrial carbon cycle¹⁴. The rate of their decomposition is markedly affected by the length of the hydrocarbon chain¹⁴.

Aromatic hydrocarbons contain the benzene ring as the parent hydrocarbon. Several benzene rings joined together at two or more ring carbons form PAHs. The toxicity of these molecules is determined by the arrangement and configuration of the benzene rings. The hydrogens in the aromatic hydrocarbons may or may not be substituted by a variety of groups. Some of the common substituents are -Cl, chloro; -Br, bromo; -I, iodo; -NO₂, nitro; -NO, nitroso; and -CN, cyano⁶⁰.

Sources and Formation

Most of the aromatic hydrocarbons are initially formed by the pyrolysis of organic material¹⁵. In this process, the temperature determines the type of compound formed. For example, unsubstituted PAHs are formed at high temperatures (2,000 C) whereas alkyl-substituted molecules predominate at 80-150 C. The latter temperature range is usually associated with the formation of petroleum¹⁵. Generally, PAHs are formed when organic material containing carbon and hydrogen is subjected to temperatures exceeding 700 C, which is the case in pyrolytic processes and with incomplete combustion¹⁶. Some common sources associated with incomplete combustion are cigarette smoke, automobile exhaust, and industrial processes.

The higher the number of joined benzene rings, the lower the rate

of degradation. The very high molecular weight PAHs are less significant in environmental pollution problems, due to their low volatility and solubility¹⁶. The growth rates of bacteria on PAHs are directly related to the solubilities of the PAHs¹⁶. Solubility and relative adsorbance are the most important physical properties that influence the rate of transformation. Among the chemical properties, photochemical reactivity is the most relevant. Tricyclic or larger PAH and related heterocyclic systems show a very reactive photochemical behavior. They have strong UV adsorption at wavelengths longer than 300 nm (present in solar radiation) and most are readily photo oxidized. Photo oxidation plays one of the major roles in the removal of PAHs from the environment^{17,18,19}. Adsorbed PAHs are photo oxidized more rapidly than dissolved PAHs¹⁶.

The chemical structures of some of the major aromatic hydrocarbons are shown well known¹⁵. Biological activity of these compounds depends on their inherent stereochemistry. The addition of another benzene ring in a select position of the compound can result in the formation of a powerful carcinogen, even if the parent compound does not exhibit much toxicity²⁰. The reactive sites of the molecules are called "Bay-regions"²⁰. Such a Bay region is found in phenanthrene, the simplest PAH. It resembles that of benz(a)-anthracene and benz(a)pyrene, and is the region between an angular benzo ring and the rest of the molecule^{21,22}. If dihydrodiol-epoxides are formed in this region, the molecule becomes very biologically reactive and is suspected to be a ultimate carcinogen. The primary active carcinogen is usually in the form of a diol epoxide²¹. Phenanthrene itself has been shown to be inactive or only slightly mutagenic in *Salmonella* assays, but its metabolites may be highly mutagenic and tumorigenic²².

Historically, it was believed, that a certain area, called the "K region" was related specifically to the carcinogenic potential of a hydrocarbon compound. Evidence now suggests that activation of PAHs is not likely associated with this K region, but rather occurs via a two step oxidation with the eventual formation of dihydrodiol epoxide²⁰. Another portion of the molecule, called the "L region" can increase the carcinogenic potency of the molecule, if there are substituents on these positions (i.e., the 7 and 12 carbons in benz(a) anthracene-²⁰.

Microbial Metabolism of Hydrocarbons

There are various and controversial scenarios reported in the literature as to the physical form under which the hydrocarbons are metabolized. Some studies indicate the presence of large hydrocarbon droplets, others mention micro-drops as small or smaller than the microbial cells, still others suggest the importance of the water soluble fraction (WSF) or the utilization of the hydrocarbons in a vapor phase²³. There are also reports on the importance of emulsifying agents for initiating hydrocarbon utilization. However, most reported microbial hydrocarbon metabolism processes are intracellular oxidation processes²³.

Historically, most of the investigations of PAH biodegradation were concerned with measuring the amount of CO₂ produced or the fractions of the toxicants (parent molecule) converted into CO₂. In these early studies, CO₂ production was the major focus of attention with little consideration paid to the intermediates formed. Only recently has it been recognized that there is a need to investigate these metabolites and the ratio of polar compounds to CO₂. The oxygenated polar compounds may be highly mutagenic and/or accumulative in the aquatic/terrestrial environment and thus be dangerous to living cells. Recent advances in analytical techniques (such as Thin Layer Chromatography and/or MS) have revealed the subtle complexity of biotransformation intermediates and end products.

Bacterial Transformation (Biotransformation)

Bacteria are the dominant group involved in the degradation of PAHs. The most widely occurring species are *Pseudomonas*, *Myobacterium*, *Acinetobacter*, *Arthrobacter*, *Bacillus* and *Nocardia*¹⁴. Bacteria can oxidize PAHs ranging from the size of benzene to benzo(a)pyrene. For more highly condensed PAHs, there is little evidence of bacterial oxidation¹⁵.

The mechanisms used by bacteria for the introduction of hydroxyl moieties into PAHs will depend on whether the substrate contains alkyl

substituents¹⁵. The initial step of aromatic metabolism consists of the modification or removal of substituents on the benzene rings and the introduction of hydroxyl groups¹⁷. The first metabolites of unsubstituted PAHs created by bacteria are *cis*-dihydrodiols, formed by the incorporation of two atoms of molecular oxygen. Fungi, in contrast, form *trans*-dihydrodiols. The enzymes catalyzing these processes are oxygenases, known as cytochrome P₄₅₀ enzyme complexes. Bacteria use dioxygenases, a multi-component enzyme system consisting of a flavoprotein, an iron-sulfur protein, and a ferredoxin¹³.

Although, initial phases of the degradation pathways differ, the reactions proceed such that only a few common and key intermediates are produced. These few are then metabolized by essentially similar processes. Most common of these intermediates are catechol, protocatechuic acid, and to a lesser degree, gentisic acid¹⁴. These three molecules have in common the presence of two hydroxyls. The products of these reactions, namely pyruvate, fumarate, and succinate may then be incorporated in the TCA and other biochemical cycles. The degradation pathways involved are dictated by the site of cleavage of the aromatic nucleus.

Naphthalene and its alkylated homologs are among the most water-soluble and potentially toxic compounds in petroleum. The product of bacterial oxidation of naphthalene is catechol. There are also different pathways for the bacterial oxidation of phenanthrene¹⁸. Oxidation of this compound by fungi has not been reported. Special interest has been paid by various researchers to the degradation of anthracene and its derivatives. These compounds are not acutely toxic, but possess a structure also found in other carcinogenic PAHs¹³. Degradation of anthracene has been reported by bacteria as well as fungi and follows the general degradation pattern of the other PAHs.

Fungal Transformation (Biotransformation/biodegradation)

Many fungi cannot grow with PAHs as a sole source of carbon and energy, but still have the ability to oxidize these compounds¹⁹. Fungi carry out reactions similar to mammals in the degradation process. Therefore, fungi are often used as model systems. Their enzyme systems for the oxidation of PAHs differs from that of bacteria (e.g., mono-oxygenases) and is similar to that of higher organisms. The cytochrome P₄₅₀ mono-oxygenase system catalyzes the initial steps in the oxidation of these lipophilic PAHs. Many fungi add hydroxyls to the ring structures without being able to open the ring, but subsequent ring opening and cleavage of ether bonds can then be brought about through cometabolic conversions²⁰. Cometabolism is defined as the metabolism of a compound by a microorganism that the cell is unable to use as an energy source or source of growth²¹. An example for a fungal metabolic pathway quite similar to those in mammalian systems for the oxidation of naphthalene is given by Doull^{20,21}. In contrast to bacteria, fungi incorporate only one atom of molecular oxygen into naphthalene via a cytochrome P₄₅₀ mono-oxygenase¹⁹.

BIOKINETICS OF PETROLEUM HYDROCARBONS IN SLUDGES/SOILS IN A BIOLOGICAL CONTACT UNIT (BCU)

Introduction

The following section reviews the results of data sets generated in a laboratory/field pilot test of a biological contact unit for the semi-continuous treatment of petroleum hydrocarbons. Investigations were carried out in a multiple-task effort to achieve, by microbiological methods, detoxification of contaminated soils at an abandoned petrochemical facility along the Mississippi River. This facility, designated a CERCLA/SARA site by state and regional environmental agencies, presented particular difficulties using non-biological conventional methods in accomplishing remediation due to close proximity to the flood protection levee (dike) system of the river. Waste materials, consisting primarily of aliphatic and polycyclic aromatic hydrocarbons (PAH's) found in buried soil/sludges and lagoon wastes were examined. Optimal toxicant loading levels were evaluated on the basis of

biodegradative potential tests and acute toxicity of leachate.

Microbial ATP and microbial diversity were used in conjunction with the Microtox™ Test to establish an acceptable land treatment experimental design. The biodegradative potential of the microbial consortium was evaluated using laboratory mesocosms (phase II) at a predetermined optimal waste loading rate, based on percentage oil and grease (O&G), mixed with a predetermined optimal soil mixture of river silt and sandy clay (one part river silt : two parts sandy clay). Experimental mesocosms were inoculated with an adapted indigenous microflora. Microbial ATP, microbial diversity and the Microtox™ test were used to establish the detoxification efficiency. Quantitative toxicant concentrations and transformations were documented by GC/MS methods. GC/MS data in phase II studies (mesocosms) and phase III studies (field verification studies) documented substantial biotransformation and biodegradation of the wastes at these optimized loading rates.

The hazardous waste site investigated was located on the East bank of the Mississippi River near Darrow, LA. The site was designated as a priority site for Superfund assistance in April, 1982, scoring highest out of the five qualifying sites in Louisiana, with 48.98 on the EPA Superfund list. This abandoned oil reclamation facility, the Inger Oil Refinery, was operated between 1967 and 1978. Waste oils were brought to the site by barge and truck, re-processed in cracking towers by heating, with produced final products being transported from the facility by truck. As part of plant operations, sludges were stored in large, open lagoons and/or buried shallow pits. Some wastes were spilled into an adjacent swamp in March 1978, contaminating a total of 16 acres of the surrounding area. This spill was associated with the unloading of used oil from a barge in the Mississippi River. A shut-off valve failure or human error led to overtopping a tank and a containment area. Failure by the owner to clean up the site resulted in the formal declaration by the Louisiana Environmental Control Commission in June, 1981, that the site was abandoned.

The site occupies about sixteen acres, including a 7.5 acre swamp. The most highly contaminated wastes are found in the tanks, lagoons, and diked containment areas. Contamination is found to a depth of three to five feet in the areas of the closed lagoon and filled portions of the swamp. Swamp sediments are less contaminated. The wastes identified at the site were consistent with the nature of the oil reclamation plant. They were mixtures of refinery oils, motor oils, and lubricating oils. As is typical of waste oils, hazardous priority pollutants such as benzene, toluene and PAH's were present. No PCB's were found; very low levels of chlorinated hydrocarbons and low levels of heavy metals were found.

The site soil consists predominantly of silty and sandy clays, silts and fine sands, to a depth of about 115 to 125 feet²². Below this is a substratum silty sand, a potential water supply source. The average vertical and horizontal permeability is about 1×10^{-3} cm/sec (10 ft/year). Groundwater was encountered generally at a depth of six to twelve feet, however rising to within a few feet of the ground surface. Trace amounts of some hazardous compounds had migrated vertically through the site soils to depths of 20 feet or more. Trace amounts (parts per billion) were found in the groundwater at the site to a depth of 75 feet. The potential for continued vertical and horizontal migration of hazardous compounds exists.

Pure wastes were classified as "buried waste" and "lagoon waste" with the river silt (control) for all laboratory and field tests²⁴. All were collected from the site and analyzed prior to waste application as determined by GC and GC/MS. About 24 polynuclear aromatics (PNAs) were identified (F-2 fraction) and 22 aliphatic hydrocarbons (F-1 fraction)²⁴. Quantitation was by external standard GC in all cases. Some analyses were semi-quantitative due to problems in obtaining accurate external standards. Large dilution factors necessary to prevent GC detector saturation also contributed to variability in waste analysis. Detection limits for both fractions was 10 ppm due to the large dilution factors and the lower response factors of the higher molecular weight components. The detection limit for the control soil, however, was 1 ppm.

Optimal toxicant loading rates, determined in earlier screening tests, were shown to be acceptable for inducing microbial biotransformation/biodegradation in laboratory mesocosms and field application plots with minimal acute leachate toxicity. In the above studies, all compounds

Table 2
Minor Bio-elements, their Sources, and Some of their
Functions in Microorganisms
[Adapted from *Bacterial Metabolism* (Gottschalk, 1979)]

Element	Source	Function in Metabolism
Zn	Zn ²⁺	present in alcohol dehydrogenase, alkaline phosphatase, aldolase, RNA and DNA polymerase
Mn	Mn ²⁺	present in bacterial superoxide dismutase; cofactor of some enzymes (PEP carboxykinase, re-citrate synthase)
Na	Na ⁺	required by halophilic bacteria
Cl	Cl ⁻	present in nitrate reductase, nitrogenase, and formate dehydrogenase
Mo	MoO ₄ ²⁻	
Se	SeO ₃ ²⁻	present in glycine reductase and formate dehydrogenase
Co	Co ²⁺	present in coenzyme B ₁₂ -containing enzymes (glutamate mutase, methylmalonyl-CoA mutase)
Cu	Cu ²⁺	present in cytochrome oxidase and oxygenases
W	WO ₄ ²⁻	present in some formate dehydrogenases
Ni	Ni ²⁺	present in urease; required for autotrophic growth of hydrogen-oxidizing bacteria

analyzed exhibited decreases in concentration over time for both laboratory and field tests. The decreases were mostly attributed to microbial activity by the indigenous soil microflora. However, undefined abiotic losses were noted and need to be further studied. Both waste types, the lagoon and buried wastes, at loading rates of 2.5% and 4%, were degraded by the indigenous microflora. Microtox™ data suggested, that time periods between sequential reloadings need to be carefully evaluated and adjusted according to environmental parameters to prevent downward leaching of organic constituents.

Analyses of mesocosm data provided indications of the biotic and abiotic factors affecting toxic chemical breakdown in field studies. Comparisons of toxicant half-life estimates of targeted waste toxicants in mesocosm tests and field validation tests is shown in Table 3 and Table 4.

Addition of Commercial Inoculum

In addition to investigations of the biotransformation processes by autochthonous microflora, it was of special interest to evaluate the use of a commercially available blend of bacterial cultures. These commercial cultures are marketed for their known ability to biodegrade polynuclear aromatics. Their application is referred to by the supplier as "bioaugmentation." The inoculum used in the experiment was purchased from Microbe Masters, Inc., Baton Rouge, LA. Three of the 9 mesocosms were inoculated with the commercial bacterial blend at the suggested rate of 0.01 lb/ 4.5 kg soil mixture and contained waste at 4% load plus the inoculum.

The commercial inoculum showed an enhanced degradation rate for these compounds over the first 14 days of the experiment. The rate of degradation was almost linear for the observed time period. The autochthonous or adapted mesocosms at the 4% load again exhibited an initial lag phase of biotransformation, indicative of some microbial acclimation to the waste loading. Minimal degradation was observed over the first 14 days of the experiment. Following day 14, however, there was an increase in toxicant degradation rates. Biotransformation rates, at concentrations at or approaching 40% residual of the original toxicant addition for both autochthonous and commercial inoculum, were similar. However, these rates were noted for commercial mesocosms on day 7 and autochthonous microcosms at day 28. This was directly attributable to relative viable biomass contributions. Commercial inocula exceeded autochthonous levels during the first two weeks of the study. Final residual concentrations for both inocula were similar. Half-life estimates for compound disappearance for all mesocosms are summarized in Table 3.

At the conclusions of field investigations, noticeable variation in biotransformation/degradation by the commercially available mutated bacterial cultures over the autochthonous microflora was evident. Residual levels for 4% O&G loadings

Table 3
Residual Concentrations of Toxicants in Mesocosms

Mesocosm	Toxicant(Load*)	Residual*	Half-Life°
2.5% O&G (autochthonous)	Acenaphthalene(20) Anthracene(97) Phenanthrene(138)	0.2 (1.0) 4.2 (1.0) 1.3 (1.5)	6.94 5.31 4.67
4.0% O&G (autochthonous)	Acenaphthalene(46) Anthracene(118) Phenanthrene(167)	3.6 (1.1) 12.1 (1.0) 6.6 (1.5)	19.72 18.91 14.36
4.0% O&G (autochthonous)	Acenaphthalene(43) Anthracene(154) Phenanthrene(142)	Adjusted Adjusted Adjusted	7.14 4.98 5.01
4.0% O&G (commercial)	Acenaphthalene(57) Anthracene(149) Phenanthrene(202)	0.4 (1.0) 4.6 (1.1) 5.5 (1.5)	6.47 4.65 4.32

* expressed as mg/kg dry weight soil (based on GC/MS)

° expressed in days

Adjusted: correction for acclimation to waste loading

Table 4
Residual Concentrations of Toxicants in
Field Verification Study

Field Plots	Toxicant(Load*)	Residual*	Half-Life°
4.0% O&G (autochthonous)	Acenaphthalene(66) Anthracene(235) Phenanthrene(288) Phytane(131)	2.9 (1.1) 11.8 (1.0) 5.9 (1.0) 26.8(1.0)	17.24 14.98 15.01 19.66
4.0% O&G (allochthonous)	Acenaphthalene(48) Anthracene(212) Phenanthrene(290) Phytane(144)	1.9 (1.1) 6.8 (1.0) 0.9 (1.0) 13.7(1.0)	9.24 8.98 12.01 10.66

* expressed as mg/kg dry weight soil (based on GC/MS)

° expressed in days

are shown in Table 4. Specific toxicants were biotransformed at different rates and reflected not only loading rates (%O&G) but also inoculum source. Correcting for acclimation by the indigenous microflora at 4% O&G, economic differences in microbial populations are then seen. Thus, commercial inocula would appear to be effective in site remediation from two perspectives: (1) the inocula used in this study was technically viable in achieving acceptable rates of toxicant biotransformation; (2) although autochthonous (adapted) populations were equally effective, an acclimation period must be considered for initial waste loading, i.e., the commercial inocula provides a commercially significant advantage in kinetics performance.

A decision to proceed with site remediation, using a modified biotreatment approach, was approved by state and federal environmental agencies. Post-closure monitoring of soils and leachate collected from the site was recommended for a time period of 30 years after completion of soil biotreatment.

BIOKINETICS OF PETROLEUM HYDROCARBONS IN SLUDGES/SOILS IN A LIQUID SOLIDS CONTACT REACTOR

Introduction.

The five-ring polynuclear aromatics and related compounds are known to exist in many sludges, contaminated soils, and contaminated slurries of materials having significant hydrocarbon content. Of particular concern to state and federal agencies are the benzo(a)pyrene, benzo(a)anthracene, and chrysene found in chloroaliphatic wastes such as creosote waste materials, particularly those materials containing high oil and grease concentrations¹⁴. To document to EPA biokinetic data on these and other PNAs of concern, liquid /solids contact (LSC) reac-

tors, were constructed and placed in an environmentally closed laminar flow hood and inoculated with acclimated microbial populations developed in earlier pentachlorophenol studies¹². Specific measurements included microbial ATP for the determination of microbial biomass¹³, parent compound disappearance, contribution of incident UV light on photolytic decomposition processes, and post-treatment residual determinations of dioxins using GC/MS. Particular emphasis was on following the degradative pathway of benzo(a)pyrene in creosote sludges.

Each unit consisted of a 1,000-ml reaction vessel in which toxicants or substrates were introduced via peristaltic pump. Temperature was maintained by a heat lamp system regulated by a proportional indicating temperature controller. The pH/Eh of the reaction vessel was maintained by a series of controllers connected to the peristaltic pumps or gas regulators. Samples were withdrawn aseptically from the reaction vessel by means of micropipet or syringe. Samples consisted of aqueous slurries, grab-sampled from reactor vessels, at periodic intervals. Contents of the agitated reactors were presumed to be homogenous suspensions. However, all calculations of toxicant residuals were determined on a dry weight basis.

LSC Creosote Studies Roughing Cell Reactor and Biotreatment Reactor Tests

At the conclusion of initial abiotic and biotic tests on PAH wash waters, contaminated creosote waste was suspended in LSC reactors over a seven-day period followed by a 14-day biotreatment test. This seven-day roughing step provided indications of mixing phenomena for creosote, predominantly K001 constituents, and also provided indications of fate of percent ring PNAs associated with these wastes. After seven days of high energy contact, the supernatant was transferred to a polishing biological reactor cell where additional biological treatment was again performed for a 14-day period. Over these time frames, GC/MS determinations were made of the primary K001 constituents as well as the chlorinated dioxin and chlorinated furan contaminants.

To identify microbial contributions to PNA degradation, two approaches were considered. Sterile L/S contact tests were conducted using the aforementioned laboratory approach. Antibiotics were used to hinder microbial growth and kinetic response. Comparisons were made between abiotic and biotic tests for targeted removal.

Biotransformation Of Creosote Waste K001 Constituents

Figures 5 and 6 provide information on the residual levels of key K001 constituents for all reactors for roughing cell and biological treatment. The roughing step involves the actual resuspension and solubilization of creosote and pentachlorophenol materials over a seven-day period.

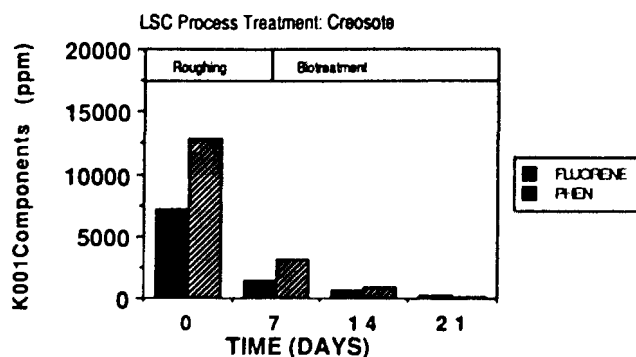


Figure 5
K001 Biotransformation

This key initial step forces the solubilization of the K001 constituents as a result of the addition of surfactant (Triton X100, Sigma) and pH adjustment (to 7.3) resulting in the increased availability of these materials for biological attack.

The data presented show high concentrations of fluorene, phenanthrene, and fluoranthrene for initial waste loading. Reactor cell #1 had the highest levels of these K001 constituents in concentrations exceeding 7,000 ppm. Reactors cells #2 - #4 had concentrations approaching 8,000

ppm or less with the exception of phenanthrene, averaging 15,000 ppm. It is important to note that the initial concentrations varied in terms of chemical content, however, they all represented a 20% loading rate based on solids for all reactors. With combined microbial addition and surfactant addition, the residual level for fluorene, phenanthrene, fluoranthrene, and pyrene were greatly reduced after seven days of continuous aeration and agitation.

Residual concentrations from this roughing cell step, which is then normally transferred to a polishing reactor step, averaged in concentration between 500 and 4,000 ppm with phenanthrene appearing to be the most resistant to the continuous agitation over a seven day treatment period. In reactor test #3, minimal microbial levels were noted as determined by direct plate counts and microbial ATP estimates. As a consequence of this, minimal removal levels for all K001 constituents were noted. In particular, pyrene and chrysene resulted in negligible biodegradation. Phenanthrene was marginally reduced from 13,000 ppm to approximately 10,000 ppm. Fluoranthrene and fluorene appeared to be the most significantly reduced of the K001 constituents.

Reactor #1, having the highest K001 constituents loading rates, had the greatest reduction in total hydrocarbon content. In particular, pyrene and chrysene were more dramatically reduced in reactor cell #1 as compared to reactor cell #3. High biomass levels were noted in reactor cell #1. Microbial ATP levels exceeded 10^9 cells per ml for continuous treatment. For final biological treatment, phenanthrene and fluorene were both significantly degraded to below 100 ppm residuals within 21 days. Fluoranthrene and pyrene were reduced to levels below 500 ppm over the same time frame.

Carcinogenic PAHs

Figure 7 provides information on the initial and final concentrations of key five-ring polynuclear aromatics found in creosote/pentachlorophenol waste materials. Of particular interest is the benzo(b)fluoranthrene and benzo(a) pyrene constituents of these wastes. As in the previous data sets on K001 constituents, reactors #1, #2 and #4 provided significant reduction in the five-ring polynuclear aromatics. Reactor cell #1, having the highest accumulated biomass, indicated the greatest reductions to < 500 ppm for all constituents. Reactor cell #3 which experienced incomplete mixing showed negligible reduction in the benzo(a) pyrene. Note in particular that benzo(b) fluoranthrene was not significantly reduced during this 7-day mixing step. With biological treatment, notable reductions were seen for all 5-ring PNAs. However, as was noted previously, benzo(b) fluoranthrene was not as significantly reduced as the other PNAs.

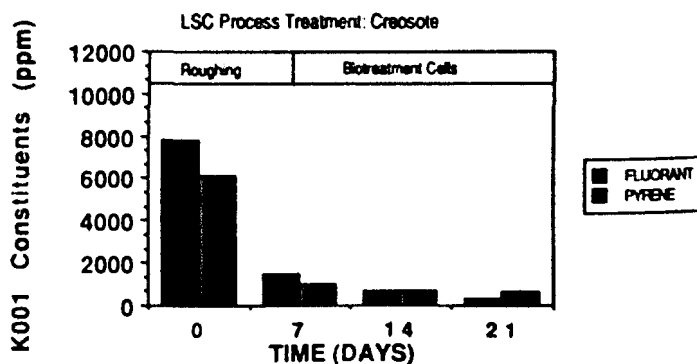


Figure 6
K001 Biotransformation

Summary

Table 5 provides kinetic expressions for LSC biotreatment of highly concentrated PAHs.

LSC Rationale

Optimal mixing of PAH waste materials such as creosote can result in significant reductions in K001 constituents. Reactor cell #3 had minimal performance in K001 reductions. This correlated with poor

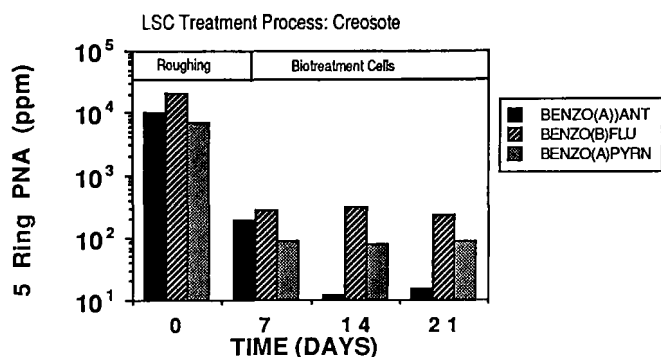


Figure 7
Biotransformation of Carcinogenic PAHs

Table 5
Biokinetic Rates of K001 Reductions in LSC Reactors

K001 Constituent	Initial Concentration(ppm)	Rate (mg/kg soil/day)
Phenanthrene	13,000(mean)	584.8
Fluorene	7,200(mean)	316.6
Fluoranthrene	8,000(mean)	367.4
Pyrene	6,000(mean)	261.9
Benzo(a) pyrene	9,000(mean)	366.7
Benzo(b)fluoranthrene	13,300(mean)	595.2
Benzo(a)anthracene	11,000(mean)	521.4

Mean values are based on 4 replicate LSCs for each experimental and control test and 3 GC sample analyses for each day sampled.

microbial performance and mixing. Thus, a key component in the ability to biologically transform these materials rests with the ability to sufficiently mix and suspend by wet weight the creosote materials in question. In subsequent investigations not reported here, more optimal mixing of the K001 materials was achieved with a reconfiguration of the reactor cell. This reactor cell includes baffle systems to prevent settling and incomplete mixing. Rates of K001 disappearance responded to this improvement in reactor design.

BIOTRANSFORMATION OF POLYNUCLEAR AROMATICS. GEOCHEMICAL INFLUENCES IN REFINERY BIOREMEDIATION

The Requirement For Some Metals By Microorganisms.

Very low concentrations of certain metals are required by all microorganisms for normal cellular functioning. These include potassium, magnesium, manganese, calcium, iron, cobalt, copper, zinc, and molybdenum. For example, copper zinc and molybdenum are constituents of specialized enzymes. Cobalt is found in vitamin B₁₂ and its coenzymes. Magnesium, iron, manganese, calcium and potassium are also enzyme cofactors²⁴. Of these metals, copper, iron, potassium, and magnesium are required to a greater degree than the others, which are usually required only in trace amounts. These micro-nutrients are often, in fact, toxic at high concentrations²⁵. Cadmium, however, has no known metabolic role.

Metal Toxicity and Microorganisms

High levels of heavy metals in the environment are usually toxic to microorganisms. Some microorganisms may even be affected by quite low concentrations of particularly toxic metals. For the overall cell population toxicity may manifest itself as a drop in cell numbers due to cell death, bacteriostasis, or extension of the lag phase of the cell cycle²⁵. If bacteriostasis, or a lengthened lag phase occurs, cell metabolism is interfered with, but not severely enough to cause cell death. Heavy metal toxicity may also manifest itself in altered cell morphology²⁶. The toxic metal is likely to interfere with transport systems within the cell²⁷. This may be a result of interference with cell function by protein denaturation²⁸, disruption of enzyme structure, and

disruption of DNA²⁵.

In general, the toxicity of a heavy metal is determined by its degree of attraction to natural metal binding sites on and within the cell. The similarity in chemistry of some heavy metals to other elements required for cellular functioning may result in some being actively accumulated within the cell. In general, the ability of a toxic metal to penetrate through to the cell cytoplasm is a significant measure of its potential toxicity²⁵. However, metal toxicity is mediated by several factors. The nutritional state of the organism may alter toxicity as cells in a nutrient-depleted environment are often more susceptible to metal toxicity. Environmental factors heavily influence heavy metal toxicity and some of these are reviewed below.

Influence of the Environment On Metal Toxicity

The presence of metal-chelating compounds, other ions, and pH of the environment all affect the toxicity of heavy metals to microorganisms. Other cations, particularly those of similar ionic radii, can decrease toxicity due to competition for binding sites^{25,28,29,30}.

Low pH, (i.e., high hydrogen ion concentration) reduces metal toxicity^{25,28}, probably due to ionic competition between hydrogen ions and metal ions³¹. High pH may enhance metal toxicity³² due to low hydrogen ion concentration leading to less ionic competition, but for some metals, increase in pH beyond a particular point may lower toxicity because of precipitation removing metal from solution^{29,30}. Agents capable of chelation can affect toxicity by binding the metal. For example, in nature Kaolinite and montmorillonite clays can reduce heavy metal toxicity by binding the metal. Humic, fulvic acids and proteins can also have the same effect²⁸. The presence of synthetic chelating agents such as E.D.T.A. have been shown to reduce heavy metal toxicity toward micro-organisms²⁵.

Resistance To Metal Toxicity By Microorganisms

Microorganisms exposed to adverse environmental conditions may soon produce strains capable of surviving in a hostile environment through genetic modification. In many cases the evolved mechanisms are highly specific. In bacteria this metal resistance is often plasmid-linked^{26,33,34} and often associated with antibiotic resistance^{33,35}. Two general strategies exist for achieving resistance to toxic metals:

- Increase impermeability of the cell to the metal
- Biochemically achieved transformation of the metal.

The former process protects the cell from toxic elements in its environment. The latter detoxifies the immediate environment of the cell by eliminating the toxic metal from it or altering it to a non-toxic form^{26,34}.

Increased impermeability may be achieved non-specifically by production of an outer protective layer around the cell. This allows some metal to be bound at a distance from the cell wall with little damage being caused³⁰. This non-specific mechanism appears to be employed by the bacterium *Zooglea ramigera*, a common member of sewage sludge microbiota. Comparison of metal toxicity on strains of *Z. ramigera* capable of producing extracellular polysaccharide around the cell with that of a strain incapable of exopolysaccharide indicated that the former fared better in metal contaminated solutions and also accumulated more metal than the latter³⁰. Encapsulated strains of *Azobacter* have been found to survive better in lead-rich solutions than non-capsule producing *Micrococcus luteus*, due to the former's ability to immobilize lead without the metal being able to exert toxic effects at the cell surface or intracellularly. Some periphytic pseudomonads have been found to take up copper predominantly in their extracellular polymer, with only a fractional amount actually reaching the cell.

Capsulate strains of *Klebsiella aerogenes* were found to survive in 10mg/l cadmium better than a strain that did not secrete extracellular polysaccharide around the cell. Furthermore, when capsular polysaccharide was separated from polysaccharide producing strains and added to non-producing strains in cadmium solution, the survival of the latter was enhanced²⁵. A layer or matrix of extracellular polymer therefore appears to enhance cell tolerance of toxic metals by immobilizing them away from the immediate proximity of the cell where they cannot bind to functional groups on the cell surface or within the cell. It should

be noted, however, that extracellular polymer capsules and matrices may not have evolved specifically to protect bacterial cells from toxic metals; they are also known to offer resistance to phagocytosis ingestion by amoebae or phagocytes, protect against bacteriophage and desiccation, and might also act as a food reserve³⁶.

More specific resistance mechanisms to toxic metals are known in which cellular permeability to the metal is decreased. Some strains of *Staphylococcus aureus* are more resistant to cadmium toxicity than others, due to an alteration of the specific transport system responsible for bringing cadmium into the cell. Some *Escherichia coli* strains are cobalt resistant due to a change in the specific uptake system responsible for translocation of cobalt²⁵.

The alternative strategy to increasing cell impermeability is transformation of a toxic metal into a non-toxic form. This may be achieved intracellularly, but is more commonly achieved extracellularly. Alternatively, a toxic metal may be transformed into a form that is inassimilable by the microorganism. Toxic metals may be oxidized, reduced or methylated to produce less toxic compounds. Mercury resistance is often plasmid-linked via a plasmid-determined enzyme which can transform mercury and organo-mercurials into volatile forms which are soon lost from the environment. Another mechanism for removing metals from solution is production of hydrogen sulphide by microorganisms. As most heavy metals form insoluble sulphides, the production of sulphide by the bacterium *Desulphovibrio desulphuricans*, the fungus *Poria vailantii* and some strains of the yeast *Saccharomyces cerevisiae* results in precipitation of the metal from solution²⁸. Some fungi are also capable of producing chelating agents which bind metal away from the cell. *Corrollus palustris*, among others, can produce oxalic acid to enhance its copper tolerance by this means²⁸. Thus it can be seen that many mechanisms exist by which microorganisms may enhance their tolerance of toxic metals.

Accumulation of Heavy Metals By Microorganisms

Several mechanisms exist by which microorganisms remove heavy metals from solution. These may be divided into two general categories: metabolism dependent uptake into the cell and binding of metal ions to extracellular material (e.g., capsular polymer), or the cell wall which is not an active process^{36,37,38}. Some potentially toxic metal ions have already been previously mentioned to be micronutrients at low concentration. Most are divalent metal ions (for example, *Alcaligenes eutrophus* exhibits a growth requirement for nickel) and active uptake systems exist to bind these ions.

These divalent cation uptake systems tend to be particularly specific; however some do transport metals into the cell apart from those primarily required. The magnesium uptake system of *E. coli* is suspected also to accumulate Ni^{2+} , CO_3^{2-} and Zn^{2+} . The Mg^{2+} transport system of *Saccharomyces cerevisiae* is known to take up Co^{2+} , Mn^{2+} , Zn^{2+} and Ni^{2+} . Generally, ion uptake systems are specific for ions of a certain ionic radius. Thus monovalent cation uptake mechanisms tend not to take up divalent metal ions or metal ions of a higher valency, excluding the toxic heavy metals. However, caesium and radio isotopes of caesium and Tl^{+} have been observed to be taken into the cell via the potassium transport system³⁸.

Anion transport systems have also been implicated in carriage of toxic metals into cells. Metals that exist as oxanions in solution may be accumulated by such systems. Chromate for example, has been demonstrated to be competitive with sulphate ions for uptake via the sulphate permease system of *Neurospora crassa*. Many of the cases of intracellular uptake of toxic metals known are active processes, but intracellular uptake of toxic metal by non-viable cells is also known to occur²⁴.

The term 'biosorption' has been coined to describe the non-active adsorption of heavy metal ions by microorganisms or biological polymers. This process has been defined by Shumate and Strandberg²⁴ as "the non-directed, physical-chemical complexation reaction between dissolved metal species and charged cellular components, akin in many respects to ion exchange. Such processes usually occur as interactions between negatively charged ligands and metal ions and may occur as ion-exchange or formation of complexes. The most likely components

of microbial polymers capable of ion exchange are carboxyl groups, organic phosphate groups and organic sulphate groups. Chelation or complex formation tends to occur on biopolymers where neutral divalent oxygen, sulphur atoms, or trivalent nitrogen atoms are present. Examples include amino- and heterocyclic nitrogen groups of proteins and nucleic acids and also the carbonyl and hydroxyl oxygens of the same polymers. The latter two groups are also found in polysaccharides, polyheterocyclics and polyphenics³⁹. As previously mentioned, extracellular polymers have been demonstrated to bind heavy metals, such as the binding of metal to the extracellular polymers produced by the bacteria *Z. ramigera* and *K. aerogenes*. Extracellular accumulation of metals has also been demonstrated to occur with the extracellular polysaccharides of the algae *Mesotaenium kramstei* and *Mesotaenium caldarium*⁴⁰.

Accumulation of metal at or within the cell surface has been observed to occur with many microorganisms. The bacteria *Bacillus subtilis*⁴¹, *Bacillus licheniformis*⁴¹, and *Escherichia coli*⁴² have been demonstrated to bind heavy metal ions to their cell surfaces. Among the fungi *Saccharomyces cerevisiae*⁴³, *Neocosmospora vasinfecta*²⁸, *Rhizopus arrhizius* (Tsezos and Volesky, 1981), *Neurospora crassa* and a *Penicillium* species⁴² have all bound metal to their cell walls. Considerable diversity exists between the cell wall composition of bacteria and fungi, yet all apparently contain groups capable of metal binding.

Beveridge and Murray⁴⁴ and Doyle et. al.⁴⁵ have identified the predominant divalent metal ion binding group in *Bacillus subtilis* cell walls as the glucamic acid carboxyl groups of the wall peptidoglycan. Beveridge and Koval⁴¹ proposed that the polar heads of the cell envelope phospholipids of *E. coli* were primarily responsible for its metal binding. For *Bacillus licheniformis* the predominant metal binding sites in the cell wall have been shown to be the teichoic acids⁴⁴. For *Rhizopus arrhizius* the chitin of the cell wall has been implicated in uranium binding⁴⁶ and thorium binding⁴⁶. Accumulation of metals by microorganisms is widespread and occurs by a variety of mechanisms.

CONCLUSIONS

Biokinetic Data Bases

Microorganisms, whether in a constructed remediation cell or deep ocean environment, are constantly faced with fluctuating environmental conditions. Tidal action, upwellings, storms, and solar radiation cause changes in salinity, temperature, pH, and oxygenation; they can also transport microbes to new environments. The most important parameter is the availability and quality of nutrients. The majority of microorganisms in stressed soil/sludge micro-environments are oligotrophic, and their inhabitants must cope with the uncertain, and often unsuitable, conditions for survival. The complexity and diversity of these microorganisms, and of their environment, makes it virtually impossible for optimal conditions to exist for each organism. Therefore, at any one time, most microbes are surrounded by waters lacking sufficient energy-yielding substrates (nutrients from which ATP can be produced). Without energy, can viability be maintained? The concept of "starvation survival" deals with this particular situation, and the adaptations that organisms have evolved to deal with the problem.

This discussion has concentrated on heterotrophic microbial populations. Biodegradable organics are the "energy-yielding substrates" of these genera. When water or allochthonous forces deposit a bacteria in an area of nutrient deficiency, the organism must adapt or perish. Inherent in any living thing is the necessity for the continuation of the species. Microorganisms enter a transient state of dormancy until external conditions improve. Apparently, bacteria are very "patient" and can maintain this state for many, many years. Starvation survival dormancy is a physiologically complex occurrence.

Each species has a characteristic threshold for utilizing nutrients. The threshold may be lower in organisms that have a high affinity, and low specificity for nutrient uptake. Below this threshold concentration, the organism is unable to grow, and reproduce; it must take drastic action to remain viable itself. Onset of the starvation survival condition is often characterized by division of the bacteria, without concurrent growth, to produce ultramicrocells. *In vitro*, the increase in cell numbers has

been observed up to 400% as a result of introduction into a starvation media. Miniaturization results in a larger surface to volume ratio, which is an advantage in scavaging; the increase in cell numbers increases the probability of survival of the species. Upon encountering an area with utilizable nutrients, the ultramicrocells will resume normal size proportions, indicating that dormancy is reversible, and is a function of the availability/concentration of suitable energy yielding substrates.

Microbial uptake of nutrients is a competitive process, so dormancy includes several mechanisms, that *operate primarily under low nutrient stress*, to increase the inherent ability to compete. The capacity of an organism to find an essential nutrient, "capture" it, and then bring it into the cell is especially important in oligotrophic environments. The oligotrophic organism must be able to capture the substrate and then hold it on its surface long enough for active transport to occur across the cell membrane. Periplasmic binding proteins are the structural entity that perform this task. It appears that some binding proteins also function as chemoreceptors. This chemotactic ability further increases the efficiency of a bacterium in its search for energetically rich substrates. Lab experiments have shown that there is an "optimum chemotactic period." It is possible that if the organism has not been successful at the end of that period, it may then enter its state of dormancy. During dormancy, endogenous metabolism is reduced virtually to zero, although laboratory studies have demonstrated that dormant bacteria maintain high levels of RNA and amino acids, and a high energy charge. *In vitro*, this build-up begins shortly after introduction to low nutrient conditions. Although energetically expensive, this allows the organism to immediately (and efficiently) utilize a nutrient when it becomes available.

Microbes can be considered as living catalysts. Technically, a catalyst is a substance whose presence alters the velocity at which a reaction proceeds; a catalyst can be recovered *unaltered* at the completion of the reaction. Microbes often cannot be recovered from the reactions in which they participate (much less do they remain unaltered). Bacteria function to convert DOC to POC for higher order consumers. Other microorganisms produce organic metabolites which serve as food for other organisms. However, they themselves are eventually consumed, as are the bacteria, by organisms of the next trophic level. Strictly from a biomass perspective, the catalyst could be recoverable at each intermediate. Therefore, as the base of the food web, microbes do facilitate the flow of organics through the system. By increasing the efficiency, microbes affect the rate of carbon cycling through the ecosystem. In this way they do serve a catalytic function, but are not "catalysts" in the strictest sense of the word. But as catalysts, they are the central focus in biotreatment effect in a bioremediation system.

REFERENCES

- Pfaender Frederic K., and G.W. Bartholomev. 1982 Measurement of Aquatic Biodegradation Rates by Determining Heterotrophic Uptake of Radiolabeled Pollutants. *Appl. Environ. Microbiol.* 44 (1):159-164.
- Chibata I, T. Tosa, and T. Sato 1974. Immobilized aspartase-containing microbial cells: preparation and enzymatic properties. *Appl. Microbiol.* 27:878-885.
- Walter William G., R.A. McBee, and K.L. Temple. 1973. *Introduction to Microbiology*. Litton Educational Publishing, Inc. Pp. 1-7, 59-71, and 121-141.
- Wilkinson J.F. 1975. *Introduction to Microbiology*. Vol. 1. Second Edition. Blackwell Scientific Publications. Pp. 11-91.
- Poindexter J.S. 1971. *Microbiology an Introduction to Protists*. Pp. 23-66, and 149-199.
- Walter William G, and R.H. McBee. 1962. *General Microbiology*. Second Edition. D. Van Nostrand Company, Inc. Pp. 27-114, and 145-180.
- Nester Eugene W, C.E. Roberts, N.N. Pearsall, and B.J. McCarthy. 1973. *Microbiology*. Second Edition. Holt, Rinehart and Winston. Pp. 237-274.
- Ucko David A. 1977. *Living Chemistry*. Storage and transfer of energy. Academic Press, Inc. Pp. 388-419.
- Caldwell Douglas E, and John R. Lawrence. 1986. "Growth kinetics of *Pseudomonas fluorescens* microcolonies within the hydrodynamic boundary layers of surface microenvironments." *Microb. Ecol.* 12 : 299-312.
- Volk Wesley A, M.F. Wheeler. 1973. *Microbiology*. Third Edition. J. B. Lipincott Company. Pp. 3-129.
- Neff, Jerry M. 1979. "Polycyclic Aromatic Hydrocarbons in the Aquatic Environment." Sources, Fates and Biological Effects. Applied Science Publishers LTD, London. 61-73 and 102-149.
- Sisler, F.D. and C.E. ZoBell. 1947. "Microbial Utilization of Carcinogenic Hydrocarbons." *Science*, Nov. 28, 1947. Pp. 521-522.
- Cerniglia, C.E. 1984. "Microbial Transformation of Aromatic Hydrocarbons. in: *Petroleum Microbiology*," edited by R.M. Atlas. Macmillan Publishing Company N.Y., London. 99-129
- Alexander, M. 1977. *Introduction to Soil Microbiology*. John Wiley & Sons. N.Y. Chichester, Brisbane, Toronto. 115-225
- Gibson, D.T. "Microbial Metabolism." in: Hutzinger, O.1980. *The Handbook of Enviro. Chem.*, Vol. 2 Part A, Springer-Verlag Berlin Heidelberg New York Tokyo 1980. pp. 161-189 and 231-244.
- Zander, M. 1980. "Polycyclic Aromatic and Heteroaromatic Hydrocarbons." in: Hutzinger, O.1980. *The Handbook of Enviro. Chem.* Vol.3 Part A, Springer-Verlag Berlin Heidelberg New York Tokyo 1980. pp. 109-128.
- Alexander, M. 1981. "Biodegradation of Chemicals of Environmental Concern." *Science*, Vol. 211, 9. Jan. 1981. pp. 132-139
- Mandelstam, J. and K. McQuillen 1982. *Biochemistry of Bacterial Growth*, Third edition, Blackwell Scientific Publications, Oxford, London, Edinburgh, pp. 142-158
- Hutzinger, O. 1985. *The Handbook Of Enviro. Chem.*, Volume 2, Part C, Springer Verlag, pp 117-147.
- Casarett and Doull, J. 1980. *Toxicology. The Basic Science of Poisons*. Sec. edition. edited by J. Doull; C.D. Klaassen and M.O. Amdur. Macmillan Publishing Co, Inc. New York. pp. 91-93 and 632-661.
- Harvey, R.G. 1985. "Synthesis of Dihydrodiol and Diol Epoxide Metabolites of Carcinogenic Polycyclic Hydrocarbons." in: Harvey, R.G. *Polycyclic Hydrocarbons and Carcinogenesis*. 1985. ACS Symposium Series 283. 19-35.
- Cerniglia, C.E. 1983. "Microbial Metabolism of 4-, 7-, 10-Methylbenz[a]anthracenes." in: Cooke, Marcus and Dennis, Anthony J. 1983. *Polynuclear Aromatic Hydrocarbons: Formation, Metabolism and Measurement*. Battelle Press, Columbus, Richland, pp. 283-293
- London, S.A., C.R. Mantel and J.D. Robinson 1984. "Microbial Growth Effects of Petroleum and Shale-derived Fuels." *Bull. Environm. Contam. Toxicol.* 1984. 32: pp. 602-612. Springer Verlag New York Inc.
- Strandberg, G.W.; Shumate, S.E.; Parrott, J.R. (1981) *Appl. Environ. Microbiol.* 41:237.
- Bitton, G.; Freihofer, V. (1978) *Microb. Ecol.* 4:119-125.
- Ehrlich, H.L. (1978) In *Microbial Life in Extreme Environments*. Kushner, D.J. (ed):p.381-408. Publ. Academic Press.
- Maxwell, W.A.; Metzler, R.; Spoerl, E. (1971) *J. Bacteriol.* 105:1205-1206.
- Gadd, G.M., Griffiths, A.J. (1978) *Micro. Ecol.* 4:303-317.
- Tuovinen, O.H., Kelly, D.P. (1974a) *Arch. Microbiol.* 95:153-164.
- Tuovinen, O.H.; Kelly, D.P. (1974b) *Arch. Microbiol.* 95:165-180.
- Friis, N.; Myers-Keith, P. (1986) *Biotech. Bioeng.* 28:21-28.
- Babich, H.; Stotzky, G. (1977) *Appl. Environ. Microbiol.* 33(3): 681-695.
- Hardy, K. (1983) In: *Bacterial Plasmids*. p62-3, 71-2. Publ. Nelson.
- Iverson, W.P.; Brinckman, F.E. (1978) In: *Water Pollution Microbiology* pp.201-232. Mitchell, R. (ed) Publ. Wiley & Sons.
- Nakahara, H.; Tomoaki, I.; Sarai, Y.; Kondo, I; Mitsuhasi, S. (1977) *Nature*, 266:165-167.
- Wilkinson, J.F. (1957) *Bact. Rev.* 22:46-72.
- Shumate, S.E.; Strandberg, G.W. (1985) In: *Comprehensive Biotechnology*, 4:Ch. 13 p. 235-. Robinson, C.W.; Howell, J.A. (eds).
- Kelly, D.P.; Norris, P.R.; Brierly, C.L. (1979) In: *Microbial Technology: Current State, Future Prospects*.
- Hunt, S. (1986) In: *Immobilization of ions by bio-sorption*. p.11-15. Eccles, H.; Hunt, S. (eds).
- Mangi, J.I.; Schumacher, G.J. (1979) *Am. Midl., Nature*, 102:134-139.
- Beveridge, T.J.; Murray, R.G.E. (1976) *J. Bacteriol.* 127:1502-1518.
- Gadd, G.M., (1986) In: *Immobilization of ions by bio-sorption*, p.149-159. Eccles, H.; Hunt, S. (eds).
- Beveridge, T.J.; Koval, S.F. (1981) *Appl. Environ. Microbiol.* 42(2):325-335.
- Beveridge, T.J.; Forsberg, C.W.; Doyle, R.J. (1982) *J. Bacteriol.* 150:1438-1448.
- Tsezos, M.; Volesky, B. (1981) *Biotech. Bioeng.* 23:583-587.
- Corpe, W.A. (1975) *Dev. Ind. Microbiol.* 16:249-255.

TOPIC 2: Land Treatment Case Study

Biological Detoxification of a RCRA Surface Impoundment Sludge Using Land Treatment Methods

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BACKGROUND

Remediation of contaminated soil presents a major challenge to business, scientists, and regulators. Remediation of solid and hazardous waste sites containing soils were first required under the Resource Conservation and Recovery Act of 1976 (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). The authority of regulators to order cleanups preferentially through permanent, on-site remedies was established under the Hazardous and Solid Waste Amendments of 1987 (HSWA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA). SARA in subparagraph 121 (1)b says in principal part:

"Remedial actions in which treatment permanently and significantly reduces the volume, toxicity or mobility of the hazardous substances, pollutants, and contaminants as a principal element, are to be preferred over remedial actions not involving such treatment. The off-site transport and disposal of hazardous substances or contaminated materials without such treatment should be the least favored alternative remedial action where practicable treatment technologies are available."

This regulatory authority has laid the groundwork for allowing bioremediation and thermal treatments to be considered as permanent remedies.

BIOLOGICAL TREATMENT FOR SOILS

A number of biological remediation technologies have been used in demonstration or in full-scale on contaminated soils. Those technologies include:

- Land Treatment—or soil reactors
- Compositing—a type of land treatment system using well-mixed pile material with chemical, nutrient, and biochemical amendments. The piles may be aerated to enhance degradation rates.
- In-Situ Treatment—or initiation of biological action in the subsurface environment.
- Liquid Solids Contact (LSC)—A methodology using high energy, suspended growth reactors capable of 10-20 percent solids suspension to treat the organics in contaminated soil. This process resembles a batch-activated sludge process.
- Biological Soils Conditioner (BSC)—a variant of the LSC process where the solids concentration is as high as 50% dry weight solids.

LAND TREATMENT SURFACE IMPOUNDMENT CLOSURE

A Fortune 500 chemical company located in Plaquemine, LA, had a 30,000-cubic yard surface impoundment called the "North-South Pond." The impoundment was 180 feet by 250 feet by 25 feet deep and contained sludge and soil arising from previous spill cleanups, including a rail tank car spill cleanup. The impoundment was classified as a RCRA facility. The principal chemical constituents shown in Table

I were aromatic chemicals. Table I depicts the contaminants and range of concentrations.

Table I
Constituents of the RCRA Chemical Contamination

Chemical	Range of Contaminant Concentration mg/kg	Post Closure Care Levels, mg/kg
Phenol	10-3600	<10
Cumene	<1-48	<1
Acetophenone	<1-212	<1
Benzene	<1-16	<0.5
Benzyl Alcohol	<1-150	<1
Tar	500-2500	<100 ¹
Vinyl Chloride	<1-6.5	<0.5
Styrene	25-100	<1

¹As measured by Total Petroleum Hydrocarbons Method 418.1

A bioremediation closure was designed using excavation and above-ground treatment. The soil residual was treated to specified postclosure care limits and will be placed in the original impoundment and capped.

The closure was developed after six months of bench-scale piloting and five months of field demonstration work treating 20 cubic yards of soil. After preparation, the soil was placed in a Biological Closure Unit (BCU). An EPA precedent was used to construct this temporary facility without TSD permits. Its construction featured 80-mil HDPE liners and a leak-detection system. Aeration was achieved through weekly tilling of the site and moisture was maintained using a sprinkler system developed for this closure. An overview of the remediation process is shown in Figure 1. The design of the BCU is shown in Figure 2. Three lifts of contaminated soil were to be pretreated and placed in the facility. The loadings were designed on the pilot studies. Table II depicts the treatment design parameters.

QUALITY ASSURANCE/QUALITY CONTROL

To analyze the degree of treatment achieved with high accuracy, a quality assurance/quality control program was designed into the closure. The features of this program were:

- Replicate initial lift composites of at least twenty locations, four replicates taken.
- Repeat of sampling at least bimonthly.
- Double-blind sample labeling, and
- Use of spiked and blank samples.

Control analyses consisted of pH, total organic carbon, total Kjeldahl nitrogen, orthophosphate, and adenosine triphosphate (ATP). Target

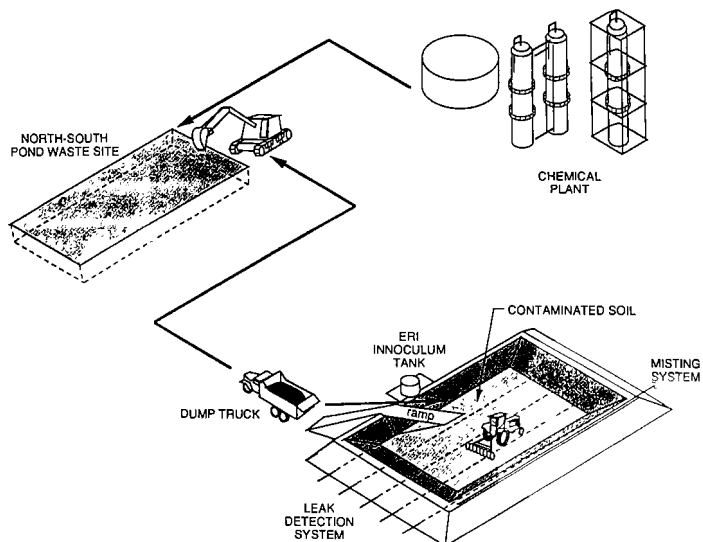
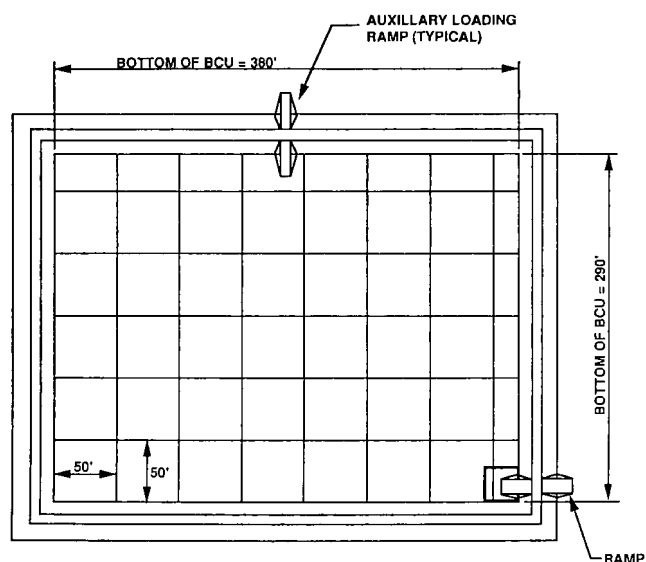
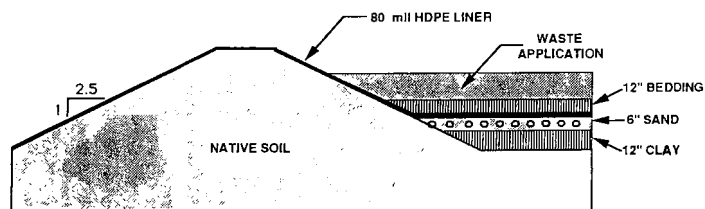


Figure 1



BIODEGRADATION CLOSURE UNIT, GRID
PLAN VIEW



CROSS SECTION DETAIL
ENLARGED FOR CLARITY

Figure 2
Biodegradation Closure Unit

hydrocarbons consisted of total phenol and a GC/MS analysis of Table 1 constituents at lift beginning and end.

AIR MONITORING AND EMISSION CONTROL

During the field demonstration phase, air monitoring showed low potential for hydrocarbon release outside the BCU. During full-scale remedial design, all measures to prevent air emissions were considered. Eventually high ring levees, moisture control covers, and masking agents

Table 2
Land Treatment Design

Lift #	Volume c.y.	Initial Concentration T. Phenol ¹ , mg/kg	Target Concentration T. Phenol, mg/kg	Treatment Time (Design) days
1	7,000	~500	<10	90
2	4,300	~200	<10	75
3	5,300	~200	<10	75
4			<10	
5			<10	
TOTAL 16,600				240

¹Total phenol was used as a design and QA/QC parameter. TCLP was used as guidance for post closure care levels.

were used to control emission. During Lift One, five air monitoring stations were set up. One was inside the BCU at the decontamination pad, while four were outside the BCU. None of the units outside the BCU showed detectable hydrocarbons of interest above background.

RESULTS

The replicates from the BCU Lift One initial treatment averaged mg/kg phenol on Day 0. A hot spot was found in Quad 1, which had phenol concentrations of 4,000 mg/kg phenol. This spot was diluted by spreading it throughout the BCU to allow biodegradation. After regular addition of bacterial product and tilling of the soils, treatment target levels of <1 mg/kg was achieved by Day 71. Phenol values of <10 mg/kg in all quadrants were used as a guide for reloading events. Lift One was accepted as complete by all parties on Day 71 of the closure. Table III depicts the treatment results. The mean value of phenol during the closure of Lifts One and Two is shown in Figure 3. Figure 4 depicts quadrant phenol levels versus time.

Table 3
Treatment Results (Actual)

Lift #	Volume cu. yds	Initial Concentration T. Phenol, mg/kg	Final Concentration T. Phenol, mg/kg	Treatment Time, days
1	7,200	137	<1.0	71
2	4,300	19	<1.0	28
3	5,300	15	<1.0	28
4	3,600	20	<1.0	30
5	2,600	38	<1.0	28
TOTAL 23,000				185

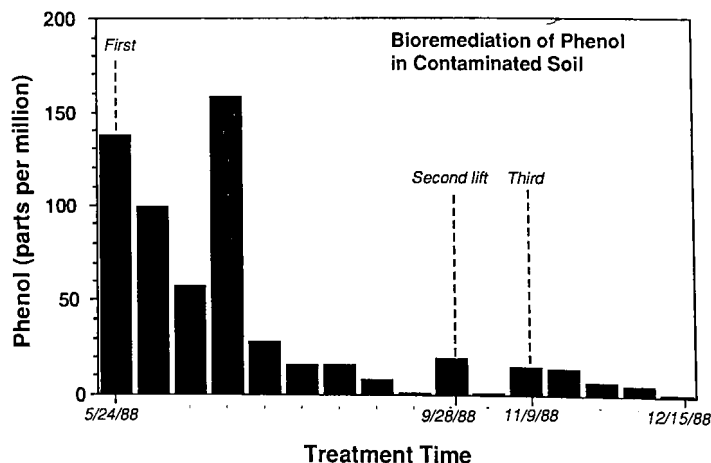


Figure 3
Bioremediation of Phenol in Contaminated Soil

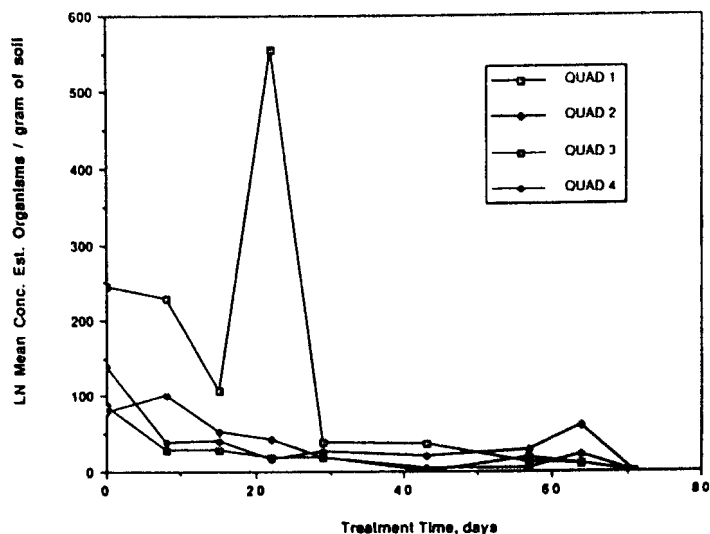


Figure 4
Soil Phenol Concentration VS Time

Due to excessive rain in the BCU area, reloading with 4,300 cubic yards of material for Lift Two was not completed until Day 135. This 8-inch lift was mixed with up to 6 inches of the previous lift to allow the microorganism population grown on Lift One to metabolize new substrates. During Lift One, ATP and microorganism concentration had markedly increased as shown in Table IV.

Table 4
Microbial Activity
Estimated Organisms Soil Bioremediation (Lift One)

Day Microbes/gram Soil
 (Mean Values)

0	2.4×10^3
8	1.3×10^3
15	5.0×10^6
36	4.0×10^6
43	4.9×10^6
57	6.3×10^6
64	5.6×10^6

This data is based on individual quadrant microbial concentration depicted in Figure 5. The relationship of the phenolic substrate to mean microbial concentration is shown in Figure 6. Additional bacterial product was added to enhance the existing microbial population. A commercial microbial culture, Micro Pro "Cee," was used on Day 8 as inoculating seed.

As a result of the mixing of the lifts, Lift Two had an initial phenol concentration of 24.3 mg/kg. On Day 147 or 14 days after the Lift Two application, all quadrants exhibited phenol values of <10 mg/kg. The lift was accepted as complete by all parties on Day 147 of the closure.

The third reloading of 5,300 cubic yards of waste was completed by Day 177 of closure. Reloading was carried out as before by mixing the new material with some of the previously remediated soil to introduce acclimated bacteria and augmentation by bacterial product. By Day 21 of Lift Three (Day 194 overall) three of the four replicates had phenol levels of <10 mg/kg. By Day 205 (Day 28 of Lift Three), all phenol levels had fallen below 10 mg/kg and the closure was complete.

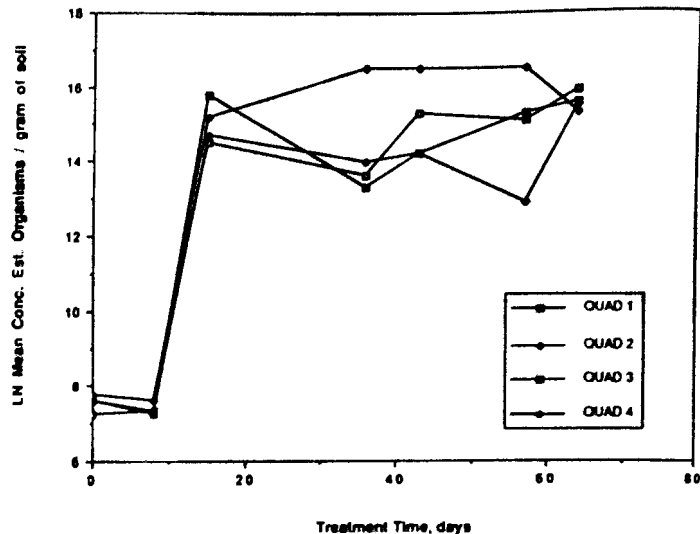


Figure 5
Estimated Organisms Concentration

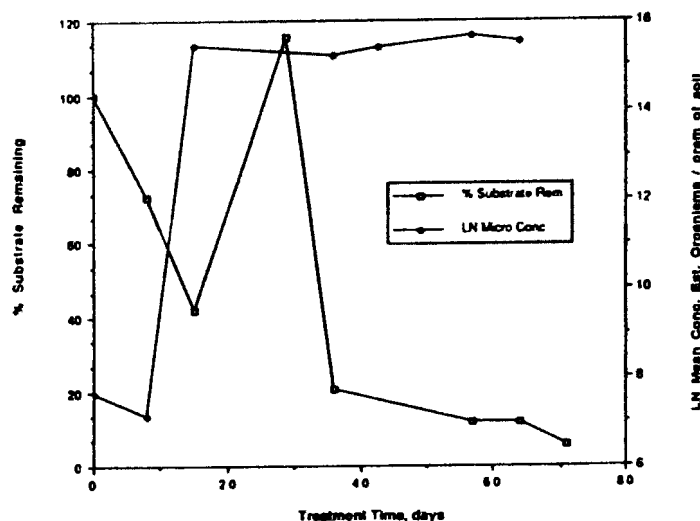


Figure 6
Estimated Organisms

Additional material above that of the original contamination was treated in two lifts of 3600 and 2600 cubic yards respectively. All material passed a TCLP screening prior to initiation of post-closure care.

CONCLUSIONS

A land treatment closure of a RCRA surface impoundment was carried out using a temporary treatment facility. Over 30,000 cubic yards were excavated and 23,000 cubic yards were treated to achieve final phenol levels of <10 mg/kg and meet TCLP criteria. A microbial seed was added which appeared to increase microbial concentration as measured by adenosine triphosphate (ATP). The authors recommend consideration of similar treatment methodology for contaminated soils with characteristics like those of the Plaquemine, Louisiana site.

LITERATURE CITED

1. U.S. Environmental Protection Agency, SW-846, U.S. Government Publication, September 1986.
2. Christiansen, John et al., "Biodegradation Closure of Organic Hazardous Waste Impoundments," *Proceeding of the Fourth Annual Hazardous Materials Management Conference*, June 2-4, 1986.
3. Bogart, J., et al., "Biodegradation—A Viable Clean-Up Technology for Chlorinate Polynuclear Aromatics and Creosote," *Proceedings of the Fourth Annual Hazardous Materials Conference*, June 2-4, 1986.
4. WPCF Manual of Practice No. 8, 1977.

TOPIC 3: Liquid/Solids Contact Case Study

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A major petrochemical company operates a refinery and an olefins plant in Houston, Texas. The refinery and petrochemical plant combined to form the fifth largest chemical complex in the continental United States. The refinery crude oil capacity exceeds 265,000 barrels per day. The olefin plant contains two surface impoundments on site which are part of the complex's NPDES permitted treatment facility. The impoundment serves as wastewater surge capacity immediately after an API separator. The two impoundments are depicted in Figure 1. OPI had an initial sludge volume of nearly 4000 cubic yards while OP2 had an initial sludge volume of 2600 cubic yards. The sludge was classified by the refinery/olefins complex environmental staff and found to be nonhazardous solid waste. An analyses of the sludges is shown in Table 1. During chemical plant turnaround, a project was initiated to clean the surface impoundments for future use. The alternatives presented to the refinery complex were:

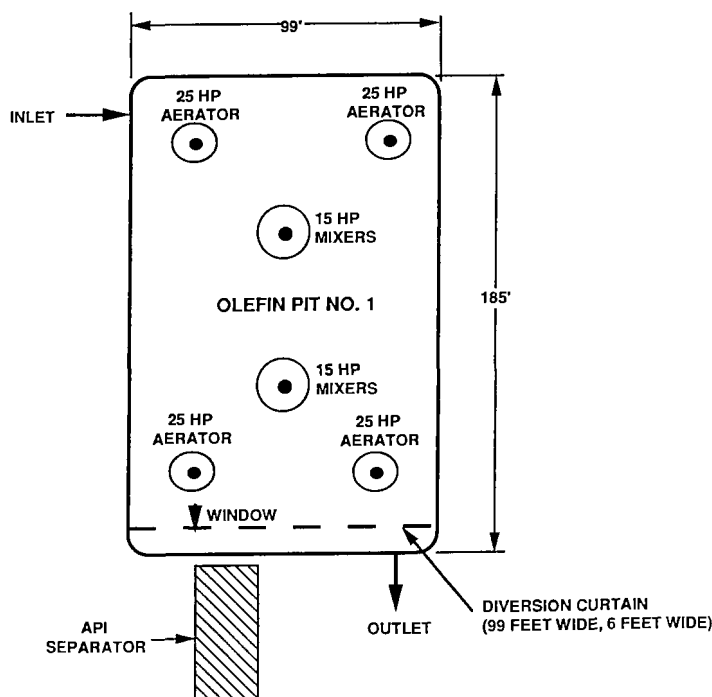


Figure 1
Olefins Pit No. 1-Two Typical

Table 1
Analyses of Olefin Sludges, Selected Parameters

Parameter	Concentration mg/kg		Method
	OP1	OP2	
pH	6.5	6.3	
Oil and Grease	32.5%	41.4%	9071 ¹
Benzene	15	28	8240 ¹
Toluene	4	5	8240 ¹
Xylene	0.93	17.30	8240 ¹
Ethylbenzene	17	33.4	8240 ¹
Napthalene	360	448	8270 ¹
Phenanthrene, Anthracene	860	410	8270 ¹
Moisture	66%	68%	209A2
Solids	34%	32%	209A2
Ash	9%	4%	209D2

¹USEPA SW-846, Third Edition

²Standard Methods for the Examination of Water and Wastewater, 16th Edition.

- Sludge dewatering by belt or plate-and-frame press followed by off-site disposal of solid waste,
- Sludge removal and stabilization followed by off-site disposal (without volume reduction), and
- Sludge volume reduction through Liquid/Solids Contact Bioremediation processes.

The third alternative was selected as a form of remediation which offered volume reduction in place at competitive costs, while ensuring that the residual would be low in objectionable organics. The residual was to be removed from the impoundment at the end of biological treatment and placed on the refinery complex's existing land treatment facility. In order to meet the refinery's requirements regarding volume of material applied to this land treatment facility each year, a minimum sludge volume reduction of 50⁴ was required.

PRELIMINARY LABORATORY ASSESSMENT AND STUDIES

An initial assessment of the sludge was conducted using composite sampling techniques. A survey crew with a boat divided the pond into grids and pulled sludge samples from at least 8 locations within each surface impoundment. Samples were taken by inserting a 6-inch PVC casing and pumping out free liquid. A 2-inch-diameter PVC pipe was then inserted into the sludge portion and used to take a vertical section of sludge. This step was repeated until all 8 locations within each pond had been sampled. The sludge was composited in a 5-gallon bucket

and mixed with a paint mixer. The analysis of the constituents is shown in Table 1. The waste contained low concentrations of volatile hydrocarbons and higher concentrations of semi-volatile base neutrals. Oil and grease ranged from 32 to 42 %. As free liquid disposal to the wastewater plant and solids residuals to disposal to the land farm were controlled by oil and grease. This was used as a target hydrocarbon for the treatment program.

A Liquids/Solids Contact (LSC) simulation reactor, was set up to determine feasibility of sludge reduction. Oil and grease samples were also taken periodically throughout a study which lasted 14 days. The study was run with indigenous as well as commercially available microbial products in replicate. The study was run for 17 days and a vigorous bacterial population was established with indicator protozoa appearing in both reactors within 10 days. Sludge volume in the augmented reactors was reduced 50% and oil and grease reduced 60% by mass. Based on acceptable reduction of sludge and mass, a target reduction of 50% volume reduction and 60% mass oil and grease reduction was set for the performance portion of the project. Treatment then proceeded to the field.

LIQUID/SOLIDS CONTACT REACTOR DESIGN

Each existing impoundment was set up as an in-situ Liquid Solids Contact reactor. The reactor was designed to suspend sludge in liquid in a 1:1 (v/v) ratio. In each impoundment, five 25-horsepower surface aerators (modified to pump 14,000 gpm) and a 15-horsepower, direct-drive floating mixer were placed to supply mixing and aeration. The units were energized through a local power system controlled on-site by a field operator. The unit was energized in OPI on October 1, 1988, and on OP2 on November 2, 1988. After 24 hours of mixing, liquor samples were taken to ensure solids were suspended at at least 15% dry weight solids. A chemical amendment consisting of surface active agents, pH control chemicals, macro and trace nutrient amendments, and an adapted microbial culture (Micro Pro Super "Cee") were added to enhance microbial degradation. Sludge and liquid depth were measured weekly throughout the impoundment. Composite samples were analyzed for oil and grease content using EPA Method 9071. Composite samples taken on a weekly basis from the sludge were analyzed for oil and grease concentration in a similar manner. Mixed liquor control samples were also taken weekly. These were analyzed for pH, total Kjeldahl nitrogen, total phosphorous, adenosine triphosphate, and COD. Samples were also settled to determine supernatant COD because ultimate disposal of free liquid to the wastewater treatment plant would require a COD of less than 450 mg/l and an oil and grease of less than 100 mg/l.

AIR MONITORING AND PERSONNEL SAFETY

Personnel at the site were trained in accordance with OSHA 29 CFR 1910.120 and outfitted in minimum level C personal protective equipment. Air monitoring was provided in the vicinity of each pond during start-up and on a daily basis during the first week of operation. As part of the written health and safety plan contained at the site, measurements exceeding 0.5 ug/n³ resulted in the operator shifting to level B personal protective equipment or breathing air. It was found that breathing air was adopted during the first week of each treatment operation when fugitive benzene emissions were at their height. During this period of time, benzene measurements taken at the top of the reactor levee measured as high as 2 ppm benzene. An exclusion zone established at the bottom of the corresponding levee was another measurement site. Benzene was not measured at any location outside the exclusion zone during the entire treatment process.

MIXED LIQUOR AND SLUDGE SAMPLING

Mixed liquor and sludge were sampled on a weekly basis throughout the project. To do this the reactor was de-energized and a crew (equipped in level B personal protective equipment) entered the area with a boat. One operator in the boat took level measurements. These were taken using 1-inch-diameter PVC pipe marked off in 1-foot and 1/2-foot increments. At the end of this pipe was a 12-inch square plate which was coupled to the PVC pipe. The plate was thrust down and the operator

probed for resistance, first to the settled sludge layer, then to the hard clay soils at the bottom of the impoundment. The operator doing the work signaled another operator and engineer who recorded measurements of liquid and sludge depth. After measuring sludge depth of 8 stations throughout the impoundment, the operator returned and took his sludge samples in accordance with the procedure described previously. These sludge samples were labeled and retained for analysis with full chain-of-custody procedures. Preservation, transportation, and analytical methods were in accordance with USEPA SW 846. The reactor was re-energized and the crew took 4 mixed liquor samples approximately 15 minutes later. The 4 mixed liquor samples were then combined to perform a single liquor composite. The liquor was analyzed for the parameters to determine microbial population (adenosine triphosphate (ATP) and nutrients). Sludge was analyzed for oil and grease, acid extractable and base neutral compounds (Method 8270), and moisture solids and ash.

RESULTS

Table 2 provides the sample dates and a summary of analysis and calculations from settled sludge and the final supernatant sample in in OPI. Initial oil and grease was 32.5% on 11/2/88. The final sludge samples taken on 11/22 /88 showed a settled sludge oil and grease of 36.3%. The measurable sludge at that time was 1288 cubic yards or a volume reduction of 68%. This met the performance standard of at least 50% volume reduction. Table 3 shows the mass balance calculated for OPI. This was calculated by taking the initial sludge volume and multiplying it by the dry weight oil and grease to derive the mass of oil and grease in the sludge on a dry weight basis. This amount was tracked throughout the 21 operating days until adequate volume reduction was achieved. On the last day, 11/22/88, samples of both mixed liquor and sludge were analyzed to allow closing of the mass balance of oil and grease. These values were added together to produce a total mass on Day 21 of 299,372 pounds oil and grease dry weight, or a 62% removal over the 21-day period. Figure 2 depicts this mass removal for OPI sludges.

Table 2
Lyondell Petroleum Data OPI - Oil and Grease

Date	Day	Sample	O & G (%)	Moisture (%)	Density (lb/cf)	Volume (cu yds)	Mass O&G (lb)
11/02	0	Settled Sludge	32.5 ¹	64 ¹	68 ¹	3987 ²	808875 ³
11/08	7	Settled Sludge	52.3 ¹	72.5 ¹	68 ¹	2883 ²	783080 ³
11/18	11	Settled Sludge	61.3 ¹	65 ¹	68 ¹	1898 ²	459,567 ³
11/22	21	Settled Sludge	36.3 ¹	65 ¹	66 ¹	1288 ²	291,607 ³
11/22	21	Supernatant	0.4 ¹	10.8 ¹	62.4 ¹	1.33mga ⁴	7765 ³

¹The actual sample and data are from the site survey on 9/6/88. Samples were run 9/12/88 by ERI Lab

²lbs dry wt. = free dry wt. x O&G % Sludge cy. x 27 cf/cy Density

³Average two estimates, Site Log 11-5-88

⁴From 11/15/88 Survey

Table 3
OPI Mass Balance

Date	Day	Mass O & G lbs, dry wt.	Sample
11/02	0	808,875	Settled Sludge
11/08	7	783,080	Settled Sludge
11/18	11	459,567	Settled Sludge
11/22	21	291,607	Settled Sludge
11/22	21	7,765	Supernatant

Total Mass Day 0 = 808,875

Total Mass Day 21 = 299,372 (291,607 + 7,765)

Removal = 62%

Time = 21 days

The average temperature during treatment was 18°C

The volume of OPI was 1.33 million gallons

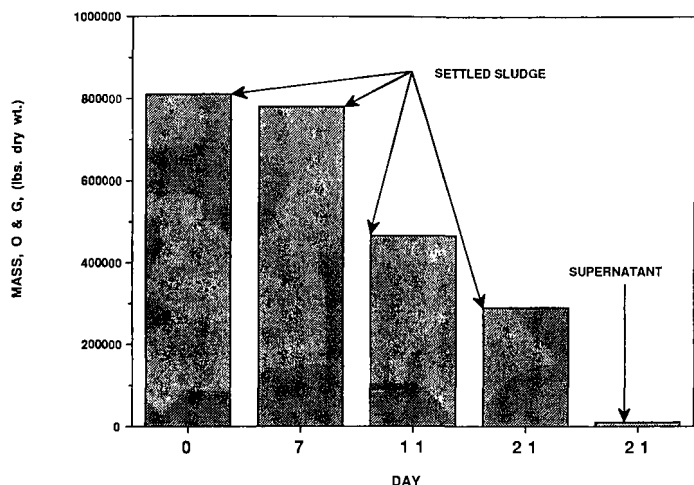


Figure 2
OP#1 Mass Balance

In a similar manner, calculations shown in Tables 4 and 5 depict the mass balance calculation for OP2. Figure 3 depicts the mass oil and grease reduction. OP2 was run a much longer period of time because of treatment initiation late in the year. Actual treatment of OP1 operating temperature for mixed liquor averaged 18°C. Oil and grease was calculated to have a half-life of 16 days based on the field data. During OP2, average operating temperature was 14°C or much lower. This resulted in extended oil and grease degradation. The final mass balance shows an 85% mass reduction of oil and grease in 61 days at 14°C. This is consistent with an oil and grease half-life of 40 days for OP2, which can be converted to a 32-day half-life at 20°C.

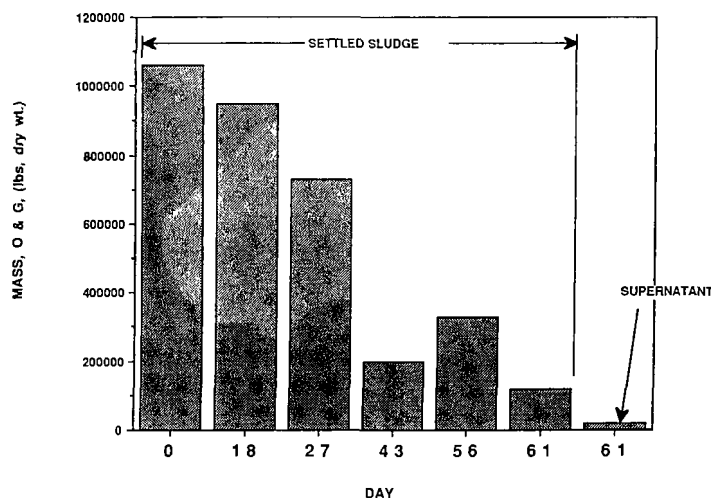


Figure 3
OP#2 Mass Balance

The final material which was disposed in the complex land farm was characterized for parameters equivalent to those shown in Table 6. As is indicated in Table 6, these parameters show the volatile hydrocarbons to be stripped or biodegraded during the treatment process. It is interesting to note that naphthalene, phenanthrene, and anthracene (significant base-neutral compounds) did not significantly increase in the reduced-volume residual left over from the treatment process. This indicates significant reduction of those hydrocarbons above the amount identified in the volume reduction.

Table 4
Lyondell Petroleum Data OP2 - Oil and Grease

Date	Day	Sample	O & G (%)	Moisture (%)	Volume (cu.yds)	Mass O&G (#)
12/02 ¹	0	Settled Sludge	41.4	62	2590	1,058,897
12/19	18	Settled Sludge	49.0	29	1491	952,368
12/28	27	Settled Sludge	64.0	76	2576	726,456
01/12	43	Settled Sludge	56.0	55 ¹	1762	205,437
01/25	56	Settled Sludge	28.1	55	1424	330,599
01/31	61	Settled Sludge	18.6	65	1017	121,556
01/31	61	Supernatant	0.67	99.8	1.08 mgal	12,070

¹Assumed, not recorded

Table 5
OP1 Mass Balance

Date	Day	Mass O & G lbs, dry wt.	Sample
12/02	0	1,058,897	Settled Sludge
12/19	18	952,368	Settled Sludge
12/28	27	726,456	Settled Sludge
01/12	43	205,437	Settled Sludge
01/25	56	330,599	Settled Sludge
01/31	61	121,556	Settled Sludge
01/31	61	12,070	Supernatant
Total O & G Mass Day 0		= 1,058,897	
Total O & G Mass Day 61		= 133,626 lbs (121,556 + 12,070)	
Removal		= 87.3%	
Time		= 61 days	

The average temperature during treatment was 14°C

The supernatant volume of OP2 was 1.08 million gallons on Day 61

Table 6
Chemical Characteristics of Sludge Residual

Parameter	OP1 Residual	OP2 Residual
pH	6.9	6.6
Oil and Grease	36.3	18.6
Benzene	<0.1	<0.1
Toluene	<0.1	<0.1
Xylene	<0.1	<0.1
Ethylbenzene	1.2	6.1
Napthalene	423	117
Phenanthrene, Anthracene	620	406
Moisture	65	65
Solids	35	35
Ash	13	18

SUMMARY

A Liquids/Solids Contact reaction technology was used to reduce sludge volumes and oil and grease content in two wastewater treatment lagoons at a major olefins refinery outside of Houston, Texas. In OP1, a degradation time of 21 days was required to achieve 68% volume reduction and 62% mass oil and grease reduction at an operating temperature of 18°C. In OP2, a treatment time of 61 days was required to achieve 61% sludge volume reduction and 87.3% mass oil and grease reduction in a lagoon containing 2590 cubic yards operating at 14°C.

For sludges which have similar biodegradable characteristics, this offers a major alternative to standard dewatering practices such as plate-and-frame press. Selection of a method of treatment for individual sludges should be based on site or laboratory treatability studies conducted to account for losses from volatilization, absorption, and other nonbiodegradable sources.

TOPIC 4: Modular Bioreactor Approaches For Remediation Of Groundwater: A Case Study With Volatile Chlorinated Aliphatics

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ABSTRACT

Most of the current efforts in biotechnology of waste management have relied upon conventional genetic and microbial technology. The genetic engineering of microorganisms has found very limited use, mainly due to concerns regarding the question of environmental release. In this manuscript, a technology will be presented which is based upon the principle that natural populations of microorganisms are able to adapt to biotransform mixtures of refractory molecules. Information on a field investigation in which an immobilized microbe bioreactor was used to treat high concentrations of the chlorinated aliphatic ethylene dichloride (EDC) will be provided. EDC is one compound in this class of xenobiotics which have been implicated as the most common contaminants in industry effluents and groundwater.

THE BIODEGRADATIVE POTENTIAL

People commonly associate bacteria and most microorganisms with pathogenicity, but the majority are benign and are essential to the ecology of our planet. They assimilate nitrogen for plant growth, and recycle carbon (from plant and animal tissues, biological and chemical wastes) for both aquatic and terrestrial primary consumers. It is this natural ability to biotransform and mineralize organics that we harness, and manipulate in biological remediation of hazardous waste. Bacteria either feed directly on an organic pollutant, degrade it concomitantly with another primary carbon source, or secrete enzymes to break down the compound. Many biodegradation events proceed through a cometabolic pathway. In the process of breaking down an abundant primary carbon source, the pollutant is fortuitously catabolized. Bacteria have been isolated to degrade a wide range of toxic and recalcitrant compounds.¹ (Balthazor, 1986, Haley¹, 1988, Roberts, 1987 and Portier, 1982) The bulk of bioremediation research is being conducted with organisms whose natural abilities have been enhanced. Timmis and his collaborators at the University of Geneva (Timmis and Harayama 1987) are dedicated to designing original catabolic pathways, locating the genes necessary for the reactions, and engineering, by recombinant DNA, the complete pathway into a host cell. However, recombinant DNA is still a new technology and as fate-and-effect data regarding releases accumulates, the regulations will become more consistent.

Nature has the ability to recycle and purify itself, but in recent years, the demand placed on the environment by huge amounts of anthropogenic pollution exceeds its capacity to recover. Bioremediation technologies simply attempt to optimize the natural capacity of microorganisms to degrade organic compounds by supplying essential inorganic limiting reactants and minimizing abiotic stress. Biodegradation techniques are versatile and can be utilized at various stages of treatment. There are three basic ways that the above can be accomplished: 1) *Direct Release*. Bacteria, or their extracellular products

may be released directly into the contaminated environment. 2) *Enhancement of Indigenous Microbes*. Enhancement of the indigenous population's degradative potential may avoid the aforementioned problems of predation, nutrient competition, and subsequent colony inactivation. Enhancement is achieved primarily by supplementing the natural supply of nutrients at the site with additional oxygen, nitrogen, phosphorous, essential vitamins, or an organic compound necessary for cometabolism. 3) *Microbes in Contained Reactors*. Microorganisms may be used in contained reactors to circumvent the problems of a complex, and often unfavorable, natural environment. The methods to be presented in this paper involve use of such specialized biological reactors. In an enclosed bioreactor, parameters like pH/Eh, oxygenation, nutrient concentration, temperature, and salinity can be controlled for optimal biodegradation. Applications include removal of contaminants from raw materials prior to processing; treatment of pipeline wastes before discharge; treatment of effluent streams; and decontamination of soils, sediments, surface water, and groundwater. (Portier et al., 1986)

IMMOBILIZED CELL BIOREACTORS

The technology to immobilize whole cells for the decomposition of toxic organics has only been developed within the last decade. Bacterial immobilization involves the entrapment of cells onto a matrix. Once bound, the cells are then readily accessible to the surrounding substrate (Portier et al., 1986). Chitin, cellulose, glass, and diatomaceous earth have been tested for use as the solid support material. Bacteria adhere to chitin, cellulose, and diatoms through covalent bonding and to glass through adsorption. (Portier, 1987). Chitin and diatomaceous earth act as sorptive surfaces for many organics and nutrients (Portier, et al, 1988). There are threshold concentrations below which microorganisms cannot scavenge nutrients. Chemical sorption creates a microenvironment about the organism that is more copiotrophic than the surrounding medium—a situation that greatly enhances growth and decomposition. Immobilized column bioremediation technology is based on the theory that natural populations of bacteria can be adapted to break down refractory compounds. The purpose of the packed bed is to provide a large surface area for microbial colonization.

GROUNDWATER BIOLOGICAL REMEDIATION OF CHLORINATED ALIPHATICS

Due to the volatility and environmental persistence of low molecular weight chlorinated hydrocarbons, a very large fraction of them simply volatilize into the atmosphere when wastewaters contaminated with them are discharged into conventional industrial aeration lagoons, discharged into conventional industrial aeration lagoons has simply volatilized into the atmosphere. The major route for their vapor phase abiotic destruction is thought to be photo-induced tropospheric hydroxyl ion attack (Pearson, 1982). When EDC is oxidized in this manner, the

intermediates are thought to be the mutagenic compounds 2-chloroacetaldehyde, formyl chloride, and 2-chloroacetate (McCann, et al., 1975).

The challenges to building an effective aerobic biotreatment system for volatile organic chlorinated aliphatics are creating conditions under which aerobic organisms can account for a large fraction of the compound disappearance rate and selecting/maintaining a biological population with maximum degradation kinetics and minimal exogenous production of dangerous intermediate compounds. A 75 L, continuous flow, immobilized cell bioprocess system was developed specifically for volatiles degradation and was tested at a chemical production site having extensive halocarbon contaminated ground water. The groundwater contains a variety of one- and two-carbon chlorinated compounds. EDC is present in far greater concentration than any of the other organics, and was routinely observed at concentrations in excess of 1,800 mg/L.

A detailed discussion of the reactor design has been presented elsewhere (Friday and Portier, 1989) and is summarized as follows: the current system consists of three functionally distinct subsystems. The first is a raw effluent conditioning system which removes foreign materials via a 100 μ filter, dilutes recovered ground water to the degree required to achieve biologically acceptable toxicant concentrations, adds nutrients, and adjust/maintains media pH and temperature. Biological conversion occurs in the second subsystem (reactor vessel) which is partitioned into two distinct volumes. In the first, air is sparged into the feed waters to mix and aerate the influent water. Admixed air is then separated from the water before it enters the second reaction stage. In the second section, the water moves in plug flow through a bed packed with porous biocarrier on which the selected chlorinated aliphatic-degrading organisms are immobilized throughout the support. Modular column units have been fabricated which can be mechanically coupled to provide a desired packed bed volume and control the extent of the bioconversion. Design considerations have included gas sparging/gas distribution, maintenance of carrier integrity, gas/liquid separation, and materials of construction. The reactor is instrumented to allow pH, temperature, and dissolved oxygen levels to be continuously monitored and controlled. In addition, a gas scrubbing unit is attached to remove organic vapors from process off-gases prior to release into the environment. A third subsystem provides final clarification of the decontaminated water.

Adapted Microorganisms

Bacterial cultures which aerobically metabolize EDC as a sole source of carbon and energy were adapted for continuous degradation of EDC using protocols as discussed in detail in Portier, et al. 1983. These strains were adapted for detoxification applications using mechanisms outlined in earlier aquatic microcosm studies. Particular efforts were made to insure that no other sources of carbon were available for metabolic maintenance and that volatilization losses were controlled to avoid erroneous estimates for substrate availability.

Site Deployment

The reactor was deployed on site at the facility and connected to the existing ground water recovery system to provide a continuous source of contaminated water. Compressed air (oil-free), was introduced at the base of the well-mixed section of the reactor at approximately 500 standard cc/min. The reactor operating pressure was regulated to 30.0 psig and temperature was controlled at 30°C. The pH of the ground water was automatically maintained between 6.5 and 7.5 by addition of 1 M sodium hydroxide solution. Ambient temperatures ranged from 11-35°C over the 30 day field trial. Approximately 12.75 kg of diatomaceous earth carrier (Type R-630, Manville Filtration and Minerals) was installed in the system for the initial pilot test. This carrier is unique in that it has a controlled porosity for optimal colonization of microorganisms, thus providing a considerable biocatalytic capability.

BIOTREATMENT OF EDC-CONTAMINATED GROUNDWATER

Contaminated ground water, diluted 33%, was treated during the course of the field pilot study. Ethylene dichloride (EDC), the primary

waste constituent of concern in this process stream, was monitored for microbial mineralization at dilute and elevated levels of contamination. Both batch and continuous modes of operation were investigated. Batch tests were initiated with initial concentrations of 1.5 to 2.5 mM EDC, while continuous flow tests were run on influent streams with more than double this concentration. Time zero concentration averaged 2.30 mM EDC (Molecular Weight EDC = 98.96 g/gmole) for Batch Tests #3 (Figure 1). EDC concentration was undetectable after 20 hours of holding time. Thus, for batch #3, a mineralization rate of 0.14 mM/L/h was realized. As reported elsewhere, with an influent flowrate of 2.85 L/h, steady-state removal rates for continuous flow mode were 1599 mg EDC/h (Friday and Portier, 1989). Influent feed concentrations entering the system averaged 5.68 mM EDC. Effluents from the reactor averaged 0.009 mM EDC (see Figure 2). A carbon trap in series with the reactor off-gas sorbed volatilized EDC at the rate of 4.84 mg/h, inferring that in excess of 99% of the observed removal rate was due to biodegradation. GC/MS analysis of an off-gas sample collected downstream of the carbon trap just prior to removing it showed non-detectable levels of EDC, indicating that no organic break through occurred.

Chlorinated Ethane Ground Water Study: Gas Chromatography Analyses
Batch Operation #3

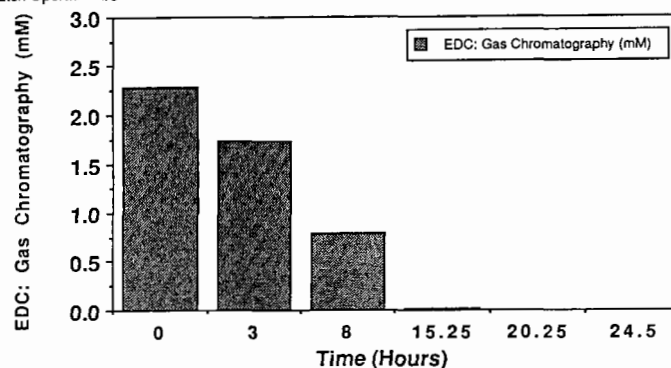


Figure 1
Batch Biotreatment of Ethylene Dichloride (EDC)
Using an Immobilized Bioreactor
(Adapted from Friday and Portier, 1989)

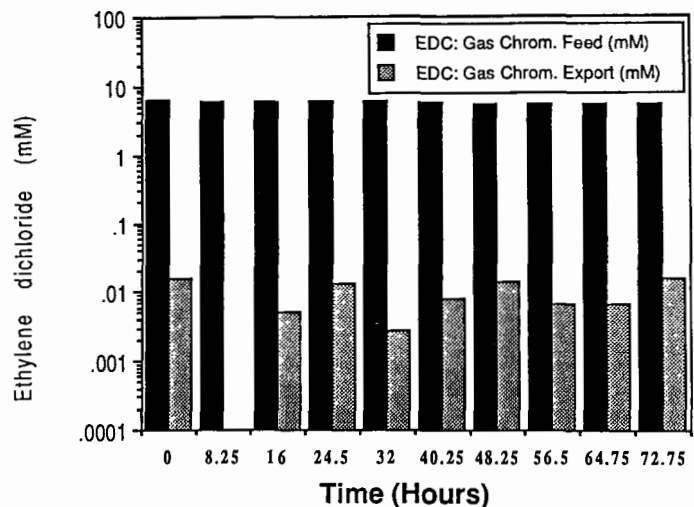


Figure 2
Reactor Influent and Effluent Ethylene Dichloride (EDC)
Concentrations in Continuous Flow Operation
(Adapted from Friday and Portier, 1989)

DISCUSSION

The technologies evaluated to date for the effective treatment of

contaminated ground waters and industrial effluents in industrialized corridors have provided pragmatic, cost-effective solutions for the removal of xenobiotics.

"Once developed and proven, biodegradation is potentially less expensive than any other approach to neutralizing toxic wastes. Such systems involve a low capital investment, have a low energy consumption, and are often self-sustaining operations." Office of Technology Assessment (Nicholas, 1987)

Biological treatment of many groundwater contaminants will significantly minimize the associated costs of excavation, transport and incineration of these materials which are the current commercially available technologies. Additionally, since many xenobiotics have been effectively decomposed to nontoxic substances, a permanent solution to the removal and disposal of such materials can be realized. Biological solutions which involve treatment in place further reduce the risk to the general public by minimizing the necessity of large scale excavation and transportation from contaminated sites to U.S. EPA approved disposal facilities. Future applications of these modular bioreactors in treating waste streams associated with the manufacturing of high technology systems such as circuitry, computers and advanced metallurgical processes is anticipated. Additionally, the usefulness of these systems as recycling devices in life-support systems is technically feasible and, currently, under evaluation.

ACKNOWLEDGEMENTS

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REFERENCES

1. Balthazor, Terry M. and Laurence E. Hallas, 1986. "Glyphosate Degrading Microorganisms from Industrial Activated Sludge" *Applied and Environmental Microbiology*, vol 51 No 2 Feb 1986 p. 432-434.
2. Friday, David D. and Ralph J. Portier, 1989. Evaluation of a packed bed immobilized microbe bioreactor for the continuous biodegradation of halocarbon-contaminated ground waters *Proceedings of AWMA/EPA International Symposium on Hazardous Waste Treatment: Biosystems for Pollution Control*, Cincinnati, OH. Feb 20-23, 1989.
3. Haley, Roger, and Howard Simon, 1988. "Bacteria thrive on phenolic wastes" *Chemical Processing*, Feb 1988 p 156-158.
4. McCann, J., Simmon, V., Streitwieser, D., and Ames, B.N. *Proc. Natl. Acad. Sci. USA* 72 (1975).
5. Nicholas, Robert B, 1987. "Biotechnology in Hazardous-Waste Disposal: An Unfulfilled Promise" *ASM News* 53, No. 3 (1987) p. 138-142.
6. Pearson, C.R. Cl- and C2-halocarbons, In: *The Handbook of Environmental Chemistry*, Vol. 3, 1982
7. Portier, R. J., H. M. Chen and S. P. Meyers, 1983. Environmental effect and fate of selected phenols in aquatic ecosystems using microcosm approaches. *Developments in Indust. Microbiol.*, Vol. 24, Pp 409-424.
8. Portier, R. J. and K. Fujisaki, 1986, "Biodegradation and continuous detoxification of chlorinated phenols using immobilized bacteria" in *Toxicology Assessment*, John Wiley & Sons (1986) vol. 1, 501-513.
9. Portier, R. J., 1987. Enhanced biotransformation and biodegradation of polychlorinated biphenyls in the presence of aminopolysaccharides. *American Society for Testing and Materials* (Special Technical Publication 971, Aquatic Toxicology — 10th Annual Symposium, Adams, Chapman, Landis, Eds.), pp 517-527
10. Portier, R. J., et al., 1988. "Evaluation of a Packed Bed Immobilized Microbe Bioreactor for the Continuous Biodegradation of Contaminated Ground Waters and Industry Effluents: Case Studies" *SAE Technical Paper Series No 881097*, July 11-13, 1988.
11. Timmis, K. N. and S. Harayama, 1987. "Potential for laboratory engineering of bacteria to degrade pollutants." Paper presented at *Reducing Risks From Environmental Chemicals Through Biotechnology*, University of Washington, Seattle, WA. July 19-22.

TOPIC 5: A New Solid/Liquid Contact Bioslurry Reactor Making Bio-Remediation More Cost-Competitive

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ABSTRACT

The reactor system described in this paper has been developed based on slurry agitator technology used in the mineral processing industry. The reactor has been modified to act as a vessel in which naturally occurring biological degradation processes are enhanced. It provides aeration, mixing, temperature control, nutrients, and in certain applications, volatile emissions control. A bioslurry reactor approach is recommended to biodegrade organic hazardous substances in a matrix where in-situ land treatment often fails. A bioslurry reactor can also be used in a soil-washing flow sheet for the fine particle fraction which contains often the highest contaminant levels.

The bioslurry reactor presented in this paper can handle solids concentrations in the 30-50 wt% range. Energy consumption is typically only 25-50% of that needed in conventional liquid/solid contact (LSC) reactors which use turbine mixers or surface aerators. The reactor is presently being tested in RCRA and Superfund applications.

INTRODUCTION

Many of the organic substances listed by the U.S. Environmental Protection Agency (U.S. EPA) as hazardous are biodegradable.¹ On most Superfund sites organisms have been identified which can biodegrade the organic contaminants given the availability of oxygen and nutrients, and under the right environmental conditions (soil pH, temperature, moisture). Since none of these parameters are usually in the optimal range for the bacteria involved, biodegradation in nature is often very slow.

Table 1 summarizes the four methods commonly used for bioremediation. Most experience has been gained with land treatment, particularly in the oil refining industries,² and whenever hydrocarbon spills are being cleaned up. It is the bioremediation technology of choice if land is readily available and time is no constraint. In colder climate, bioremediation by land treatment often comes to a virtual standstill during the winter months as the top soil freezes. Clean-up levels in a slurry reactor system are more predictable than land treatment units.

Composting, on the other hand, produces some heat and may become a more widely used bioremediation technology, especially in colder climates.

In-situ treatment is the only alternative when the contaminants have reached deep subsurface levels or are primarily under buildings and excavation is not possible. Hydrogeologists play a major role in the effort to get nutrients and oxygen to the contaminated areas and stimulate bacterial activity.

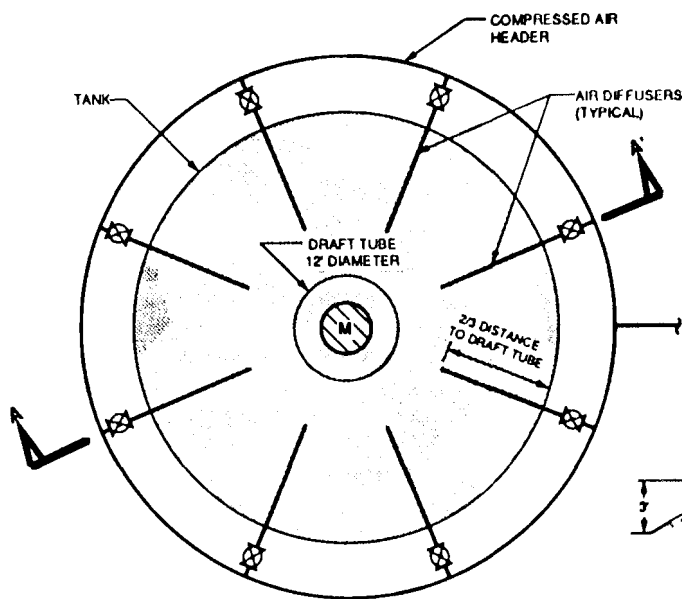
Liquid/solid contact systems have been used, primarily in lagoons (in-situ) or where tanks are available on site. However, it has been found that energy input has to be kept quite high in order to keep the soil particles suspended. Solids concentrations often have to be limited to 10-20 wt% in order to keep the particles sufficiently suspended. Power outages can cause significant operating problems as the materials settle

Table 1
Bioremediation

- Land Treatment
- Composting
- Liquid/Solids Contact systems
- In Situ Treatment

out and compact. Air is often provided through spargers which can clog quite easily during a prolonged power outage. An LSC reactor is shown in Figure 1. This features above ground tank construction, draft tube with direct-drive mixing, and control of volatiles.

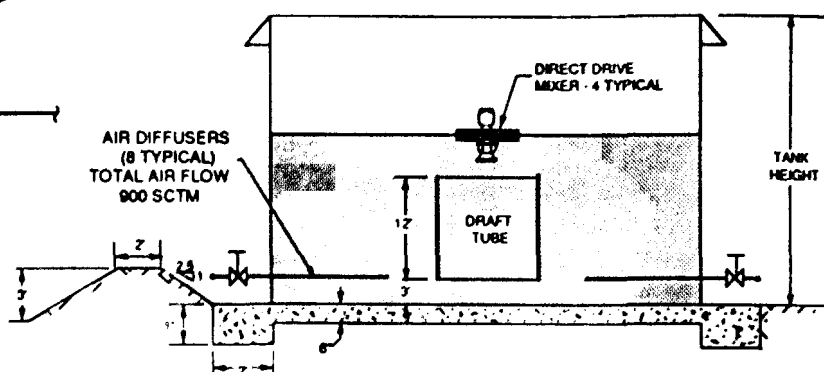
The EIMCO Biolift™ reactor, shown in Figure 2, is basically a modified slurry agitator that uses a dual drive design which EIMCO has manufactured for its Reactor Clarifier™ for decades. This dual drive allows independent operation of the axial flow impeller and the rake arms at two distinctly different speeds. In a large diameter tank, the impeller, mounted on a separate shaft, typically rotates at 20-30 rpm while the rake arms turn at less than 2 rpm. Diffuser panels consisting of vertically stacked diffuser tubes are mounted on the rake arms. The diffuser tubes are of a special rugged design, allowing rotation through an often viscous slurry without breaking at the point of connection to the air manifold. The diffuser membranes typically consist of a slotted elastomeric material which has been selected to chemically resist the organic contaminants found in the soil slurry. Such diffusers are known to be relatively clog free and to have superior oxygen transfer efficiency. In addition, release of the rotating curtain of fine air bubbles keeps most of the fine particles in suspension and creates the necessary turbulence to enhance the mass transfer of oxygen, nutrients and substrate molecules into the bacteria cell. The impeller turning at a higher speed causes a downward flow and affects bulk blending. Variability in contaminant concentrations in the feed stream is less a problem in such a completely mixed reactor than it would be in a batch reactor, where high substrate concentrations at the onset can be inhibitory to the bacteria.



TYPICAL BSC TANK REACTOR
PLAN VIEW NOT TO SCALE

TANK DIAMETER = 45'

TANK HEIGHT = 48'



SECTION A-A'
NOT TO SCALE

Figure 1
Liquid Solids Tank Reactors

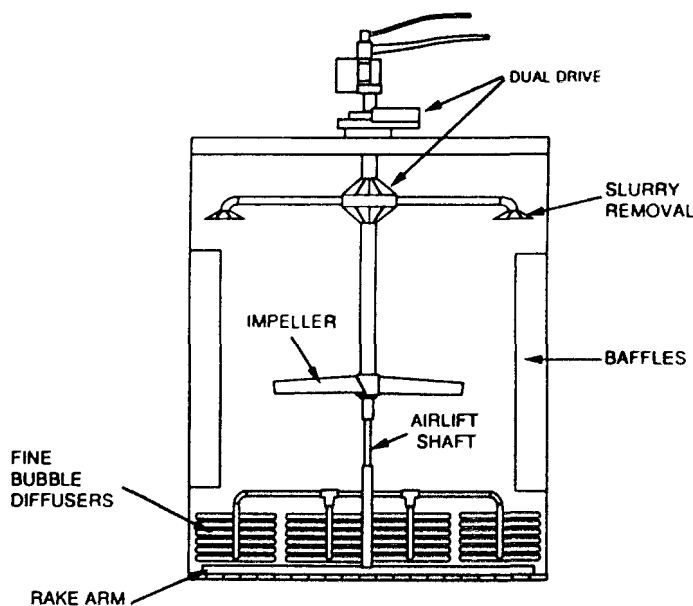


Figure 2
Emico Biolift™ Reactor

The tank is baffled to enhance mixing. Coarser particles which are not kept in suspension by the fine bubble diffusers and have settled to the tank bottom are raked to a central airlift which pumps them to the top, where they are discharged into a specially designed slurry removal system. A Y-shaped pipe with a vertical leg connected to a funnel collects the slurry directly from the airlift. Since the airlift transporting material from the tank bottom will contain a higher concentration of coarse solids than the average slurry in the reactor, it is possible to regulate the quantity of coarse solids within the tank by means of this take-off device and pass a fraction of this material on to the next reactor or out of the system. Control of coarse solids

is essential in order to minimize torque on the mechanism.

Depending on the application, any number of reactors can be arranged in a cascading system to permit continuous feed and overflow. The more stages are arranged in series, the more the system approaches true plug flow conditions. At the same time, optimum biokinetic rate is achieved in each stage. The bacteria population is fully acclimated to the organic contaminants and biomass concentration has reached an optimum in accordance with substrate concentrations available.

Alternatively, the EMICO Biolift™ Reactor can be run in a batch or a semi-continuous feed mode. From a process engineering point of view, such a mode of operation is more easily controlled, but kinetic rates will be slower because of a lag phase in bacterial activity as a result of acclimatization and biomass growth.

In order to use a slurry reactor effectively in a soil remediation project, some pretreatment will be required to remove all oversize material. A proposed remediation flow sheet is shown in Figure 3. The excavated contaminated soil is first moved through an attrition mill to slurry up the material. After this, it passes through a trommel screen to remove any gravel, debris, and other oversize material. The soil passing through the screen is then fed into a counter-current washing screw classifier. Most of the sand will be clean after these three washing steps and can be discarded. The finer materials and the excess wash water that can not be recycled are then passed into a series of bioslurry reactors.

Total hydraulic residence time in these reactors will vary depending on the nature of the organic contaminants, their concentration, and clean-up level required. The soil slurry is finally dewatered in either a pressure filter, vacuum filter, or centrifuge. The most efficient and economical dewatering equipment is dependent on the soil characteristics and the quantities of slurry to be processed. It must be evaluated on a case-by-case basis.

The process shown uses bioslurry reactors as the primary treatment step. Other flow sheets are possible as long as they achieve the pretreatment objectives of slurring, washing, and classifying into different size fractions.

VOLATILES EMISSION CONTROL

In many instances volatiles emission control is very desirable,

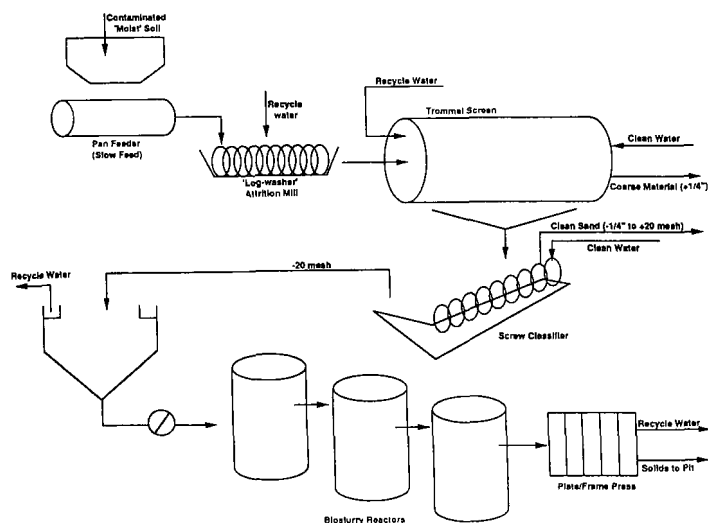


Figure 3
Bioremediation Flow Sheet

particularly if discharge of toxic air emissions would exceed applicable air pollution control standards. Since a number of these volatile organic compounds are readily biodegradable, but are air-stripped by the diffusers before the bacteria have metabolized them, a mode of operation was devised whereby the off-gas, collected in the reactor top, is recirculated back into the slurry via the diffusers. The reactors are gas-sealed and the compressor recompresses the off-gas. This gas stream is continuously analyzed by on-line oxygen and carbon dioxide analyzers. The flow schematics are illustrated in Figure 4.

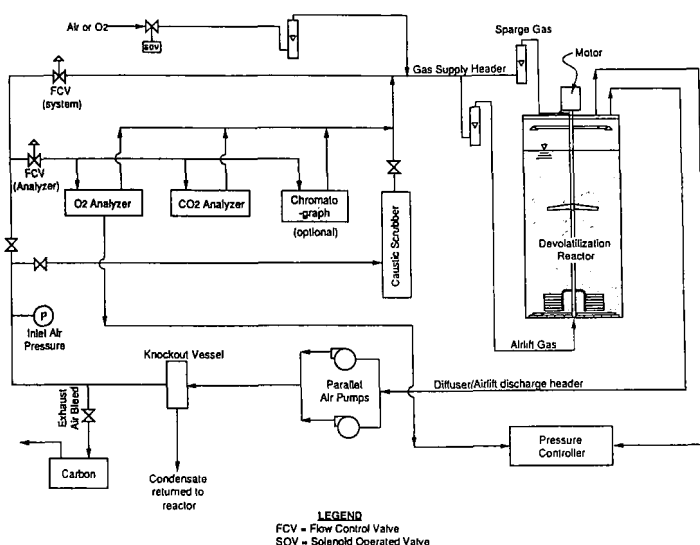


Figure 4
Liquids/Solids Reactor With Volatilization Control System

The gas analyzers have control capability and can actuate solenoid valves at pre-determined setpoints. For example, if carbon dioxide, due to the bacteria's metabolic activities, increases above the setpoint, a portion of the gas stream is passed through a scrubber until the carbon dioxide concentration has been reduced to an acceptable level again. Likewise, when the oxygen concentration due to bacterial uptake drops below the setpoint, air or pure oxygen is admitted to the system until ambient oxygen concentration has been restored. An equivalent volume of air is treated through a carbon adsorption column to remove any residual non-biodegradable organic volatile compounds. Operation in the gas recirculation mode reduces the cost for expensive volatile

emissions treatment significantly. The reactor is always operated at a slight vacuum of 1" to 2" W.C. to avoid any undesired emissions.

FIELD EXPERIENCE

The EIMCO Biolift™ reactor has been used to date in two applications. In one application a RCRA refinery sludge with an oil and grease concentration of approximately 40 wt% was aerobically digested. Total solids concentration in the reactor was 25 wt%. The reactor was operated in the batch mode and a 60 wt% reduction in the oil and grease was obtained after 39 days. After all of the carcinogenic compounds of concern have been removed to acceptable levels, the material can then be further treated in a land treatment cell. In this application, gas emission control was particularly important.

In a second application, the reactor is presently being used to treat the fine particles stream, residue from a soil washing operation. The contaminants are primarily PAH's and pentachlorophenol. Based on preliminary results, a 90 to 95% removal can be achieved in a three-stage continuous flow system.³

ECONOMIC CONSIDERATIONS

The advantages of the EIMCO Biolift™ reactor are primarily related to operating and maintenance costs. Energy consumption is typically less than one half of what is required when turbine mixers or surface aerators are employed. In a recent cost comparison between the two technologies for the bioremediation of approximately 30,000 yd³ of contaminated soil, capital costs were \$76/yd³, and operating costs were \$60/yd³ for employing surface aerators and draft tubes. Using the EIMCO Biolift™ reactor would result in the same capital costs but would show operation cost savings of \$13/yd³, primarily due to energy savings. Because of the large size reactors required to meet the clean-up schedule, all the bioslurry reactors would be depreciated over the life of the project as reuse on another project would be difficult.

Capital costs are strongly influenced by the size of the project and the time schedule in which it has to be executed. In order to achieve further economies, it is important to standardize the bioslurry reactor as much as possible. Presently it is envisioned to build four reactor sizes from 70 m³ to 1,100 m³. The first size reactor would still be transportable completely assembled and thus would require only minor erection work in the field. After its use and decontamination on site it would be shipped and reused on the next site. Any reactor larger than can be transported by road in one piece will need to be assembled and erected in the field. The rake and airlift mechanism can be constructed such that it can be dismantled into several pieces which can be reconnected and reused. Tanks may or may not be reusable depending on the circumstances.

OUTLOOK

EIMCO Process Equipment Company is presently engaged with several process engineering firms in the proposal of pilot and full-scale remediation projects intending to use bioslurry reactors. The issue of scale up is being investigated in order to design large scale reactors based on the kinetic data obtained at the bench scale. Several alternatives to provide mixing and aeration in a more cost-effective manner are being examined as well. It is believed that bioslurry treatment in large scale reactors will one day be as common as Activated Sludge processes in waste water treatment. To reach this point a concerted effort will be required between process engineering companies and equipment manufacturers.

REFERENCES

1. Nicholas, R.B. and Giamporcaro, David E. Nature's Prescription, *Hazmat World*, June 1989.
2. ReTec, *Effectiveness and Cost of Various Bioremediation Technologies*, RCRA Conference New Orleans, April 1989.
3. EPA SITE Demonstration, Biotrol Soil Treatment System, Sept. 1989.
4. David R. Hopper, Cleaning Up Contaminated Waste Sites, *Chemical Engineering*, August, 1989.
5. C.H. Vervalin, Bioremediation on the Move, *Hydrocarbon Processing*, August 1989.

Calcining Rotary Kiln For Detoxification of Non-Autogenous Wastes

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ABSTRACT

An advanced multiple burner system has been invented and is being developed and tested. The multiple burner is designed to direct and focus a plurality, usually 30 to 40 individual burner flames, directly on the tumbling bed of contaminated feed stock to be thermally treated, detoxified, and calcined in a rotary kiln combustion system. Combustion air which is pre heated, natural gas or LP gas and/oxygen is delivered to each burner through a patented and proprietary free spanning, air cooled, platform and manifold. The principal objects of this new burner system are to increase throughput, improve destruction efficiencies, decrease particulate entrainment and fundamentally improve the thermal destruction/treatment and calcination of feed stocks, which are contaminated with organic constituents and are non-autogenous in nature such as soils, sludges, slurries and excavated landfills, for example, in rotary kilns.

INTERACTION

For many decades, rotary kilns have been widely viewed as the "work horse" of the calcination and toxic/hazardous/industrial waste incineration/thermal treatment/destruction industry. Globally, thousands of rotary kilns are in use thermally treating/incinerating thousands of feed stocks, many contaminated with various organic chemicals. It is widely accepted that virtually any solid, sludge, slurry, etc., or combination thereof, can be processed in a rotary kiln. Many kilns calcine lime and cement, as well.

In spite of rotary kiln's advantages and abilities to accommodate and process almost all solid feedstocks, kilns have traditionally been an inefficient process. Rotary kilns have been sized with very large combustion volumes in order to reduce velocities of the gases as they exit the kiln, in the effluent, in order to reduce particulate entrainment. Kilns normally have to be fitted with large and expensive scrubbers to reduce particulate discharges to permissible levels. The relatively large volume of kilns has increased their Capital costs as well as their operating costs, particularly the replacement of refractories periodically, a time-consuming and costly operation. Additionally, the inefficiencies of the heat loss and dissipation of heat energy, through the kiln shell, which often is a significant waste of energy, increases operating expenses. Traditionally, kilns calcinating non-autogenous materials utilize large oil, gas or combination burners which are mounted in the firing hood(s) or breeching(s) of the kiln. Normally, the burner's flame pattern covers or contacts only a portion, often only a small zone or section of the tumbling bed of feed stock, an inefficient method. The poor contact between the burner flame and the tumbling bed of non-autogenous feed stock being thermally treated typically requires rotary kilns to be quite large and particularly long.

MULTIPLE BURNER SYSTEM

The multiple burner system is typically 30 to 50 individual, small burners, usually with thermal outputs of 0.5 to 1,000,000 BTU/HR burner. These burners are distributed along an air cooled platform and manifold which spans from head/breeching to head/breeching, generally in an offset, axial location within the kiln. The offset location allows for the individual flames, which are typically 3 ft in length, to be directed at and on the tumbling bed of soil, sludge, slurry, lime, cement or excavated landfill feed stock.

The thermal output of these burners can be regulated by adjusting the combustion air, gas and oxygen flow rates. The combustion air is also the cooling air for the platform and is pre-heated due to the cooling effect. The cooling effect enables the maintenance of the structural integrity of the air cooled platform system. The flame temperature can be regulated from 2,500°F to 4,000°F with maximum oxygen enrichment.

The flame is positioned so that it is generally tangential to the kiln shell. This tangential flame direction positioning has an additional benefit in that a cyclonic, swirl, helical pattern of air, gas and particulate is induced. Previously, tangential combustion air injection systems and technologies developed by the author have repeatedly demonstrated the ability to centrifuge particulate out of the air/gas/particulate mixture in rotary kiln incineration systems due to this beneficial tangential injection of air and other gases.

US Department of Energy studies have documented the dramatically reduced particulate loading in a kiln's flue gases due to the centrifugal effects derived from the tangential injection of combustion air, in swirling patterns, throughout the entire length of rotary kilns via a plurality of combustion air injection nozzles. Particulate loadings of flue gases have been consistently demonstrated and documented at 0.08 GR/SCF utilizing the earlier combustion air injection version of this free spanning system. Particulate entrainment rates, in flue gases, below 0.08 GR/SCF have been demonstrated with certain feed stocks, as well. This cyclonic effect on particulate entrainment can eliminate the need for scrubbers. In other cases, gas cleaning systems can be down-sized and are subject to less wear, maintenance and abrasion than is typically the case.

KILN DOWNSIZING

This new system is showing great promise with its ability to shorten rotary kilns. A great many very large rotary kilns are operating in calcining modes, producing lime and cement. Most of these kilns are 150 to 400 feet in length. Our studies indicate that this system of multiple burners, directed and focused on the tumbling bed of feed stock, rather than one large flame, with its uneven heat transfer and hot/cold zones, can dramatically reduce lengths of kilns from 150 to 400 ft down

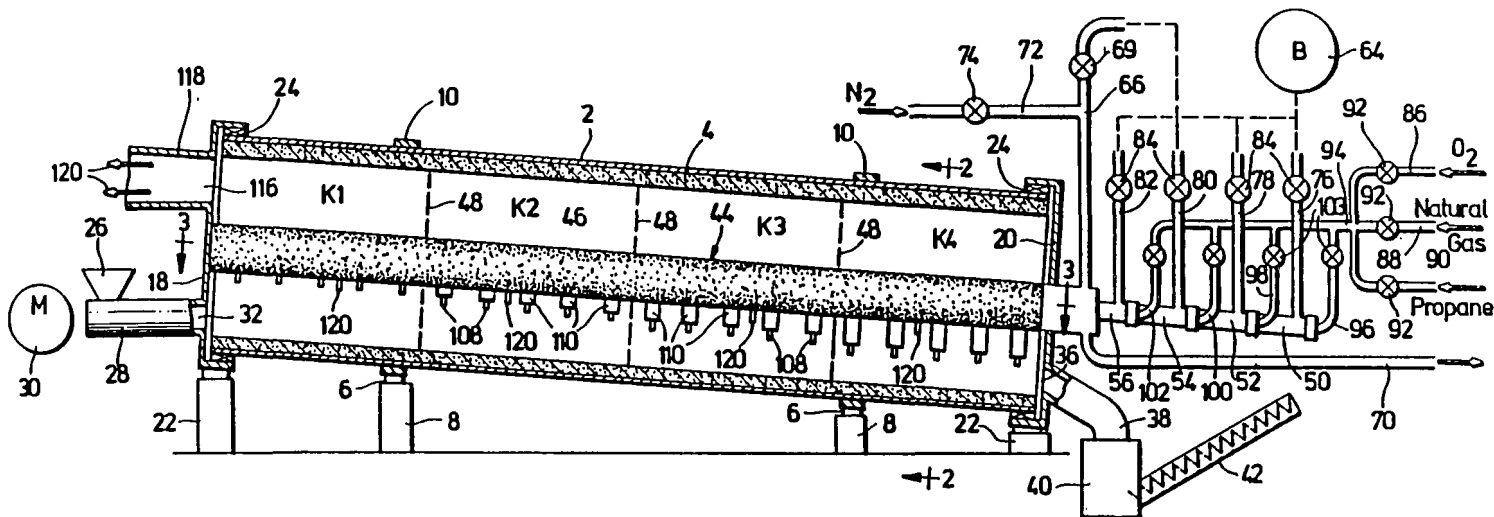


Figure 1

to 60 ft in length while maintaining throughputs. Thermal processing and efficiency are improved and fuel is saved.

An additional goal in the testing and demonstration of the process is to improve destruction efficiencies of the organic contaminants in the non-autogenous feed stocks.

Another feature of the process is its ability to divide a rotary kiln into four or more independently controllable zones.

These systems typically are outfitted with thermocouples which are distributed along the air cooled platform. There usually is one thermocouple per zone and four usually are installed. The thermocouple bases and wiring are protected in the air cooled, free spanning system.

RESEARCH AND DEVELOPMENT PROGRAM

A Research and Development/Demonstration project is being implemented for this patented and proprietary system now assigned to Universal Energy International, Inc. The system discussed herein will be installed on a test center rotary kiln owned by Fuller Company's Fuller Power Corp. of Bethlehem, Pennsylvania. Additional participants are Air Products & Chemical, Inc.'s Applied Research and Development group. A wide variety of non-toxic, non-hazardous materials will be pyro-processed. Destruction of surrogate contaminants in feed stocks

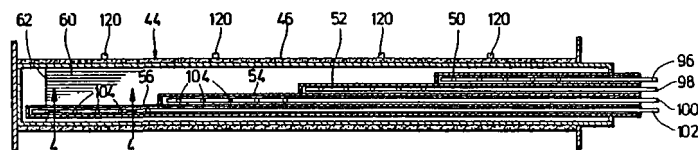


Figure 3

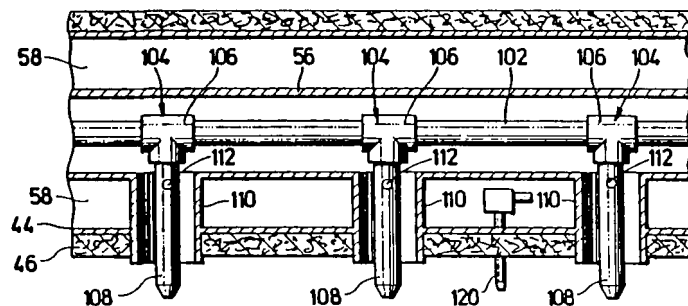


Figure 4

will be studied and destruction efficiencies will be established. Air Products & Chemicals, Inc. is providing oxygen control and regulation systems and technical input.

Certain versions of these systems and technologies are being offered for immediate commercialization. The assignee of this technology has offered proposals to sell two systems which are approximately 60 ft long for commercial soils detoxification and incineration projects, both portable and fixed sites and systems.

Grant applications are pending with the U.S. Department of Energy and the National Science Foundation. Plans are being developed to demonstrate this system under a U.S. EPA SUPERFUND program, the innovative technology program. Research and development funds have been allocated and set aside by the U.S. Department of Energy/Pittsburgh Energy Technology Center for a similar test demonstration, and R & D program where an air/sorbent injection/data acquisition version of this proprietary will be operating during the parallel program.

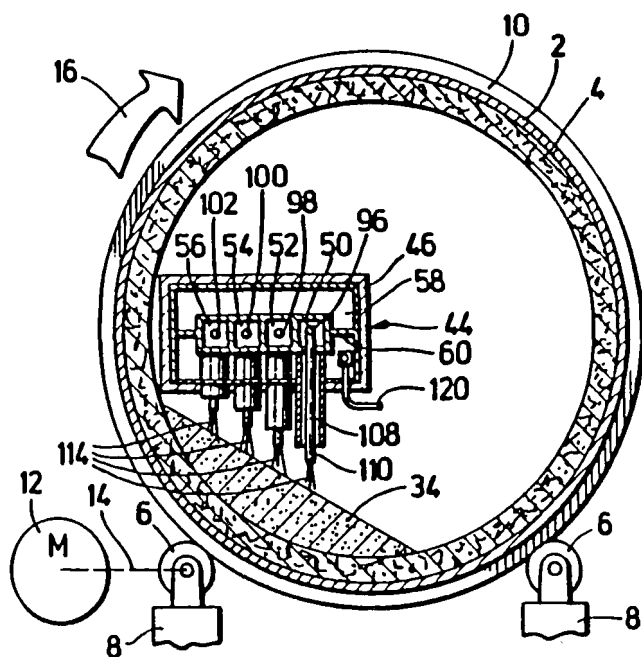


Figure 2

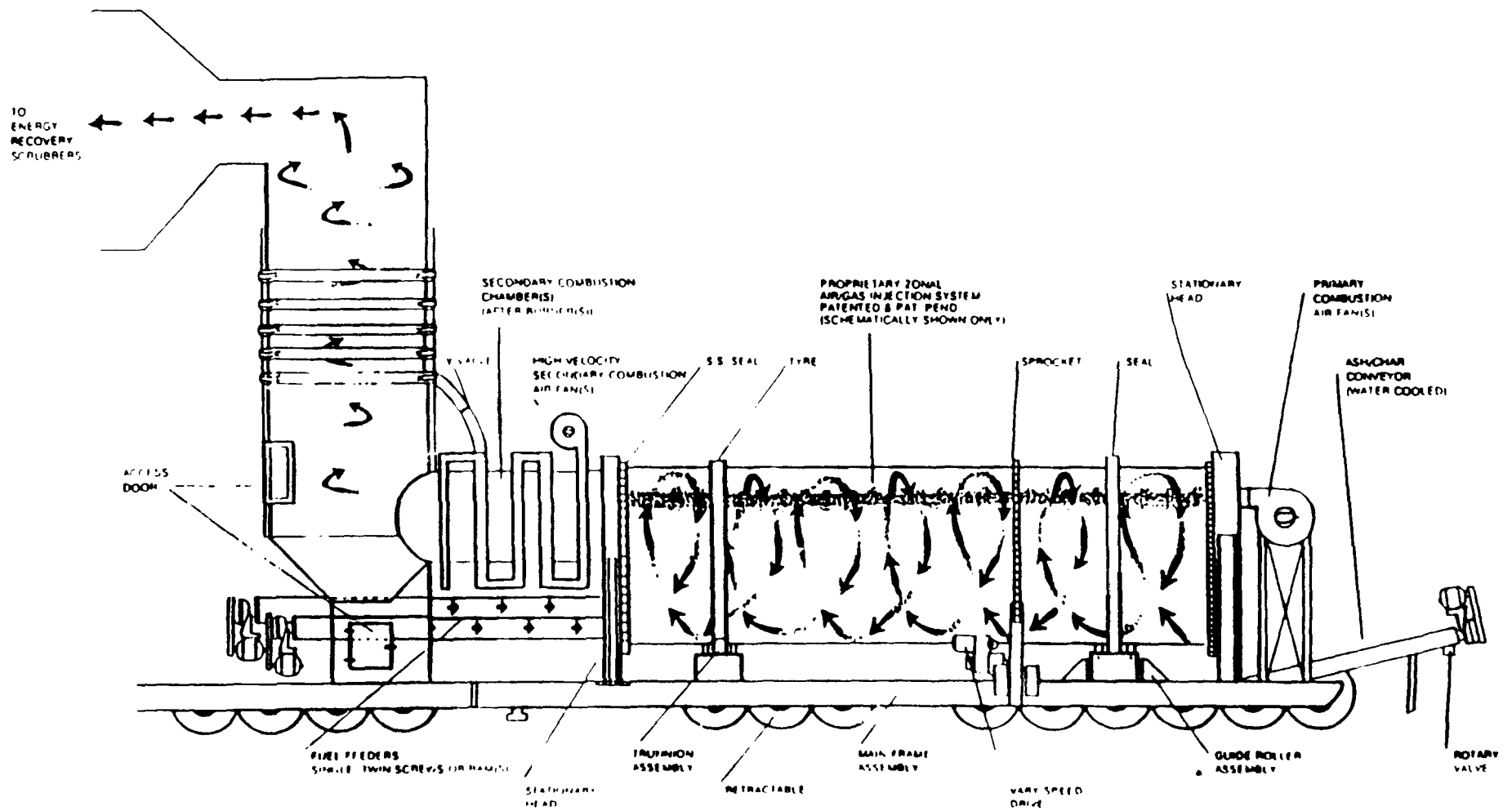


Figure 5

Site Remediation Using Mobile Thermal Destruction At the Electric Utilities Site in LaSalle, IL

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Richard M. Lange
Greg R. Michaud

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ABSTRACT

Electric Utilities Co. (EUC) was a manufacturer of capacitors in LaSalle, Illinois until 1981. EUC left this site in 1981 and filed bankruptcy in 1983. During operation, EUC had used PCB dielectric fluid in the product and had used waste oils for dust control both at the facility and in an adjoining residential neighborhood. Subsequently, wind erosion and vehicle traffic transported PCBs up to 1.2 mi from the site. In addition to PCB soil contamination, the local groundwater has been impacted by chlorinated solvents.

Two phases of remedial action (RA) were planned: to (1) off-site soil contamination in Phase I, and (2) on-site soils, groundwater and stream and sewer sediments in Phase II. On-site thermal destruction is the selected alternative to remediate this site. Phase I is in progress with Phase II in the procurement process.

The Phase I RA which involved 1.2 of inner city state highway required relocation of 25 families during excavation. After excavation, extensive landscaping was required to restore the neighborhood to pre-excavation conditions. This landscaping required replacement of \$120,000 in trees and perennial plants and 27,000 yd³ of sod.

The excavated material was segregated into two stockpiles based on levels of PCB contamination. One stockpile contained less than 50 ppm PCB-contaminated material while material with more than 50 ppm PCBs was placed in the other. The total payable yardage excavated was 23,258 yd³ and was nearly equally divided between less than 50 and greater than 50-ppm contaminated material. Thermal destruction is ongoing at this time on the greater than 50 ppm waste under authorization by IEPA, with concurrence by the U.S. EPA. Treatment of the less than 50 ppm material is complete. Thermal destruction services are being provided by Westinghouse-Haztech utilizing an infrared unit originally manufactured by SHIRCO.

The thermally treated soil has to meet a cleanup criterion of 2 ppm total PCBs and originally was regulated as a State of Illinois Special Waste. The Phase I RA treated soil is going off-site for disposal to a landfill where it is permitted to be used as daily cover. The Phase II treated soil will be used as on-site backfill where possible. This handling of treated soil allows control of the material but does not consume valuable landfill capacity.

The unique feature of this RA is the extensive interaction with the residential population due to the extensive excavation of lawns. This project posed a major community relations challenge.

INTRODUCTION

The Electric Utilities Company (EUC) site in LaSalle, Illinois is currently the subject of Phase I of a multiphased Remedial Action (RA). The EUC manufactured industrial capacitors utilizing PCB as a dielectric fluid. In 1981, the company left this location and relocated their

operations to North Carolina. Soon after moving, EUC entered bankruptcy and dissolved the company. During their final years in LaSalle, EUC had been the subject of a number of regulatory complaints and enforcement actions by both the Illinois Environmental Protection Agency (IEPA) and the U. S. EPA.

In 1983 and 1984, Immediate Removal actions by the U.S. EPA removed some waste material and redirected surface water flow back onto the site and into a pond for sedimentation and infiltration. An adjacent off-site business parking lot and driveway were asphalted to limit access to contaminated soil. In 1986, the IEPA conducted a followup Immediate Removal action to dispose of 260 drums of waste and 735 gal of trichloroethylene (TCE). Following in IEPA's tradition of reducing quantities of waste for disposal, this solvent was analyzed and determined to be of sufficient quality to appropriately re-enter the commercial market.

The Remedial Investigation identified extensive on-site soil contamination by PCBs on-site, certain soils contaminated by chlorinated naphthalenes, on- and off-site contamination of groundwater by various chlorinated solvents (predominantly TCE) and PCBs (including free oil) and extensive off-site PCB contamination. The off-site PCB contamination of soils unexpectedly included widespread contamination in residential yards, business properties, agricultural fields and approximately 1.2 mi of street right of way. Some of the more unusual areas contaminated with PCBs included the presence of PCB dust in the interiors of homes and businesses including furnace ducts, storm and sanitary sewer sediments and stream sediments where the storm sewers surface.

The measured quantities from Phase I of the RA and the Engineers' estimate for the Phase II RA revealed the extent of contamination. The following quantities and types of waste have or will be remediated: over 23,500 yd³ of off-site soil and 42,000 yd³ of on-site soil with PCB concentrations ranging up to 113,000 ppm; as much as 1000 gal of transformer oil with PCB concentrations expected in the 50 to 60% range; up to 1000 ft of a remote off-site stream requiring excavation. Over 7500 ft of storm and sanitary sewer will be hydraulically and mechanically cleaned and 3500 ft of passive groundwater collection will be piping placed at depths to 25 ft to feed a water treatment plant which will be constructed for remediation of the solvent- and PCB-contaminated groundwater. This water treatment plant is expected to generate an additional 188 tons of PCB-contaminated oil.

The factory building complex is so heavily contaminated with PCB that demolition is the selected option followed by thermal destruction of all amenable materials. Additionally, the factory buildings and remaining process equipment harbor significant quantities of asbestos contaminated with PCB. This material will require off-site disposal in an appropriate secure facility.

The Feasibility Study (FS) evaluated the standard options to protect the human health and environment including the No Action Alternative, Waste Consolidation and the construction of an On-site Landfill and Off-site Disposal in a Landfill. Additionally, the FS evaluated the long term permanent solutions of Off-site Thermal Destruction and On-site Thermal Destruction. The landfill options seemed to meet the criteria for appropriate alternatives but did not satisfy citizens' concerns about removing the contaminated material from their town and making the property a usable resource. Additionally, this option was not fully acceptable to the State of Illinois because it failed to provide the permanence of destruction, leaving the state a long-term operation and maintenance responsibility. The alternative which was ultimately selected utilizes on-site mobile thermal destruction for all treatable material, with off-site landfill disposal held to a minimum. The only on-site disposal will be for innocuous, thermally treated material.

PHASE I REMEDIAL ACTION

During Phase I RA, 23,258 yd³ of PCB-contaminated soil from off-site locations was excavated and placed in stockpiles on the site pending thermal treatment. The containable material was placed into two separate stockpiles based on the level of contamination. One stockpile was reserved for material with PCB concentrations of less than 50 ppm and the other for material found to have concentrations greater than or equal to 50 ppm. Thermal treatment of the less than 50 ppm material was initiated on Nov. 29, 1988, under an interim Operating Approval Letter issued by the IEPA. Completion of thermal treatment of this material was accomplished on June 14, 1989, and treatment of the 50 ppm or greater material began on that date. Treatment of the greater than 50 ppm material is also taking place under an Operating Approval Letter issued by IEPA with U.S. EPA Region V concurrence.

The thermally treated soil from this RA was originally being transferred as Special Waste to a local, IEPA-permitted Illinois Special Waste Landfill under Illinois' Special Waste Manifest system (Special Waste, as defined in Illinois, means any industrial process waste, pollution control waste or hazardous waste). After sufficient experience with the treated soil was gained (both chemically and physically) by IEPA, the RA Contractor and the landfill operator the following program has been approved: the thermally treated soil from the Phase I RA has been delisted as Illinois Special Waste and is simply considered waste; the treated soil is no longer subject to manifesting requirements and the treated soil is permitted to be utilized at the landfill as daily cover material. This delisting resulted from a coordinated effort by all parties. This delisting and daily cover use meets two needs. The material is sufficiently innocuous to require no manifesting or special management. Useable as daily cover, the material is being removed to an appropriately secure facility for public comfort but is not consuming valuable landfill capacity.

In addition to the excavation and thermal treatment of PCB-contaminated soils, the Phase I RA included cleaning of the interiors of 25 private homes and 2 businesses and the replacement of all landscaping material removed during excavation in their yards. This effort involved the laying of 27,000 yd² of sod and the replacement of over \$120,000 worth of landscaping.

PHASE II REMEDIAL ACTION

In the Phase II portion of this RA, a contractor will demolish the existing factory complex with the goal of decontaminating or thermally destroying all possible materials, in order to reduce off-site disposal to a minimum, thereby reducing disposal facility consumption and reducing the State's long-term liability. This waste minimization effort is being encouraged by the absence of various pay items in the bid specifications and financial encouragement of thermal destruction, the payment for certain decontamination efforts and the return of all salvage dollars to the contractor. One example of these specifications will be an extensive coring and sampling effort directed at over 68,000 ft² of concrete flooring; this concrete will be analyzed in an attempt to identify the depth of PCB penetration. Where the concrete overlays uncontaminated soil the contaminated surface of the concrete will be mechanically removed and the collected material will be thermally

treated. Following decontamination, this concrete may go to a "Demolition Debris Only" landfill or, in the absence of reinforcing steel, may be used as clean fill in land reclamation or as rip rap in local surface water projects (the town of LaSalle is located on the North bank of the Illinois River).

Following demolition of the factory buildings, excavation of an estimated 42,000 yd³ of PCB-contaminated soil can proceed unencumbered. One significant difference between Phase I and Phase II is that in Phase II the area of excavation will be under complete control of the remediation contractor and the State of Illinois. This control will allow the use of treated soil as backfill on site. In Phase I, the excavation and backfill had to proceed rapidly to reduce impact on various residential and business property owners, thereby requiring an immediate source of backfill material; in Phase II, the excavation of contaminated material can more closely follow the production capacity of the thermal destruction unit. This item is not specifically required in the specifications but is encouraged by the absence of both a Backfill pay item and an Ash Disposal pay item in the contract documents. Obviously, the contractor is financially encouraged to utilize treated soil as on-site backfill. The chemical quality of the treated soil will be closely monitored, and the treated material will not be used within 1 ft of final grade; this requirement should assure rapid establishment of vegetative cover and reduce the potential of light tillage operations turning treated material to the surface, thereby unnecessarily raising public concern.

The removal of contaminated sediments, soils and debris from the off-site stream will follow relatively standard cleanup methods as will the sewer cleaning operations. One exception is to the standard methods, is that trees and brush must be removed to construct a temporary access road to the stream area. All woody vegetation growing in uncontaminated areas, and vegetation not in contact with contaminated soil, must to be mulched for landscaping use or destroyed in an Air Curtain Destructor. None of this material will be allowed to consume landfill capacity. All sediments, soil and potentially contaminated vegetation must be collected and treated in the Thermal Destruction Unit.

The remaining significant portion of the Phase II RA is the groundwater treatment system. As previously stated, the aquifer under the site is contaminated with both chlorinated solvents and PCBs in both a free oil and dissolved state. This treatment plant will be supplied by approximately 3500 ft of perforated PVC pipe in a washed gravel bedding with the bedding encased in a filter fabric outer casing. This piping network will be placed at depths of up to 25 ft and will be placed in such a manner as to gravity feed a single wet well collection point for pumping to the water treatment plant. The treatment plant will consist of an oil/water separator, a particulate filter system, two air stripper columns and a pair of carbon filters. The plant will duplicate air strippers and carbon units to allow a higher initial flow rate by using these units in parallel. Later, during normal operation, series operation will be employed to obtain higher effluent quality. Finally, one unit may be placed in standby status to allow operation to continue when a unit must be removed from use awaiting service.

The water treatment plant will discharge its effluent to the City of LaSalle wastewater treatment plant and be relatively maintenance free to allow ease of operation. The operation of this plant will be turned over to another party when the Phase II RA contractor exits the site. The groundwater treatment effort is expected to be operated an additional 8 to 10 yr.

COMMUNITY RELATIONS

Three factors suggested that community interest would be relatively high at this site: (1) location in a residential area with over 10,000 residents; (2) presence of PCB in high concentrations; and (3) location in the hometown of a state legislator who is an active member of the legislative committee which reviews the IEPA's budget.

Following a community assessment in the fall of 1983, the first community relations activity was a joint presentation with U.S. EPA officials at a City Council meeting in January, 1984. During the RI/FS, personal interviews, telephone calls, fact sheets and "living room" meetings were used to identify and respond to community concerns.

During the RI, soil and groundwater sampling revealed high concentrations of PCBs on-site and, unexpectedly, on adjacent property. A literature review and discussion with state and federal potentially impacted groups as a result of contact with PCB-contaminated soils: (1) children when playing in yards and, (2) adults when gardening. This discovery was presented individually to the City Council, LaSalle County States Attorney, owners of the 26 affected properties and finally the news media, in personal meetings conducted by two teams of community relations and technical staff. It was felt that releasing this information only through a letter or news release would be inadequate and could create confusion or panic in the community. None of the residents reacted negatively.

Four risk communication guidelines were followed in designing this public information effort to inform the community of these results. First, the Agency wanted to explain what the numbers meant, with a special emphasis on exposure and routes of exposure. In this case, a literature review and discussion with the Illinois Department of Public Health (IDPH) and the Centers for Disease Control (CDC) indicated two exposure routes: (1) children playing in the dirt and, (2) to adults gardening. Second, IEPA needed to coordinate both internally as well as between agencies (U.S. EPA, IDPH, etc.) to prevent sending out mixed or contradictory messages. Third, the IEPA followed a strict sequence for releasing the results to prevent affected families from hearing about this problem through the news media first and to enlist others, notably, City officials and the States Attorney's office, to provide a calming effect from within the community. Finally, a practice session was held in which the IEPA developed and critiqued an approach based on a simple, candid, low-key explanation using words easily understood by each resident.

A year later the FS, describing proposed remedies, was completed and presented to the community. At this time, IEPA preferred a remedy which included mobile incineration. However, several issues existed which threatened community acceptance of this remedy. A newly elected Alderman was openly critical of the IEPA. A popular state senator from LaSalle expressed reservations about incineration of hazardous waste. A small portion of the community still doubted that the site posed any health threat and 25 families would have to temporarily leave their homes while their yards were excavated. Also, at the time this remedy was being considered, a mobile incinerator had not been successfully used to destroy on hazardous waste anywhere in the state.

Upper management agreed that if significant opposition from the community arose towards this remedy, another remedy would be selected. A fact sheet summarizing the proposed remedies, their advantages and drawbacks and explaining how to submit comments was distributed through the mail and made available at the LaSalle City Hall. Small group meetings with, interested citizens, city and county officials and local news media were held to discuss the proposed remedies. Following these meetings, a public hearing and a 3-wk public comment period were scheduled. A list of anticipated questions was prepared and answers were critiqued before the hearing. Verbal and written comments received at the hearing and during the public comment period supported the proposed remedy which included mobile incineration. Both the Alderman and state senator, who had previously expressed concern, provided statements of support for the incineration project.

Yard excavations were conducted during the summer of 1988. The excavation offer was voluntary. In addition to the 25 families which would have to temporarily vacate their homes, approximately 80 more residents were offered partial excavations, primarily of the right of way area in their front yards. Every affected resident provided access and cooperated.

Nearly 8 mo of planning preceded the first yard excavation and hundreds of hours of planning were devoted to identifying and preparing for the multitude of details which were expected to arise. The families, many of whom were lifelong residents of the area, faced considerable anxiety at the prospect of moving out of their homes and seeing their yards and lawns excavated to depths up to 4 ft.

Food and lodging for the families were provided through the Superfund program at no charge to the residents. Some of the special accommodations arranged by the Community Relations staff included: professional health care for the blind; sick and elderly; around the clock security for the vacated residences; strongboxes at a local bank for personal items; meals to meet different dietary needs as well as different eating arrangements for those on unusual work schedules; care for pets; customized room arrangements for special family needs; and schedule adjustments to meet business needs.

The project's Community Relations staff served as liaison between residents, the contractor and a landscaping subcontractor to coordinate landscaping changes and respond to differing aesthetic values. Drought conditions reinforced the need for the Community Relations staff to assist in advising homeowners about proper care of new sod and landscaping.

The safety of nearby residents, particularly children, was a major concern. Community Relations and other Agency staff met with city officials, state police officers and officials of the State Department of Transportation to discuss traffic safety. Truck drivers hauling contaminated soil from the excavated yards to the storage area were instructed to take special precautions as they drove through an adjacent neighborhood where many grade school children resided.

The close working relationship developed with city officials over the previous 3 yr proved to be very useful in the summer of 1988. City officials helped with closing streets during excavation, posting new speed limit signs and maintaining water service despite disruptions caused by the excavation work.

An important part of any effort to mitigate fear is providing timely, accurate information. Tours were arranged for the news media, the community, government officials and other interested parties, to show and discuss both the excavation process and the incinerator operation. A time-consuming, yet worthwhile method of preventing fear is maintaining regular contact with affected residents. This contact was accomplished through visits, telephone calls and letters. More than 1,600 contacts were made by the Community Relations staff with the families scheduled to have excavation done in their yards.

RESULTS

"Knowing that the PCBs are gone is a tremendous relief," one resident said. "It takes a lot of worry and fearful thoughts away, regarding my children and how it would affect them in the future."

Phase I of the RA will be completed in the spring of 1990, and the Phase II specifications require completion of activity in the summer of 1993. Including the Immediate Removals, the RI/FS and the Phased RA, this site will be fully remediated about 2001 to 2003. Although this process will have taken over 18 yr by the time the RA is complete, the site will be free of use restrictions and all waste will have been destroyed or placed in facilities of the utmost environmental integrity and away from the residents of LaSalle, Illinois. Property values are already on the rebound in the adjacent neighborhood and the EUC site can be returned to the local tax base or placed in use for the public good. Although the process was lengthy, it will result in an effective and permanent solution to the problem.

Dioxin Destruction on a Small Scale Adjustments and Achievements

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ABSTRACT

Dioxin has been called "the most toxic chemical known to man." As a result, incineration of dioxin-contaminated material requires stringent preparation and extensive safety precautions to assure all involved parties that operations and procedures are safe. These requirements must be met irrespective of the amount of material that needs to be remediated.

Reported here is a case study of a successful small-scale remediation of 190 tons of dioxin-contaminated materials at Fort A.P. Hill—a job site that was scrutinized closely because it previously had been publicized as a dioxin site in local, state and national media. All site procedures were critically researched to satisfy the review of the U.S. EPA, the U.S. Army Toxic and Hazardous Materials Agency, the U.S. Army Environmental Hygiene Agency, the Commonwealth of Virginia interested individuals and public participation groups.

The remediation was performed according to an engineering and design report prepared and approved by the Army agencies and U.S. EPA prior to the commencement of field work. The design report detailed the plans, equipment, procedures, rationale and methodology for each activity performed on-site during the remediation. The report included an evaluation of the effectiveness of a mobile rotary-kiln incinerator, the required performance criteria for the incinerator, the necessary sampling, analysis and health and safety considerations and the procedures necessary to effect the overall implementation of the thermal treatment of dioxin-contaminated materials.

More than 190 tons of dioxin-contaminated material were successfully decontaminated despite numerous obstacles encountered. On such a small-scale site, however, numerous adjustments were required to complete the remediation. This paper describes how appropriate treatment technologies were combined with effective site management, engineering expertise and advance planning strategies to safely remediate a dioxin-contaminated site.

INTRODUCTION

Metcalf & Eddy (M&E) was contracted by O.H. Materials, on behalf of the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), for the Phase I (engineering/design) and the Phase II (subsequent remedial action) programs at Fort A.P. Hill. Fort A.P. Hill, a U.S. Army installation located in Bowling Green, Virginia, needed to dispose of building debris and soils contaminated with acutely hazardous organic materials—including 2,3,7,8-Tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD). On-site incineration using a mobile rotary kiln had earlier been recommended as the remedial method of choice in the site feasibility study prepared for USATHAMA.

For Phase I, M&E researched and provided the specific engineering and design plans needed to assure that each remediation task would

be properly performed. For Phase II, M&E implemented the remedial action—the on-site thermal treatment of the contaminated material—according to the Phase I Engineering/Design Report. All work was performed in accordance with U.S. EPA guidance, in compliance with the CERCLA.

The U.S. EPA has mandated that thermal treatment (incineration) is currently the only sufficiently demonstrated treatment technology for dioxin-containing wastes (51 *FR* 1733). However, the successful application of incineration to a dioxin cleanup at the Fort A.P. Hill site differed from the approach used for other dioxin remediations, such as Denney Farms, because a much smaller quantity of material needed to be cleaned up. Since the total volume of waste treated at the Fort A.P. Hill site was only 190 tons, the remediation was a very temporary operation. All activities (excluding residue disposal) were completed in 51 days.

A site involving a smaller volume of waste actually requires much more advance planning (including anticipation of problems that may arise and resolutions), effective site management and appropriate treatment technology. Due to the short duration of the remediation, any problem causing system down-time results in a major percentage increase in the effort and time required for the completion of the project.

Regardless of the volume of material to be treated, implementation of a dioxin remediation requires all of the same quality assurance and health and safety safeguards and all of the same tasks as a longer disposal project. At the Fort A.P. Hill site, M&E had to perform these tasks under media scrutiny because the site had received national publicity due to the Boy Scouts of America jamboree that is held at the Fort every 4 yr. M&E provided two tours of the remediation site for concerned citizens and newspaper and television reporters. The Army had kept the public informed throughout the planning for the remediation. As a result, there was public support for the remediation of the dioxin-contaminated material, in part because everyone was eager to "close this chapter of the dioxin saga" prior to the August, 1989, Boy Scouts jamboree.

SITE BACKGROUND

The Fort A.P. Hill site is a 76,000-ac Army installation located in Carroll County near Bowling Green, Virginia. The installation grounds are now used for Army training purposes and for other events. Fort A.P. Hill is best known for the Boy Scouts of America jamboree held at the site every 4 yr.

From 1962 to 1978, the Army stored the herbicides silver (2,4,5-trichlorophenoxy-propionic acid), 2,4-D (2,4-dichlorophenoxyacetic acid) and 2,4,5-T (2,4,5-trichlorophenol), 4 of which dioxin is a known impurity, in Building #225, which has since been demolished. The herbicide-containing containers corroded, allowing the contents

to leak onto the floor of the storage building and eventually onto the ground below. The leaking containers were repacked in 1978 and removed from the base in 1980.

In 1984, the vertical and horizontal extents of silvex, 2,4-D, 2,4,5-T and dioxin contamination were defined. In 1985, an interim response action was undertaken in which Building #225 was demolished and the soils underlying the building were excavated. The excavated soils and miscellaneous debris were containerized in 35-gal fiberpack drums which were then overpacked in 55-gal drums and stored in a warehouse (Building #P01288) inside a secure, fenced area on the Army base.

A feasibility study prepared for the site in 1987 recommended on-site incineration of the contaminated materials and subsequent disposal of the residues in a licensed hazardous waste landfill.

WASTE CHARACTERIZATION

Table 1 shows that the site was contaminated by ppm-levels of 2,3,7,8-TCDD and other related constituents. The 2,3,7,8-TCDD isomer is recognized as the most toxic of the 75 possible dioxin isomers. The U.S. EPA classifies 2,3,7,8-TCDD and related organic compounds, referred to as dioxins and furans, as acutely hazardous materials. The classification and the public awareness of the possible hazards associated with dioxin, prompted the 1985 interim response action which yielded the 1,138 drums of contaminated materials which were stored in the warehouse at the base from 1985 to 1989. The contents of the 1,138 drums were categorized as: dirt, block, wood and miscellaneous, as noted in Table 2.

Table 1
Chemicals Detected in Excavated Soils at Fort A.P. Hill

Compounds	Range of Concentrations Detected (ppm)
*2,3,7,8-TCDD	ND-1.03
Lindane	ND-0.008
O,P'-DDD	ND-0.04
P,P'-DDD	ND-0.04
P,P'-DDE	ND-1.88
O,P'-DDT	ND-0.66
P,P'-DDT	ND-2.64
Chlordane	ND-0.10
PCB (Aroclor 1260)	ND-0.25
2,4-D (2,4-dichlorophenoxyacetic acid)	ND-0.74
*2,4,5-Trichlorophenol	ND-1.98
*Silvex (2,4,5 Trichlorophenoxy-propionic acid)	ND-1.57
Pentachlorophenol	ND-0.89

* Chemical constituents for which wastes are listed under F027

METHODOLOGY FOR SITE REMEDIATION

Remediation of materials classified as acutely hazardous must be well-planned so that the thermal treatment technology selected for the job, the proposed operating conditions and the data needed to verify compliance with U.S. EPA requirements are all recognized as the best treatment to meet all relevant cleanup and operating standards. These planning requirements are not significantly reduced even if only a relatively small volume of contaminated material requires remediation.

Table 2
Contaminated Materials Stored in Drums in Building P01288 at Fort A.P. Hill

Number of Drums	Contents
767	Soil
186	Cinder block (broken up)
120	Wood (cut up)
65	Miscellaneous: VISQUEEN ^(R) , Debris, Carbon, Lab wastes (bottled liquids, primarily, methanol and trichloroethylene)
Total	1,138 Drums

Source: EPA Region 3 Report "Summary Report for ERCS Action: Dioxin Contamination at Fort A.P. Hill, Virginia."

TECHNOLOGY

The thermal treatment system used to destroy the contaminants included pre-feed shredding, a controlled waste feed system, a two-stage incineration system including a rotary kiln primary combustion chamber (PCC) and a secondary combustion chamber (SCC), an air pollution control system, a fan and a stack.

OPERATING CONDITIONS

The minimum operating conditions selected for the Fort A.P. Hill remediation are described in Table 3. These conditions were proposed after investigating data established during previous tests and remediations that have proven to be effective in destroying dioxins and/or related hazardous materials. The incinerator system operations were wholly monitored, controlled and logged by computer. Even under worst-case conditions, these conditions assured complete dioxin destruction (99.9999%).

Table 3
Minimum Operating Conditions for Mobile Incinerator at Fort A.P. Hill

Parameter	Operating Conditions
Kiln Temperature	1400 degrees F, minimum
SCC* Temperature	2048 degrees F minimum
Stack Oxygen	4 percent, minimum
Stack CO	100 ppm by volume, maximum
SCC Retention Time	2 seconds, minimum
Chloride Removal Efficiency	99% minimum or 4 lb/hr., maximum
Destruction and Removal Efficiency	99.9999%, minimum
Particulate Emission Rate	180 mg/dscm, maximum

* SCC represents the Secondary Combustion Chamber

REMEDIATION—PROCESS

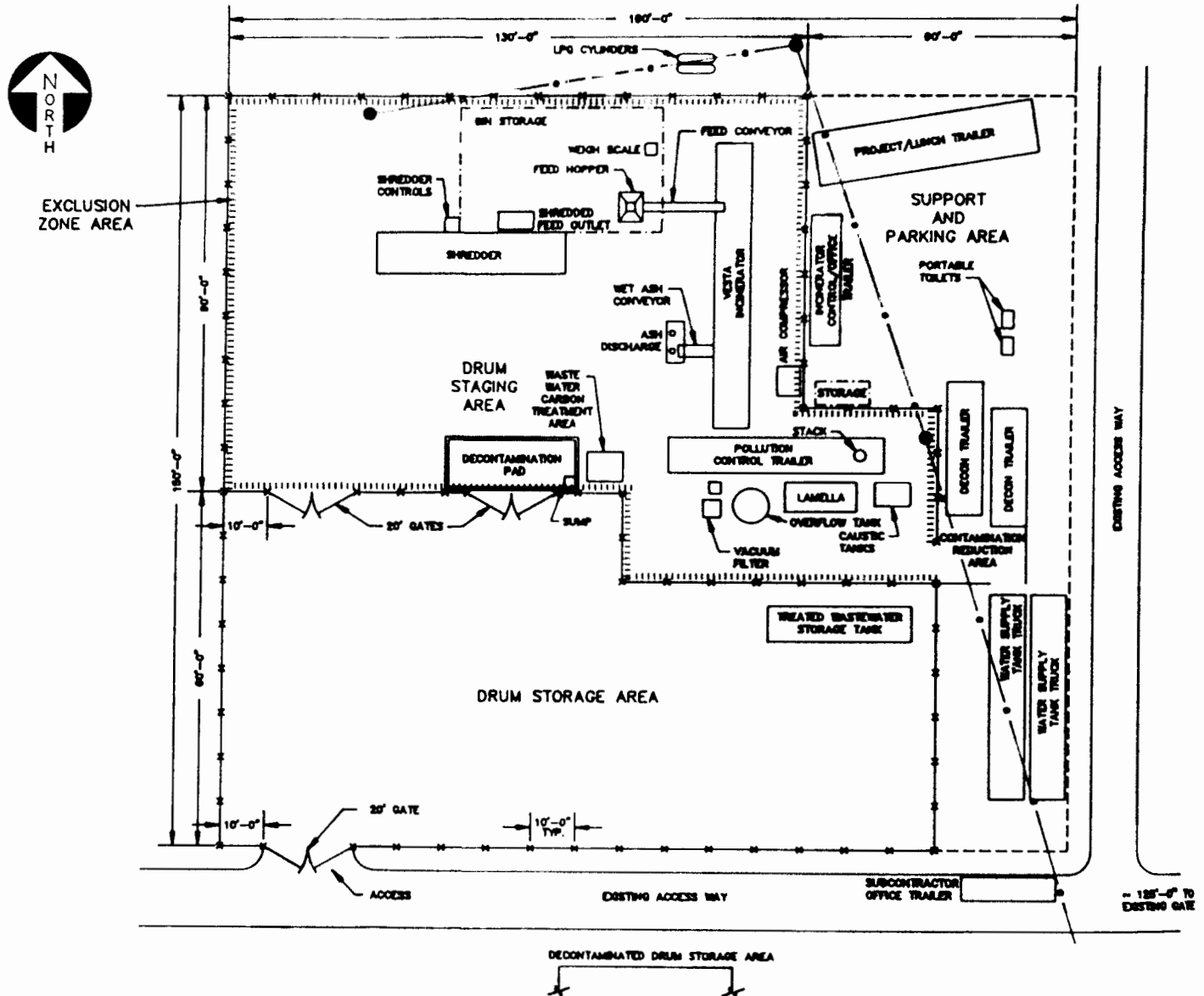
Site Preparation

The location to set up and operate the thermal destruction unit (TDU) was selected because of the availability of 3-phase power and access to an already cleared and fenced area from a paved road.

Everything necessary to do the job had to be trucked to the site. The site preparation requirements included making provisions for equipment installation, utilities, personnel, equipment decontamination areas, institutional and containment controls and a support area. Figure 1 shows the site layout. Utilities required for operations included electricity, water, telephone service and propane gas as fuel for the incinerator. Ample lighting was installed at the site to assure a well-lit area during evening and night operations.

The remedial action site was cleared and covered with gravel. Selected areas, on which the heavier equipment was to be situated, were surfaced with asphalt. The site was secured with a chain link fence after the incinerator and shredder trailers were placed in the exclusion zone.

The area outside the fence was organized into a support area. The support area consisted of two decontamination trailers, three project trailers, three water tankers and other support items. Personnel access to and from the exclusion zone was controlled to require passage through



DRAWING NOT TO SCALE

NOTES:

1. UTILITIES:
 - A. TEMPORARY TELEPHONE AND ELECTRIC SERVICE WAS INSTALLED FROM SOUTH RANGE ROAD TO SITE.
 - B. STORAGE TANKS WERE BROUGHT TO THE SITE FOR SUPPLY OF NATURAL GAS (INCINERATOR FUELS) AND POTABLE WATER. WASTEWATER WAS DIRECTED TO STORAGE TANK FOR OFF SITE DISPOSAL TO A WATER TREATMENT FACILITY.
2. LIGHTING:
 - A. ALL WORK AREAS WERE PROVIDED WITH TEMPORARY LIGHTING WITH INTENSITY IN ACCORDANCE WITH 29 CFR 1910.120 (m) TABLE H-102-1.

EXPLANATION

- - ELECTRIC/TELEPHONE POLE
- ● — - ELECTRIC/TELEPHONE LINE
- X — - FENCE
- - EDGE OF STONE AREA
- - - - - ENCLOSED AREA
- ||||| - EXCLUSION ZONE

Figure 1
Site System Layout

the decontamination trailers via the contamination-reduction zone. All other entry and exit points were restricted.

A high-vertical-clearance wooden building with a wooden floor was erected in the exclusion zone to house the outlet of the shredder, the 10 bins used to store the shredded feed material, the small forklift, the weigh scale and the incinerator feed hopper. The building was kept under slight negative pressure to contain any fugitive particulate emissions that might be generated during the waste shredding and incinerator feed operations.

A bermed decontamination pad was installed to accommodate the staging of drums and decontamination of drums and equipment. The high-pressure water spray used for decontamination was collected in an area of the decontamination pad equipped with a sump.

Health and Safety

All personnel at the site were required to abide by the master health and safety plan prepared for the remediation. All personnel were safety-trained in accordance with *CFR* 1910.120 and participated in a medical surveillance program.

The hazard posed to the workers performing activities at the Fort A.P. Hill site was generally rated as low. This low hazard rating was based on the fact that the dioxin-contaminated materials were already contained in drums, the dioxin was already adsorbed on particulates and the remediation was short in duration. The low-hazard ranking due to short-duration operation was a major benefit associated with the small-scale operation.

The remediation site was segregated into two distinct, fenced work areas: the drum storage area and the exclusion zone. The fenced drum storage area was used to store the drummed contaminated wastes, the drummed incineration residues and the storage tank for the carbon-treated contaminated water. All workers were required to be in Level D protective gear when working in the drum storage area.

Workers in the exclusion zone (where the shredding, incinerating and handling of the contaminated material were performed) were required to be in Level C protective gear, which includes a full-face air purifying respirator to protect against particulates. The standard Level C protective gear was modified to include a second layer of (TYVEK) protective clothing. This second layer of protection was added to reduce any off-site migration of contaminants via underclothing and to eliminate on-site washing of the clothing. All employees who entered the exclusion zone to perform their duties were required to shower in the shower/locker trailers prior to leaving the site. An M&E health and safety officer, assigned for each of the three shifts, was responsible for the well-being of the site workers.

Once the first waste-containing drum was opened, the safety levels for each zone were formally in effect 24 hr/day. These levels were not downgraded until incineration was completed, the temporary building was demolished, the site was cleared and all site samples were found to be free of dioxin.

Materials Handling Prior to Incineration

Drums were trucked to the incineration site in 31 trips between the site and the warehouse. Drums were stored within the fenced areas.

Once the incineration began, the drums were staged on the decontamination pad in the exclusion zone, opened and fed to the shredder. The contents of the 55-gal overpack drums were dumped into the shredder hopper with a forklift equipped with a drum-handling attachment (a grappler). The forklift and grappler replaced electronic arm hydraulic drum-handling equipment because the latter equipment was bulky and difficult to maneuver in the limited space of the drum-staging area. The drums were fed in a pre-determined sequence according to waste-type categories to assure a homogeneous feed. Drum handling posed logistical difficulties due to limited space, poor weather conditions and incorrectly marked drums, which markedly increased the amount of time required to feed drums. Mislabeled drums caused non-homogeneous feed—initially resulting in an 80% wood feed that caused incinerator temperature maintenance problems. M&E adjusted to this condition by improving quality control documentation measures and

modifying the predetermined drum feeding sequence.

Other difficulties were more difficult to overcome. The contents of some of the drums were frozen. Record-breaking low temperatures for the month of March in Virginia created significant difficulties with emptying the drums. Some of the equipment was immobilized by snow and ice. Fiberpacks leaked and their contents froze against the overpack drum walls.

Time lost due to these difficulties was minimized due to rapid adjustments and decisions made on site. Frozen contents of drums were manually removed by hitting drums with a sledge hammer. Manual equipment replaced the hydraulic equipment used to feed waste into the shredder.

M&E planned to re-use decontaminated 55-gal overpack drums to contain the ash and other residues. However, some of the overpack drums had corroded and exhibited pinholes from the deterioration resulting from 4-yr storage of wet materials. Therefore, new drums were ordered, delivered the next day and used to contain the ash.

Once shredded, materials were collected in metal bins inside the wooden building. A small forklift, dedicated to operations inside the building, was used to move the bins from the outlet of the shredder to the weigh-scale to the incinerator feed hopper.

The shredding initially operated 12 hr daily. This generated sufficient shredded material for the entire 24 hr of operation during mild weather conditions. Shredding operations were extended to 15 hr in cold weather due to the drum handling problems noted above. Shredder operation was extended to 18 hr when feed material had to be reshredded. Reshredding was required by the incineration subcontractor to reduce the shredded-feed dimensions to accommodate their ash-discharge conveyor requirements.

Incineration

The selected incineration unit had been proven to be capable of complying with all the hazardous waste incineration technical standards set by RCRA and TSCA. The primary combustion chamber (PCC) that was used was a countercurrent, cylindrical, refractory-lined rotary kiln. The non-combustible materials (ash) were discharged through the bottom ash conveyor.

Combustion of the off-gases generated during the destruction of the organic materials in the PCC (kiln) was completed in the SCC, a cocurrent afterburner. The off-gases from the afterburner were cleaned in a three-stage scrubber system to remove acid gases and other impurities in the gas stream. Cleaned flue gas was exhausted to the atmosphere.

M&E submitted, as part of the remedial design plan, an explanation why a trial burn was not necessary at the Fort A.P. Hill site. The demonstrated performance of rotary kiln systems at well-defined operating conditions on materials of similar composition was sufficient to verify that the incinerator would provide effective destruction of the hazardous organic constituents. Operational controls provided better assurance of contaminant destruction than a trial burn would have provided.

The start date for the incineration was delayed several times. The first delay occurred because the truck driver delivered the incinerator controls/equipment to Bowling Green, Kentucky instead of Bowling Green, Virginia. It took several days to locate the instrumentation/controls and have it delivered. A second major delay resulted when large pieces of refractory broke from the kiln during controlled heating of the unit to temperature. The system was cooled, the refractory was repaired and the system was reheated to temperature before incineration could begin.

The incinerator requires as long as 48 hr of controlled heating to reach operating temperatures. The unit's temperature had to be maintained 24 hr/day to avoid repeating the heatup period. Therefore, the incineration of contaminated materials was performed in a 24 hr/day, 7 day/wk operation. Each subcontractor devised his own staffing schedule, which allowed for personnel overlap. The staffing schedules of each subcontractor were staggered to avoid crowding in the decontamination trailer and the contamination reduction zone.

The short duration of the remediation allowed subcontractors to

operate with two or three shifts daily until all work was completed. This schedule allowed smaller crews to complete the remediation than would have been required for a long-term remediation.

Incinerated material totaled 190 tons. The feed rate for the system ranged from 1400 to 2600 lb/hr. The range of operating temperatures for the unit is described in Table 4.

Table 4
Incinerator Operating Temperatures

Parameter	Range of Operating Conditions Proposed		Actual
Primary Combustion Chamber Temperature	1400 - 1500° F	857	1323° F
Secondary Combustion Chamber Temperature	2050 - 1500° F	2214	2240° F

* 857° F in a counter-current kiln was determined to correspond to 1490° F in a co-current kiln

The minimum PCC operating temperature achieved during remediation differed from the proposed operating temperature. The proposed conditions, based on tests at other sites, applied to a cocurrent-fired PCC system. A countercurrent PCC has a different kiln temperature profile than a co-current kiln. M&E adjusted the discrepancy between the proposed and actual temperature and verified adequate destruction temperatures by placing five thermocouples across the outside of the primary kiln and measuring surface temperatures. A temperature of 300°F on the outside surface of the kiln was calculated to correspond to a PCC outlet temperature of 857°F and an inside kiln surface temperature of approximately 1490°F — which is above the proposed minimum kiln operating temperature.

Another problem encountered during the incineration arose due to an inconsistency between the two feed-weighing systems (a weigh-scale in the enclosure and a weigh-belt feeder to the incinerator). The measured amount of processed waste differed by more than 25% between the two weighing systems. As the incineration subcontractor was paid on a per-ton-incinerated basis, accurate feed weights were essential. This inconsistency was resolved by recalibrating the scale and weigh belt using a known amount of sand. The results of this exercise determined that the weigh belt reading was 25% too high. Other major problems included the periodic breakdown of the ash conveyor, pump failure in the air pollution control system and a buildup of fly ash in the SCC.

The shear pins on the ash conveyor failed numerous time during operations. Each conveyor failure took several minutes to fix. At other times, pieces of metal caught in the conveyor chain, rendering the conveyor inoperative. This problem took as long as six hr to repair. An improved conveyor design might have reduced these problems.

The system was shut down for several days due to excessive buildup of fly ash in the SCC. The system was cooled, the combustion chamber cleaned and the system was re-heated to temperature.

Even with the numerous difficulties encountered and the unavoidable delays, the 190 tons of material were incinerated in 18 days. The total remediation effort (site preparation to site closure) was completed in less than 2 mo (except for final residue staging and disposal).

Materials Handling After Incineration

The kiln ash was discharged through an enclosed conveyor and deposited in re-conditioned 55-gal steel drums. A sample was collected from each filled ash drum as part of a daily composite. The filled drums were sealed and labeled (date and time) and moved to a temporary area designated in the hot zone. During the night shift, after shredding operations had ended for the day, the drums were decontaminated and moved to the storage area.

At the end of every 24 hr period, each composite drum was sealed

and thoroughly mixed before being re-opened and having a sample collected for analysis. This drum was sealed, labeled and placed with the other ash drums.

Sampling and Analysis

Daily composite samples of the incinerator residue were collected and shipped to the analytical laboratory. The samples were analyzed for polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) on a 48 hr turn-around basis, using U.S. EPA Method 8280, as specified in 40 CFR 261, Appendix X. Results from the analysis of the dioxin congeners were weighted according to Toxicity Equivalent Factors (TEF). These factors convert data on dioxin/furan isomers into an equivalent toxicity of 2,3,7,8-TCDD. Toxicity equivalents for dioxins and furans are shown in Table 5.

Table 5
Detection Limits/Toxicity Equivalents for CDDs and CDFs

Compound Groups	Detection Limits	Toxicity Equivalence 2,3,7,8-TCDD	TEF Contribution at Maximum Detection Limit
Total TCDDs	≤ 0.1 ppb	1	0.1 ppb
Total PeCDDs	≤ 0.5 ppb	0.5	0.25 ppb
Total HxCDDs	≤ 2.5 ppb	0.04	0.1 ppb
Total HpCDDs	≤ 100.0 ppb	0.001	0.1 ppb
Total TCDFs	≤ 1.0 ppb	0.1	0.1 ppb
Total PeCDFs	≤ 1.0 ppb	0.1	0.1 ppb
Total HxCDFs	≤ 10.0 ppb	0.01	0.1 ppb
Total HpCDFs	≤ 100.0 ppb	0.001	0.1 ppb
Total TEF Based on Maximum Detection Limit			0.95 ppb 2,3,7,8-TCDD Equivalent

* NOTE: If each of these groups is present at 1 ppb (as in the allowable TCLP requirements) the TEF would be 1.7 ppb 2,3,7,8-TCDD equivalent.

For the Fort A.P. Hill site, the acceptance criterion for the incineration process was set so that the ash or other residues of incineration had to be proved to contain less than 1 ppb TEF of 2,3,7,8-TCDD. M&E was prepared to re-incinerate all materials that did not meet this criterion. None of the materials required re-incineration.

In addition to the PCDDs and PCDFs tests, the ash samples were also subjected to the Extraction Procedure Toxicity (EP Tox) test, as specified in 40 CFR Part 261 and a Toxicity Characteristics Leaching Procedure (TCLP) analysis, as specified in 40 CFR Part 268. The EP Tox leachate was analyzed for the eight RCRA metals and the pesticides and herbicides detected in the samples of material at the site to assure that the residues would not be considered toxic. The TCLP extraction was analyzed for PCDDs, PCDFs and chlorinated phenols to assure that the residues (F028 wastes) could be land disposed.

Dioxin-contaminated soils (F027 wastes) are considered acutely hazardous wastes. Residues resulting from incineration of dioxin wastes are still considered hazardous because of toxicity and are classed as F028.

Analytical Results

The residuals generated during the remediation that required disposal were: ash, SCC ash (the fly ash collected from the SCC), air pollution control system filter cake and the treated process water. The personnel protective gear (Tyrek clothing) worn on-site was incinerated daily. The

carbon used to treat the process water and decontamination pad sump sludge also was incinerated as part of site closure. The ash, the secondary ash and the filter cake were tested for dioxins/furans, EP toxicity and TCLP analysis.

The post-incineration residues that required disposal were: final decontamination pad sump sludge, two drums of carbon, personnel protective gear generated after the incinerator shutdown, shredded wood and miscellaneous debris. The post-incineration residuals were tested only for dioxins/furans. The analytical results for these samples are shown in Table 6, along with the regulatory limits.

Site Closure

Preliminary decontamination procedures commenced soon after laboratory confirmation that all ash samples from the drummed waste had met the U.S. EPA dioxins/furans criteria. Heavy equipment, hand tools and other miscellaneous items that were no longer needed were decontaminated and removed from the exclusion zone. The secondary wastes (decontamination pad sump sludge, carbon, vacuum filters, the floor of the wooden building and miscellaneous debris) were incinerated. This procedure insured that all of the contaminated materials had been incinerated.

Table 6
Analytical Results of the Residual Samples at Fort A.P. Hill

Matrix	No. of Samples Collected Analyzed	Dioxins/Furans 2,3,7,8-TCDD equivalent	Chlorinated Herbicides	EP Toxicity		TCLP	
				Inorganics (ppm)	Pesticides/ PCBs	Dioxins/ Furans	Phenols (ppm)
Soil sample of general area	1	ND	ND ⁽¹⁾	— ⁽²⁾	ND		
Site background soil/gravel	1	ND	ND		ND		
Ash from incineration ⁽³⁾ of dioxin-contaminated material	13	ND	ND	Barium Chromium (0.083) Nickel (0.049)	ND	ND	2,4,6-Trichlorophenol (ND 0.007)
"Fly" ash from secondary combustion chamber	1	ND	ND	Barium (0.043)	ND	ND	2,4,6-Trichlorophenol (0.006)
Post-incineration (4) "Fly" ash from secondary combustion chamber	1	0.19 ppb	ND	Barium (0.165) Cadmium (0.098) Nickel (0.091)	ND	ND	2,4,5-Trichlorophenol (0.05)
Filter cake	1	ND	ND	ND	ND		2,4,6-Trichlorophenol (0.009)
Waste water after carbon treatment	1	17.5 ppt					
Water after retreatment with carbon	1	ND					
Carbon from initial treatment of process water	1	ND					
Carbon from retreatment of process water	1	ND					
Trash	1	0.48 ppb					
Wood building	8	ND					
Wood pallets	8	ND					
Final site background soil/gravel	1	ND					

(1) ND - not detected

(2) (-) - not analyzed

(3) Chromium and nickel were only detected in one sample.
Regulatory limits:

Inorganics

Barium - 1 ppm

Chromium - 5 ppm

Nickel 16 ppm

Phenol

2,4,6-Trichlorophenol - <0.05 ppm

The ash was stabilized by the disposal facility prior to being landfilled.

(4) Regulatory limit for cadmium is 1 ppm.

Site closure activities continued by dismantling the wooden building. The shredder was then decontaminated and used to shred the wooden building and the wood pallets used to store the 1,138 waste drums. The building and the pallets were shredded separately, sampled, analyzed and stored in their own roll-off container for disposal. A temporary enclosure was constructed on top of the shredder and feed conveyor to contain fugitive emissions during closure activities.

Upon verification that all residue analyses met U.S. EPA standards, it was determined that incineration was complete. The incinerator was run for an additional 2 hr at elevated temperatures to assure complete contaminant destruction. During this time, the shredder and the remaining equipment were decontaminated. After all the equipment was removed from the fenced area, the exclusion zone was thoroughly cleaned.

The wastewater from personnel and equipment decontamination was treated by carbon adsorption and stored in a tanker. The water was sampled and found to contain traces of 2,3,7,8-TCDD (at pg/L level). The water was retreated by carbon adsorption and resampled. The carbon used for retreating the water also was sampled. When re-tested, the water and the carbon did not show detectable TCDD.

Samples of various areas in the exclusion zone were collected and analyzed to verify that the site had not been contaminated during the remediation.

Residue Disposal

M&E prepared the RCRA waste codes for each residue and the final disposal destination. A residue disposal scheme, delineated in Table 7, was approved by USATHAMA and concurred with by U.S. EPA.

Table 7
Waste Code and Final Destination of Residues Generated at Fort A.P. Hill

TYPE(1)	WASTE CODE	DESTINATION(2)
Ash	F028	USPCI
SCC Ash	F028	USPCI
Filter Cake	F028	USPCI
Treated Water	Non-Hazardous	duPont
Tyveks, Misc.	Non-Hazardous	USPCI
Carbon	Non-Hazardous	USPCI
Sump Sludge	Non-Hazardous	USPCI

(1) Shredded wood and decontaminated overpack drum disposal was arranged by others.

(2) USPCI -- U.S. Pollution Control, Inc., in Wynoka, Oklahoma
duPont -- duPont facility in Deepwater, New Jersey

All residuals generated as a result of the remediation have been properly disposed at permitted treatment and disposal facilities. The off-site disposal option is not available to large-scale dioxin sites. However, off-site disposal allowed the Army to "close the chapter on the dioxin saga" at Fort A.P. Hill by completely destroying all contamination and shipping the residues off-site.

Transportable Incineration of Industrial and Superfund Waste

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ABSTRACT

Williams Incineration Services owns and operates a 15 ton/hr transportable rotary kiln incineration system that was used to burn 9,200 tons of creosote-contaminated soil at the Prentiss Creosote Site in Mississippi in February 1989. This incinerator will be used next at Bog Creek Farm, New Jersey.

INTRODUCTION

There is considerable interest in incinerating organic wastes at Superfund sites because burning is a permanent solution for organic wastes and costs are lower than for off-site treatment. The terms mobile and transportable are frequently heard in connection with on-site incineration. While no clear delineation exists, the author defines transportable systems as those systems with more than a 5 ton/hr soil treatment capacity and construction times of less than 2 mo, with all components shippable by road with only normal oversize/overweight permits. Mobile technology is generally restricted to a capacity of less than 2 ton/hr capacity, is shipped without need for special truck permits and can be set up and ready to operate in less than a week.

This paper discusses the larger — a system with 15 ton/hr capacity. A system of this size can compete with smaller systems at a site with 10,000 tons of contaminated soil and reaches an economy of scale above 20,000 tons.

PRENTISS SUPERFUND SITE

The Prentiss Creosote Superfund site was a wood treatment facility for 19 yr, supplying treated forest products to wide variety of markets. Plant lagoons containing wastewater and creosote sludge threatened to overflow into Little White Sand Creek. In March 1987, U.S. EPA Region IV initiated a cleanup and removal action which consisted of on-site treatment of pumpable lagoon water, solidification of sludges and excavation of contaminated soils.

On Dec. 22, 1987, the U.S. EPA signed a contract with Envirote Field Services (now known as Williams Incineration Services) to incinerate the soil. The project duration was 14 mo and cost \$1,831,642, including insurance pass through and additional tonnage, for an average of \$199/ton of soil treated.

Operations commenced on-site in April, 1988. After equipment erection and checkout, incineration of soil began on July 27. The unit achieved 100% capacity within 7 wk of that date. The trial burn was completed Oct. 12, production burn finished Dec. 6 and the project was closed out on Feb. 17, 1989.

In January, 1989, a contract was signed for incineration of soil at the Bog Creek Farm site in New Jersey. This second project for the incinerator will involve approximately 22,500 tons of sandy soil contaminated with solvents and paint sludge.

CONTAMINATED SOIL CHARACTERISTICS

The Prentiss soil was a soft, sandy, clay-like material with a strong creosote odor. It contained moderate amounts of gravel, wood, metal objects and moisture. The creosote sludge had been stabilized with approximately 2,100 tons of cement kiln dust and fly ash.

Tests on a composite sample (made from over 80 core samples) showed that the soil had a relatively high heating value of 1,148 Btu/lb dry basis (Table 1). While the heating value was high, it did not on the average exceed the heat release limits of the kiln at rated capacity.

Table 1
Proximate and Ultimate Analysis of Contaminated Soil
on a Wet Basis

	Percent Weight	
	Proximate	Ultimate
Water	10.07%	10.07%
Ash	82.18%	82.18%
Volatiles	6.95%	
Fixed Carbon	0.80%	
C		6.90%
H		0.46%
N		0.22%
S		0.13%
Cl		0.12%
O ₂ (by difference)		--
Total	100.00%	100.08%

Using U.S. EPA SW-846 test protocols, the soil was found to contain seven polynuclear aromatic hydrocarbons (PAHs) (Table 2). These organic compounds were consistent with the major creosote constituents noted in the wood treating literature. No pentachlorophenol or arsenic compounds were found. Small amounts of inorganic chloride were discovered. Inorganic and organic sulfur were present in small quantities.

Table 2
PAH Analysis of Composite Core Sample

Compound	mg/kg
Phenanthrene	1400
Naphthalene	1100
Anthracene	1100
Acenaphthene	1000
Fluorene	900
Fluoranthene	520
Pyrene	220

SITE OPERATIONS

The site plan is shown in Figure 1. The incinerator was positioned on high ground adjacent to the stockpile and away from the creek to avoid flooding.

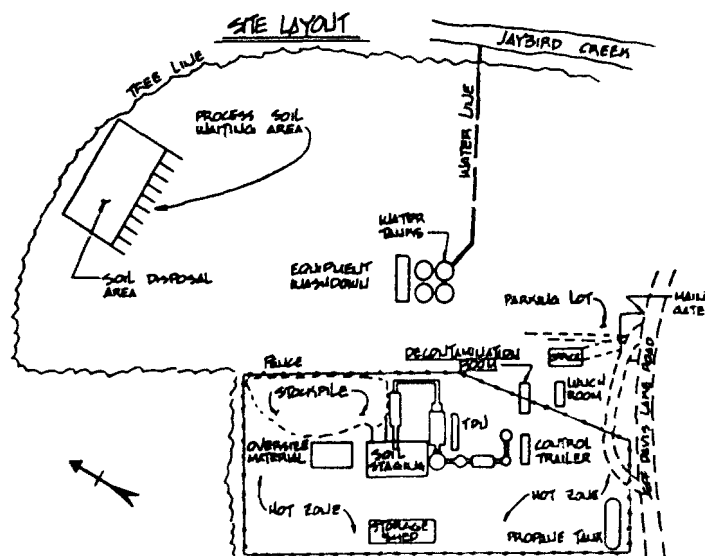


Figure 1
Site Plan Prentiss Creosote Site

The soil feed system is shown in Figure 2. Front-end loaders moved contaminated soil to the staging area, which was a roofed, concrete pad. A vibrating screen removed material larger than 2 in. Oversized material (which was not soil) was stockpiled for final disposal by U.S. EPA. Material less than 2 in size was stockpiled on the pad and then fed to the hopper of the apron feeder, which in turn fed the weighbelt. A magnet over the weighbelt conveyor removed steel scraps which were stockpiled separately. A sufficient amount of soil was screened and piled on the pad to last until the next scheduled screening operation.

Although some soil blending occurred when the lagoons were dredged and the soil was stabilized, the pile was not homogeneous and additional blending was required to maintain a stable feed system. This occurred during soil removal from the stockpile, screening operations, storage on the pad, placement into the apron feeder hopper and when the soil moved through the apron feeder, weighbelt and rotary dryer/conditioner.

DESCRIPTION OF THE TDU

The general process flowsheet of the thermal destruction unit (TDU) is shown in Figure 3, and the general TDU equipment layout is shown in Figure 4. The equipment was produced by Boliden Allis, Inc. (formerly the Allis-Chalmers Minerals Division), an experienced kiln and combustion system vendor.

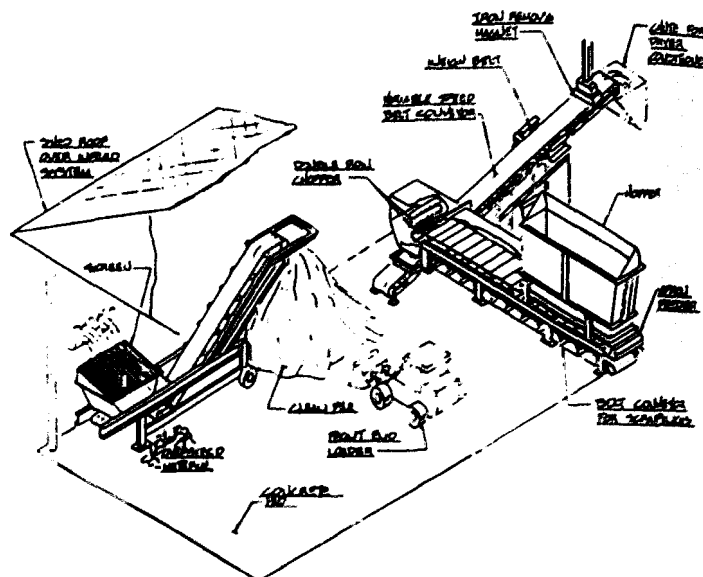


Figure 2
Soil Feed System

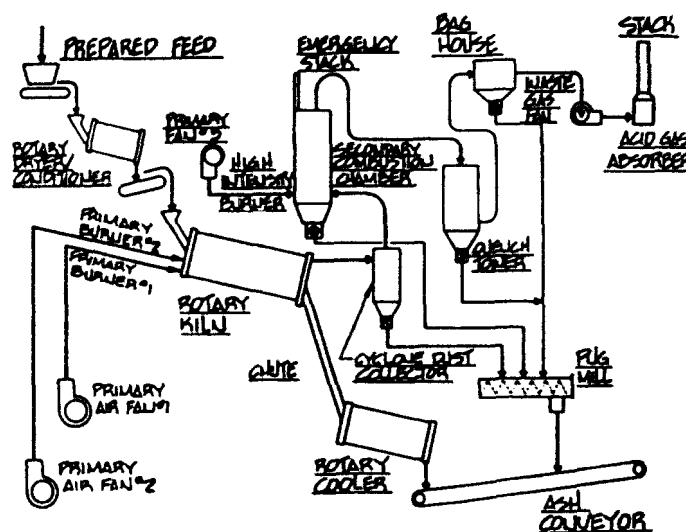


Figure 3
TDU Processing Flow Diagram.

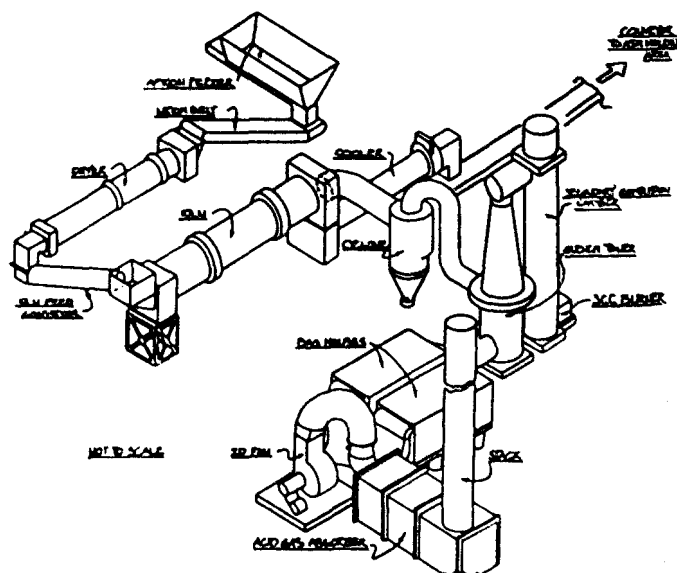


Figure 4
TDU Layout

From the apron feeder, the soil dropped onto a weighbelt which recorded the soil feed rate to the rotary dryer/conditioner. Integrated weight totals were used to report quantities of soil processed.

The dryer/conditioner partially dried the soil, broke up large agglomerated particles, homogenized the feed to the kiln and micropelletized the fines fraction of the soil. Solids moved from the dryer/conditioner in an enclosed conveyor to the rotary kiln, where drying was completed and creosote compounds were volatilized and burned.

Solids exited the kiln and were conveyed by a chute into a rotary cooler. Adding water moisturized the decontaminated soil to minimize dust emissions and promote compaction.

The rotary kiln was fired with two burners. One burner produced an intense flame (via a custom secondary air scroll) to rapidly dry the solids and initiate volatilization of the organics. The other burner had a long flame to burn the volatiles. The kiln was operated to maintain an exit gas temperature of approximately 1600°F.

The kiln exit gases passed through a cyclone dust collector, where much of the entrained particulate matter was removed prior to entering the secondary combustion chamber. A portion of the gases exiting the cyclone was diverted to the dryer/conditioner to partially dry the soil, while the dryer/conditioner exit gases were returned to the inlet of the cyclone.

After the cyclone, the gas temperature could be increased to as high as 2200°F at a residence time of 2 sec in the secondary combustion chamber. A more typical temperature level in the secondary combustion chamber for this waste was 1700°F. To ensure complete combustion, a minimum of 3% excess oxygen was maintained in the secondary combustion chamber exit gas.

Exiting gases entered a quench tower, where they were cooled by atomized water, and then entered the baghouse, where particulates were removed. Dust collected from the secondary combustion chamber, quench tower and baghouse was conveyed to pug mill where it was mixed with water prior to discharge onto the belt conveyor. Use of a baghouse eliminated the production of vast quantities of sludge which would be produced by a wet scrubber (e.g., high pressure venturi particulate scrubber). The baghouse also did a better job of removing fine salts and metals, which can be formed by vaporization in the incineration process.

After the baghouse, flue gases passed through the 350-hp induced draft fan to an acid gas absorber where HCl and SO₂ were removed. Scrubber blowdown water passed through an activated charcoal filter before being used to cool processed soil. A flue gas sampling conditioning system extracted gases from the stack and fed them into the continuous analyzers for regulatory and process monitoring and control.

TDU PROCESS PERFORMANCE SPECIFICATIONS

The TDU design criteria meet or exceed the RCRA technical requirements of 40 CFR 264. Table 3 summarizes the design data. The burner input rating of 82 million Btu/hr is the total design capacity (higher heating value) of all three burners. Most of the fuel value for the system was derived from the heating value of the creosote contaminated soil.

Process Variables Monitoring

Major variables monitored were the flow of solids and fuel, temperatures, pressures and process gas stream constituents. A weighbelt located in line with the feed conveyor monitored the feed rate of the soil to the TDU. The readout in the control room gave the instantaneous feed rate in tons/hr and integrated totals. The following data were continuously recorded:

- Waste soil feed rate
- Combustion gas velocity
- Temperature at the exit of the kiln and secondary combustion chamber
- Stack gas carbon monoxide concentration
- Particulate level
- Absorber water flow rate
- Kiln draft
- Dryer draft
- Baghouse inlet temperature

These data were recorded by strip chart recorders and a 48-channel

Table 3
TDU Process Performance Specifications

Item	Value
Waste soil rate, wet basis @ 15% moisture	15 tons/hour
Solid residence time	45 min minimum
Kiln size, diameter x length	7.5 ft x 45 ft
Kiln outlet gas temperature	1200-2000°F
Secondary combustion chamber outlet temperature	1500-1800°F
Secondary combustion chamber residence time @ 2200°F	2 sec
Fuel for burners	Propane or natural gas
Burner rated capacity, maximum	82 million Btu/hr

data logger. Sheathed type K thermocouples, shielded from direct flame radiation, sensed the combustion temperatures.

Emissions Monitoring

The TDU is equipped with several continuous gas analyzers. The oxygen concentration was measured at the kiln exhaust and at the outlet of the secondary combustion chamber. An extractive flue gas sampling and conditioning system removed gases downstream from the air pollution control system for analysis of O₂, CO₂, CO, TUHC and NO_x. A backup monitor was provided for CO monitoring.

Disposal of Processed Soil and Scrubber Blowdown

Processed soil was placed in conical piles with a volume equal to 24 hr of incinerator output. Samples were taken to ensure that the soil was clean (less than 100 ppm PAH). Clean soil was moved to the final disposal site after analysis.

The scrubber liquor and equipment wash water passed through a sediment filter and an activated carbon adsorber to be stored in a 25,000 gal tank. This water was used to cool the processed soil, eliminating the need to discharge wastewater.

TRIAL BURN

The trial burn for the incinerator was performed on Oct. 11 and 12, 1988. Naphthalene was used to test overall incineration destruction efficiency. Naphthalene was selected as the POHC (principal organic hazardous constituent) because of its relatively high stability rating (ranked 5th of 320 compounds) in U.S. EPA's Thermal Stability-Based Incinerability Ranking (revised ranking issued Dec. 14, 1988). No spiking was done, as naphthalene was present in ample concentrations in the soil along with a variety of other polynuclear organic compounds. The natural soil concentration was measured and used to calculate incinerator loading and DREs.

Two test conditions were used. The first test was at a kiln temperature of 1620°F and a secondary combustion chamber temperature of 1670°F. The second test used a kiln temperature of 1570°F and a secondary combustion chamber temperature of 1710°F. For both tests, the average waste feed rate was just above the 15 ton/hr design rate for the incinerator system (Table 4).

The incinerator stack test results showed that during all tests and under both test conditions, the incinerator achieved a ≥ 99.998% destruction removal efficiency (DRE). The DREs were unusually consistent. The DREs for total PAHs were, without exception, higher than those for naphthalene. This result suggests that naphthalene was a good choice for the POHC, for it was more resistant to thermal decomposition than the average PAH compound. The DRE data from the second test were all "more than" values, since insufficient POHC was accumulated in

Table 4
Trial Burn Test Results Using Transportable
Incinerator at Prentiss, Mississippi

TEST CONDITION NUMBER 1

Kiln Operating temperature, F	1620			
Secondary Combustion Chamber, F	1670			
PARAMETER	RUN	RUN	RUN	AVERAGE
	1	2	3	
Waste Feed- TPH	15.1	15.2	15.5	15.3
Naphthalene Feed, lb/hr	77.2	48.3	98.7	74.73
Total PAH Feed, lb/hr	340	285	418	348
Naphthalene DRE, %	99.9983	99.9988	99.9981	99.9987
Total PAH-DRE, %	>99.9995	>99.9996	>99.9993	>99.9995
Particulate Emission Rate				
gr/dscf at 7% O ₂	0.0130	0.0104	0.0107	0.0113

TEST CONDITION NUMBER 2

Kiln Operating temperature, F	1570			
Secondary Combustion Chamber, F	1710			
PARAMETER	RUN	RUN	RUN	AVERAGE
	1	2	3	
Waste Feed- TPH	15.9	15.2	14.6	15.2
Naphthalene Feed, lb/hr	74.5	70.2	44.7	63.13
Total PAH Feed, lb/hr	401	401	282	361
Naphthalene DRE, %	>99.9996	>99.9998	>99.9996	>99.9997
Total PAH-DRE, %	>99.9997	>99.9998	>99.9997	>99.9997
Particulate Emission Rate				
gr/dscf at 7% O ₂	0.0141	0.0121	0.0103	0.0125



Figure 5

chamber originally had no ash extraction system. A water cooled screw conveyor was added to remove fine solids which accumulated there.

Slagging occurred on two initial shakedown runs, resulting in agglomeration of the ash. This problem was solved by running at lower temperatures and by relocating the kiln exit thermocouple which had been reading low due to seal air leakage.

Initial tests showed inconsistent DREs. This problem was due to a duct which collected steam and dust from the product cooler being vented into the baghouse. This vent line was rerouted into the secondary combustion chamber to prevent bypassing.

General mechanical problems occurred in the material handling system, principally with the apron feeder. These problems were solved by upgrading individual drive components and by consistent feeding of the feed hopper by the front-end loader.

U.S. EPA ACTIVITIES AND REGULATORY FACTORS

U.S. EPA Region IV has taken a leadership position in the use of on-site destruction technology to remediate hazardous waste sites. The Region has attempted to move away from landfilling and other temporary solutions and toward destruction and permanent remedies in accordance with SARA which emphasizes permanent solutions. Accordingly, incineration was the chosen method for remediation of the Prentiss site.

Since this was a Superfund site, permits, per se, were not required. However, data requirements were essentially the same as those for a formal Part B permit. These data were submitted in a work plan which was reviewed and approved by U.S. EPA. Regulations were primarily federal, with the major State of Mississippi concern being SO₂ (limited to 500 ppm).

BOG CREEK FARM PROJECT

The second use for the transportable incinerator will be the incineration of approximately 22,500 tons of solvent and paint sludge contaminated soil at the Bog Creek Farm Superfund Site in New Jersey. The project is being contracted by the U.S. Corps of Engineers. U.S. EPA Region II (New York) is in charge of the site. The contract was signed the first week of January, 1989.

The wastes were deposited in trenches by a past owner. Solvents and, to a lesser degree, metallic contaminants are entering the groundwater. Chemical Waste Management is the prime contractor on this \$14 million project and will coordinate the activities of the incineration, excavation and water treatment subcontractors. As of July, 1989, all plans

the XAD resin to quantify the destruction and removal efficiency. In this case, the limits of detection were used to back-calculate DRE. An average particulate emission rate of 0.012 grains/dscf (corrected to 7% oxygen) was measured, some six times better than RCRA requirements. The DRE for the total PAH compounds was determined to be $\geq 99.999\%$, at least 10 times better than required by RCRA standards. The test data for DRE and particulates from the trial burn are summarized in Table 4.

Hydrochloric acid gas concentration, determined from preliminary tests, showed that the total HCl emission rate (as calculated from the theoretical chlorine feed rate based upon soil analysis) was less than 4.0 lbs./hr. Actual stack concentrations were negligible, at less than 0.1 lbs/hr.

Sulfur dioxide was generated by organic sulfur in the coal tars. Uncontrolled levels were expected to be in the 160 ppm range. Continuous emission monitoring data during the trial burn showed concentrations from 0 to 10 ppm, well below the state of Mississippi limit of 500 ppm.

Ash tests were performed during the trial burn and on a daily basis throughout the project. In all tests, the ash product contained less than the required 100 ppm total PAH compounds and was below the more stringent land ban requirements. The PAH level was less than detection limit for each compound (minimum detection limit 0.05 ppm) on 35% of the tests. Total PAH was below 5 ppm for 92% of the ash tests. Maximum total PAH was 35 ppm, experienced on one test during startup of the system.

Problems Encountered and Solutions Employed

The primary problem encountered during startup was the higher than expected fines content of the soil. The stabilization reagent (cement kiln dust and fly ash) and local clays produced an extremely fine ash. Approximately 40% of the ash output was from the air pollution control system (cyclone through baghouse). The conveyors on this system were undersized and were changed out. The secondary combustion

were submitted to U.S. COE, U.S. EPA and NJDEP and approvals were being issued. The project will take 400 days to complete from issuance of the notice to proceed.

CONCLUSIONS

The Prentiss project marked the first field remediation action involving the incineration of creosote wastes. The experience gained is directly applicable to remediation efforts for sites which have soils containing significant amounts of stable organic contaminants. The incinerator has been designed to meet RCRA and TSCA regulations and brings state-

of-the-art technology to field remediation of all types of organic hazardous waste.

DISCLAIMER

Because the preceding paper has not completed the U.S. EPA technical and administrative review, it does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

LEnvirite Field Services, Inc., was acquired in December, 1988, by Williams Environmental Services and is now being operated as Williams Incineration Services, Inc.

Mobile Thermal Volatilization System for Hydrocarbon-Contaminated Soils

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ABSTRACT

In view of the current major environmental concern about leaking underground storage tanks and spilled fuel, O.H. Materials Corp. (OHM) undertook the development of an innovative system for the thermal treatment of petroleum hydrocarbon-contaminated soils. The objective in the development of the Mobile Thermal Volatilization System (MTVS) was to design a technically-sound and cost-effective method for the on-site treatment of hydrocarbon-contaminated soils.

This technology is applicable to the treatment of organic compounds with boiling points of up to 800°F including diesel fuel, heating oil and high boiling point aromatics. The equipment designed for the cleanup process was limited to only non-halogenated hydrocarbon compounds which eliminates the need for a high-temperature afterburner and acid scrubbing equipment.

A prototype unit was designed in the winter of 1986 and construction was completed in August, 1987. The prototype unit has been operated at several locations from which valuable production and performance data were obtained and used in the design of the second MTVS.

The second MTVS was designed to maximize production with a design feed rate of 10 tons/hr. The air pollution system consists of a hot cyclone, an afterburner (1400°F) and a venturi scrubber. The technical basis of the design of this unit will be discussed.

INTRODUCTION

Leaking underground petroleum storage tanks are a major threat to groundwater supplies. When the tanks are removed and replaced, the contaminated soil must also be addressed. Presently, these soils are not regulated by the U.S. EPA and the authority for their treatment and disposal has fallen to the individual states. Several states require the disposal of these soils in hazardous waste landfills which can cost from \$100 to \$220/ton plus the cost of transportation and future liability.

Low temperature thermal treatment was identified by OHM as a potential on-site treatment process for hydrocarbon-contaminated soils. The objective in the development of the Mobile Thermal Volatilization System (MTVS) was to design a technically-sound and cost-effective method for the treatment of hydrocarbon-contaminated soils. The equipment designed for the cleanup process was limited to only non-halogenated hydrocarbon compounds which eliminates the need for a high-temperature afterburner and acid scrubbing equipment.

The goal of the equipment design was to achieve maximum processing throughput in a highly mobile, single trailer system of legal-sized load. The prototype unit was designed in the winter of 1986 and the construction was completed in August, 1987. The prototype unit has been operated at six locations from which valuable operational and performance data have been obtained and used in the design of the second MTVS.

EQUIPMENT

The theory behind thermal volatilization consists of heating the soil to the temperature at which the organic contaminant is vaporized and removed from the soil. The vapors are then passed through an afterburner which oxidizes the organic constituents to carbon dioxide and water. The off-gases are then cooled and scrubbed to remove particulate matter before discharge to into the atmosphere. The technical specifications which were developed during the design phase of the project are contained in Table 1.

Table 1
Prototype Volatilization System Technical Specifications

System Design:

Maximum feed rate	12,000 lbs/hr
Particle size	up to 3 inches
Maximum hydrocarbon content	5 percent
Moisture content	15 percent
Soil discharge temperature	400°F
Primary heat capacity	6.0 MMBtu/hr
Solids retention time	15 minutes
Secondary temperature	1,400°F
Secondary volume	160 ft ³
Secondary heat capacity	3.0 MMBtu/hr
Secondary retention time (min)	0.6 seconds
Water requirements	6 gpm

Performance:

Design VOC destruction	99%
Particulate emissions	<0.04 gr/DSCF

Soil Cleanup Quality:

Hydrocarbon content	<100 ppm
Benzene	<0.5 ppm
Toluene	<0.5 ppm
Xylene	<0.5 ppm

The thermal volatilization process consists of a feed hopper which regulates the flow of material into the primary chamber. The primary chamber is directly heated to approximately 800°F using natural gas or propane. This 800°F temperature results in a 300- to 600°F soil discharge temperature. The required soil discharge temperature is dependent on the vaporization characteristics of the hydrocarbon contaminants.

The conveyance system on the primary chamber of the prototype unit is a 4 by 8 ft pugmill. The pugmill consists of two shafts with paddles attached at a slight incline that rotate at approximately 60 rpm which aids in conveying and mixing the soil. The burners are mounted over the pugmill and directed down toward the soil.

The conveyance system on the second unit consists of a rotary drum which improves the heat transfer efficiency in the primary chamber. The rotary drum also allows for greater soil discharge temperatures and throughput.

Both units have afterburners which have been designed for an operating temperature of 1,400°F and a gas retention time of 0.6 sec. This temperature was chosen based on the auto-ignition temperature of the anticipated hydrocarbon compounds as listed in Table 2.

Table 2
Autoignition Temperature of Some Common Organic Compounds

Compound	Temperature (degrees Fahrenheit)
Benzene	1075
Carbon monoxide	1205
Cyclohexane	514
Ethyl benzene	870
Kerosene	490
Methane	999
Propane	974
Toluene	1026
Xylene	924

The air pollution control equipment consists of a hot cyclone which is used to remove the majority of the particulate from the gas stream before it enters the wet scrubber. The gases are quenched in a stainless steel-lined duct before passing into a venturi scrubber which is followed by a mist eliminator. The cleaned gases are then exhausted from the system by an induced draft fan which maintains a negative draft on the entire system. The fan also controls fugitive emissions from the system.

OPERATIONAL EXPERIENCE

The prototype unit has been in operation since September, 1987, when it was first tested in the Fabrication Shop. The results showed that the system achieved a significant reduction in soil hydrocarbon contamination. A summary of these results is presented in Table 3.

A total lead analysis was also performed on the feed sample and the concentration was found to be indistinguishable from background. No lead was detected in the scrubber water at a detection limit of 10 µ/L. Stack emissions testing was not performed during this preliminary program due to schedule constraints.

The first field use of the equipment was for the moisture reduction of a recyclable sludge. A metals fabrication facility was closing its primary settling lagoon. The sludge in the lagoon contained a high concentration of titanium, which could be recycled. A mobile filter press was used to the waste, producing filter cake. The prototype MTVS was then used to reduce the moisture of the filter cake from 40% to 5%.

Table 3
Results Summary of Initial Testing of the
Thermal Volatilizing System

	Test 1	Test 2
Waste	Soil spiked	Soil spiked
Description	with 3.8 percent No. 2 diesel	with 1.9 percent No. 2 diesel and 1.9 percent leaded gasoline
Feed Rate	4 tons per hour	4 tons per hour
Discharge Temperature	220 degrees F	440 degrees F
Hydrocarbon Reduction	86 percent	99.3 percent

The second project took place at a service station in Cocoa, Florida, where leaking underground gasoline storage tanks had contaminated approximately 800 yd³ of fill. Before the tanks were removed, a new set of tanks was installed in another location on the site. This enabled the service station to continue operation throughout the remediation process. The State of Florida required stack emissions testing of the unit for particulate and organic emission at the beginning of the project. The results of this testing are contained in Table 4.

Table 4
State of Florida Required Emission Tests

Soil Contamination	755 ppm total hydrocarbons 12 percent moisture	
Feed Rate	5 tons per hour	
Soil Discharge Temperature	340 degrees Fahrenheit	
Particulate (corrected to 7% oxygen)	0.011 gr/dscf average 0.31 lb/hr	
Volatile	Benzene	22.2 ug/m3
Emissions (by VOST)	Toluene	16.0 ug/m3
	Ethylbenzene	3.1 ug/m3
	Xylenes	15.0 ug/m3
Opacity	0.0 percent	
Soil Quality	Total Petroleum <100 ppm Hydrocarbons by GC Aromatic Volatile <100 ppb Organics	

Based on this testing, a Florida statewide permit to install was issued for the system in November 1988.

Using the data and operational experience gained with the prototype unit, a second unit has been designed and constructed. This unit is similar to a rotary dryer which is thermally more efficient than a pugmill. The construction of the MTVS II was completed in September, 1988.

PROCESS TESTING OF THE MTVS II

The new unit is designed with a 5-ft diameter rotary drum for conveyance of the soil. The use of this rotary drum improves the thermal efficiency of the unit and increases the soil discharge temperature and processing rate. A process flow diagram is shown in Figure 1.

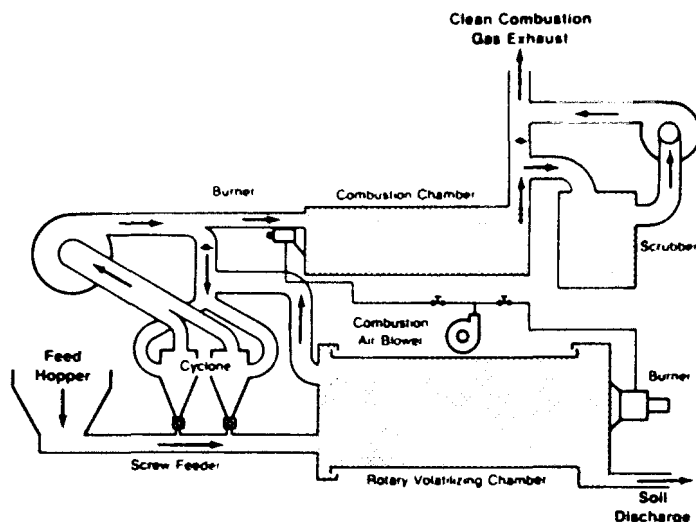


Figure 1
Mobile Thermal Volatilization System

The flow of gases from the primary chamber enters a high-efficiency cyclone where the majority of the particulate is removed. The gases then flow into the afterburner which is followed by a wet scrubber. The scrubber is mounted on a separate trailer and consists of a quench section and pumpless venturi. The technical specifications for the second MTVS are contained in Table 5.

The initial soil testing of MTVS II was conducted at the manufacturer's facility in Connecticut. The results of this soil testing are illustrated in Table 6.

The initial testing indicates that the technology will successfully remove gasoline and diesel fuels from contaminated soils.

After the unit was delivered, a State of Ohio compliance test was conducted. The test consisted of three trial runs conducted with soils spiked with a combination of diesel fuel and gasoline. Samples were collected from the exhaust stack, feed hopper, soil discharge screw and scrubber water. These samples were subsequently analyzed for total petroleum hydrocarbons, benzene, toluene and total xylenes.

The results of the stack emissions testing are contained in Table 7. These results demonstrated compliance with the State of Ohio Air Pollution regulations. The results of analysis performed on the soil and scrubber water are shown in Table 8.

CONCLUSION

The second generation MTVS has been successfully used to treat hydrocarbon-contaminated soil at several sites in Ohio and Pennsylvania. The treated soils have been placed back into the excavation areas after analytical verification that the cleanup criteria were obtained.

The use of a low-temperature thermal treatment unit for hydrocarbon-contaminated soils is now a viable alternative to off-site land disposal. The remediation of underground storage tank leaks and transportation spills can be completed on-site with minimal future liability.

Table 5
Technical Specification for MTVS II, Rotary Drum
Thermal Treatment System

System Design:

Maximum feed rate	20,000 lbs/hr
Particle size	up to 3 inches
Maximum hydrocarbon content	5 percent
Moisture content	15 percent
Soil discharge temperature	500-800 °F
Primary thermal rating	10 MMBtu/hr
Solids retention time	10-60 minutes
Secondary temperature	1400-1600 °F
Secondary thermal rating	10 MMBtu/hr
Secondary retention time	0.6 seconds
Water requirements	12 gpm

Performance:

Design VOC destruction	99 percent
Particulate emissions	<0.04 gr/DSCF

Soil Cleanup Quality:

Hydrocarbon content	<50 ppm
Benzene	<0.1 ppm
Toluene	<0.1 ppm
Xylene	<0.1 ppm

Table 6
Preliminary Test Results of MTVS II, Treatment of
Hydrocarbon-contaminated Soil

	TEST 1	TEST 2	TEST 3
Waste	Soil with	Soil with	Soil with
Description	1.5% gasoline	2.5% diesel	2.5% diesel
Percent	8.0 percent	12.5 percent	6.0 percent
Moisture			
Feed	6.5 tons/hr	8.25 tons/hr	6.0 tons/hr
Rate			
Discharge	420 °F	412 °F	550 °F
Temperature			
Discharge	<100 ppb VOA	<50 ppm TPHC	<50 ppm TPHC
Soil			
Quality			

Table 7
Demonstration Test Stack Emissions Results MTVS II for the
Rotary Drum Thermal Treatment System

<u>ELEMENT</u>	<u>TEST 1</u>	<u>TEST 2</u>	<u>TEST 3</u>
Particulate Collected (gr/dscf)	0.03	0.04	0.04
Particulate Collected (lbs/hr)	1.1	1.23	1.14
Benzene (mg/m ³)	<24	<15	<10
Toluene (mg/m ³)	<24	<15	<10
Xylenes (mg/m ³)	<24	<15	<10
Non-Methane Hydro Carbons (ppm)	71	87	79
Methane (ppm)	<3	<3	<3
Carbon Monoxide (ppm)	34	62	68

REFERENCE

1. Brunner, C. R., *Incineration Systems Selection and Design*, Van Nostrand Reinhold Co., New York, NY, 1984.

Table 8
Demonstration Test Results for Tests on MTVS II
Rotary Drum Thermal Treatment Systems

	<u>TEST 1</u>	<u>TEST 2</u>	<u>TEST 3</u>
<u>Waste Feed:</u>			
Waste Feed Rate (lbs/hr)	12,380	16,203	17,500
Calculated Hydrocarbon Feed Rate (lbs/hr)	309	405	437
Moisture (%)	10.0	10.2	9.5
Benzene (ppm)	9.50	6.47	2.96
Toluene (ppm)	198	73.1	48.4
Ethylbenzene (ppm)	46.0	20.0	18.1
Total Xylenes (ppm)	349	129	128
<u>Ash:</u>			
TPHC (ppm)	144	382	505
Benzene (ppm)	<1.0	<1.0	<1.0
Toluene (ppm)	<1.0	<1.0	<1.0
Ethylbenzene (ppm)	<1.0	<1.0	<1.0
Total Xylenes (ppm)	<1.0	<1.0	<1.0
<u>Scrubber Water:</u>			
Benzene (ppb)	<1.0	<1.0	<1.0
Toluene (ppb)	<1.0	<1.0	<1.0
Ethylbenzene (ppb)	<1.0	<1.0	<1.0
Total Xylenes (ppb)	<1.0	<1.0	<1.0

Contaminated Soil Remediation by Circulating Bed Combustion Demonstration Test Results

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ABSTRACT

The Circulating Bed Combustor (CBC) is an advanced generation of incinerator that utilizes high velocity air to entrain circulating solids in a highly turbulent combustion loop. Because of its high thermal efficiency, the CBC is ideally suited to treat organic wastes with low heat content, including contaminated soil. This paper discusses the development of the CBC technology for the treatment of contaminated soils and its application to site remediation. The CBC process, pilot plant and transportable field equipment units are described and the results of four recent tests are presented.

In March, 1989, a Superfund Innovative Technology Evaluation demonstration test burn of McColl Superfund site soil was conducted in Ogden Environmental Services' Circulating Bed Combustion research facility. In Stockton, California, two performance tests of soil contaminated with fuel oil were conducted during February and July of 1989. A demonstration test of PCB-contaminated soil was performed in September of 1988 at Swanson River, Alaska, resulting in the June, 1989 issuance of a U.S. EPA TSCA permit for operation. The results of these tests demonstrate that the Circulating Bed Combustor meets or exceeds all applicable California, Alaska and U.S. EPA criteria for each of these projects.

INTRODUCTION

The Circulating Bed Combustor (CBC) is ideally suited to treat feeds with low heat content, including contaminated soil (Fig. 1). Soil is introduced into the combustor loop at the loop seal where it contacts hot recirculating soil from the hot cyclone. Hazardous materials adhering to the introduced feed soil are rapidly heated and continue to be exposed to high temperatures throughout their residence time in the ceramic lined combustor loop. High velocity air (14- to 20-ft/s) entrains the feed with circulating soil which travels upward through the combustor into the cyclone. Retention times in the combustor range from 2 sec for gases to 30 min for larger feed materials.

A cyclone separates the combustion gases from the hot solids, which return to the combustion chamber through a proprietary, non-mechanical seal. Hot flue gases and fly ash that are separated at the cyclone pass through a convective gas cooler and on to a baghouse filter which removes the fly ash. Filtered flue gas then exhausts to the atmosphere. Heavier particles of purified soil remaining in the lower bed of the combustor are removed at a controlled rate by an ash conveyor system.

As a consequence of the high turbulence in the combustion zone, temperatures around the loop (combustion chamber, hot cyclone, return leg) are uniform to within $\pm 50^\circ\text{F}$ over the typical operating range of 1450 to 1800°F. The uniform low temperatures and high solids turbulence also help avoid the ash slugging that is encountered in other types of incinerators.

Acid gases formed during destruction reactions are rapidly captured in the combustor loop by limestone that is added directly into the combustor with the feed. HCl and SO₂ that are formed during the combustion of chlorine- and sulfur-bearing wastes react with limestone to form dry calcium chloride and calcium sulfate. Due to the high combustion efficiency attainable in a CBC, an afterburner is not needed. In more than 90% of the cases studied to date, post-combustor acid gas scrubbing is not required. Emissions of CO and NO_x are controlled to low levels by the excellent mixing resulting from turbulence, relatively low temperatures and staged combustion which is achieved by injecting secondary air at locations ascending the combustor. Because of the design and operating features, the CBC can attain required destruction and removal efficiencies (DREs) for both hazardous wastes (DRE $\geq 99.99\%$) and toxic wastes (DRE $\geq 99.9999\%$) at temperatures below those used in conventional incinerators which typically burn at temperatures greater than 2000°F.

The Circulating Bed Combustion technology is well developed and is being applied on two contaminated soil site remediation projects that will clean over 80,000 tons of contaminated soils. OES and its predecessors have pursued a systematic technology development and an applications approach comprised of the following elements:

- Definition of treatable soil contaminant waste types

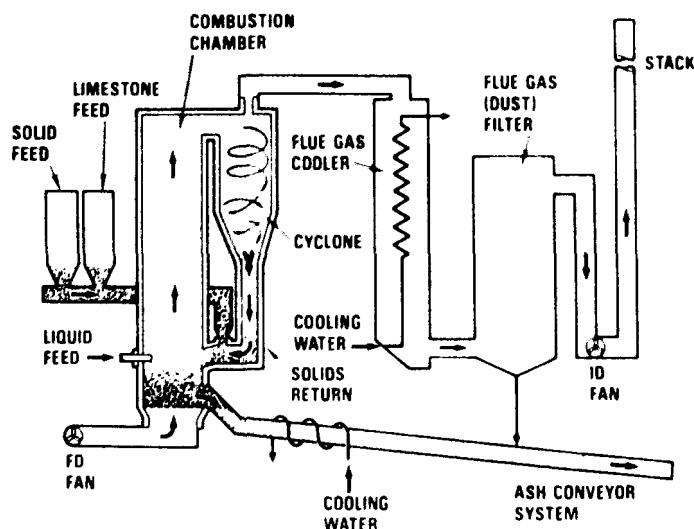


Figure 1
Schematic Flow Diagram of Circulating Bed Combustor for
Soil Treatment

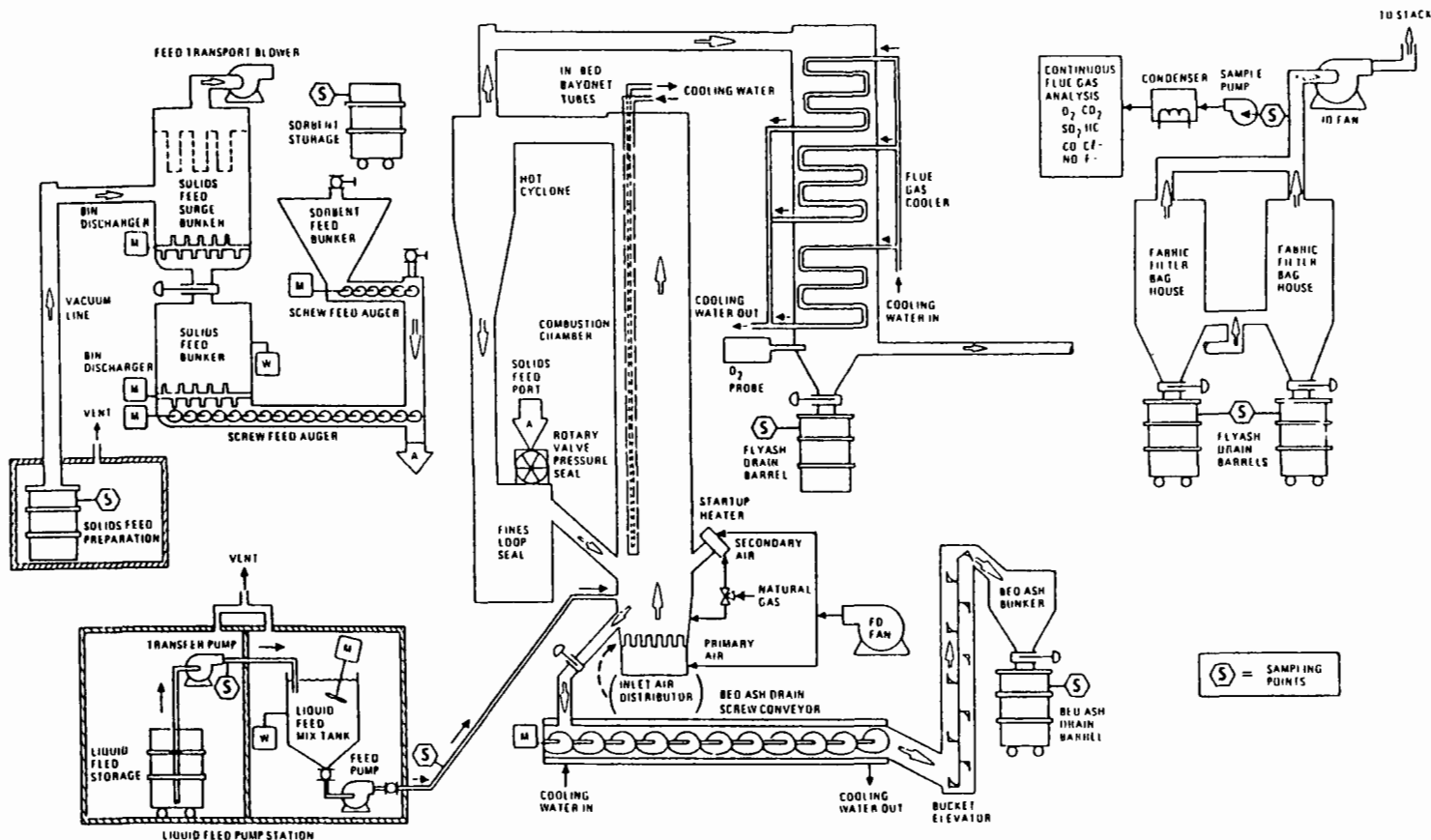


Figure 2
Research Facility CBC Process Schematic

- Fifteen years of fluidized and circulating bed pilot plant testing
- CBC performance demonstrations in private and governmental programs, including the Superfund Innovative Technology Evaluation (SITE) program
- Extensive permitting activities
- Design, engineering, fabrication, deployment and operation of modular transportable CBCs for hazardous waste site cleanups

OES CIRCULATING BED COMBUSTOR UNITS

Research Facility

Ogden Environmental Services (OES) research CBC is the heart of an integrated, highly flexible waste combustion demonstration facility located in San Diego, California. Initial CBC-soils treatment development and engineering studies were carried out in this 16-in., 2 million Btu/hr CBC. The test data obtained were used to design the larger, transportable CBCs. The configuration of the research CBC is shown schematically in Figure 2. Figure 3 is a photograph of the 16-in. CBC unit.

Transportable CBC's

The transportable 36-in., 10 million Btu/hr CBC consists of seven structural steel modules that contain the process equipment and provide the structural framework of the CBC. The modules do not exceed measurements of 8.5 ft wide, 10.3 ft high and 35 ft long. As a result, the modules can all be transported on single drop trailers that do not require special highway transportation permits. The CBC cyclone and combustor are mounted to the top of one of the structural modules. When erected, the transportable CBC itself sits on a pad of 30 by 50 ft and is approximately 60 ft in height. In field operations, the transportable CBCs are incorporated in a complete system layout which includes ancillary equipment units and transportable buildings, e.g., a control room, a motor control center, an analyzer room and a chemistry support laboratory (optional). Figure 4 is a photograph of the OES Stockton Project field assembled, transportable 36-in. (i.d.) CBC unit.

MEDIA TREATED

Circulating Bed Combustion is widely applicable to many hazardous waste forms. Solids, including contaminated soils, liquids and sludges, are treated with equal facility by using the appropriate feeding systems. OES has conducted extensive pilot-plant and field-unit testing on soils contaminated with hydrocarbons and chlorinated hydrocarbons.

PROCESS WASTE STREAMS

The CBC process typically produces solids (i.e., bed and fly ash) and stack gas, as shown in Figure 1. The composition of the stack-gas system effluent must meet U.S. EPA and other governmental requirements in accordance with permitted conditions. All the CBC incineration tests of contaminated soils verify that the purified soil treated by the CBC is non-hazardous with respect to organic residuals. Since most metals migrate to the ash during combustion, the disposition of ash is specific to each waste feed case and must be determined on an individual basis. For most organic-contaminated soil sites, the ash produced by the CBC meets the criteria for redeposition on-site. At both Stockton and Alaska the purified soil is deposited on-site as non-hazardous soil. It is expected that McColl ash will be non-hazardous since the SITE program McColl ash leach testing found organic and metal concentrations to be well below the regulatory limits. Post-combustion fixation processes may occasionally be required if the ash metals content or leachability exceeds permissible levels.

RECENT TESTS WITH CONTAMINATED SOIL FEEDS

Through the two large-scale site remediation projects that will treat over 80,000 tons of contaminated soil and the pilot-scale operations during SITE program testing, OES has proven the effectiveness of transportable CBCs by locating and operating them cost-effectively in demanding environments. Every regulatory requirement for site operations has been met. The transportable CBCs have been operated in weather as cold as -40°F and as high as 110°F. The ruggedness of the units has been demonstrated by mobilizing and operating successfully



Figure 3
16-in. CBC in the San Diego Research Facility

in a remote and ecologically sensitive wildlife refuge. OES has maintained high levels of availability through the use of careful logistics planning that includes design factors, maintenance and supply planning. A description of the projects is given below.

Superfund Innovative Technology Evaluation Program

In 1986 the CBC was selected by U.S. EPA for a demonstration under the SITE program. Contaminated soil from the McColl Superfund site in Fullerton, California was selected as the waste feed for the demonstration project. Due to multiple delays encountered in the securing all of the required permits, it was not possible to conduct the planned feasibility demonstration test until this year.

The treatability study was conducted during March, 1989. The demonstration approximately 31 hr over a 4-day period. The project was monitored by the U.S. EPA, the California Department of Health Services and the San Diego County Air Pollution Control District. A total of 7,500 lb of contaminated soil were processed through the CBC, of which 4,700 lb were actual McColl waste. The materials that were processed included: unblended waste, waste blended with clean sand and unblended waste spiked with carbon tetrachloride. The materials were processed without difficulty.

Samples of the waste feed, fly ash, bed ash and stack gas were taken by a U.S. EPA contractor for analysis. The samples were analyzed for organic compounds, (including dioxins and furans), metals, criteria pol-



Figure 4
36-in. Diameter Transportable CBC at Stockton Site Leaking
Underground Storage Tank Remediation Photo

lutants and physical properties.

Table 1 contains operating conditions and data on stack criteria pollutant and acid-gas emissions from the triplicate testing. Test, 1 fed 325 lb/hr of McColl waste blended with sand. Tests 2 and 3 processed waste alone and waste spiked with carbon tetrachloride. The tests were performed at the target temperature of 1700°F at lower than maximum throughput. While permit limits on this test precluded the evaluation of feed rates higher than 200 lb/hr of waste, the successful results indicate that processing in a commercial CBC is feasible. The criteria pollutant and acid-gas release data obtained are well within federal, state and local requirements. Particulate emissions were more than ten times lower than the 0.08 gr/dscf corrected to 7% oxygen federal limit. Combustion efficiency and DRE were consistently higher than the regulatory limits.

The U.S. EPA has officially released preliminary data which has been checked to assure that it meets U.S. EPA standards and the complete demonstration test report will be available in late 1989.

The results show organic material was effectively destroyed as exhibited by the DRE value (99.9937%) shown in Table 1. Complete stack and ash analysis for volatiles, semi-volatiles and metals indicate that no significant levels of hazardous compounds left the CBC system in the stack gas. Ash analysis indicate that no significant levels of hazardous organic compounds remained in the bed and fly ash material. A Toxicity Characteristic Leaching Procedure (TCLP) test was per-

Table 1
McColl SITE Tests: Operating Conditions

Test Conditions	Test 1	Test 2	Test 3
Combustor temp, °F	1721	1726	1709
Residence time, sec	1.54	1.52	1.55
Soil throughput, lb/hr	325	170	197
Carbon tetrachloride, lb/hr	0	0	0.22
Flue gas oxygen, dry %	11	9.9	11.8
CO emissions, ppm	30	30	26
HC emissions, ppm	5	1	2
SO ₂ capture, %	>95%	>95%	>95%
NO _x emissions, ppm	49	58	48
Carbon dioxide, dry %	9.9	11.9	9.2
HCl emissions, lb/hr	<0.0090	<0.0085	<0.0098
Particulate gr/dscf at 7% O ₂	0.0041	0.0044	0.0035
Combustion efficiency, %	99.97	99.97	99.97
DRE, (%)			99.9937

formed on the McColl CBC ash. Arsenic, selenium, barium, cadmium, chromium, lead, mercury and silver leachabilities were found to be well below the federal requirements (40 CFR Part 268).

While the McColl site waste averages 8% sulfur, the soil selected for this testing ranged between 4 and 5% sulfur to comply with research facility permit feed concentration limits. The efficiency of in-situ sulfur capture using limestone was >95%. Further quantitation is not possible as the sulfur dioxide continuous emissions monitor low range was not performing to specification.

Waste, limestone, ash and flue gas were analyzed for the following 17 metals: arsenic, antimony, barium, beryllium, cadmium, chromium, copper, lead, mercury, manganese, nickel, selenium, silver, thallium, zinc, cobalt and tin. Table 2 lists the partitioning results for the six metals found in all three waste samples at more than twice the minimum detection limit for that metal. Waste concentrations for these six metals were not high, ranging from 3 mg/kg cobalt to 211 mg/kg manganese, making it difficult to trace their fate. Total metal mass exiting the process further illustrate the small quantities. Mass balances around the metals did not account for more than 91% of the input and typically accounted for about half of the feed metal content. This is to be expected when low concentrations of naturally occurring metals are measured in complex soil matrices.

Two figures are listed as "<" to indicate that the metal was not detected. Detection limits were used to quantify these partition fractions. Partition data is therefore to be used with caution. As expected, the fly ash consistently showed both higher metal concentrations and metal mass flows than the bed ash. Zinc data is not presented due to interference from zinc coatings in the equipment.

Table 2
McColl SITE Test: Metals Partitioning

	Metal	Total mg/hr	Flyash Fraction	Bed ash Fraction	Flue Gas Fraction
Test 1	Copper	688	0.769	0.195	0.037
	Nickel	1350	0.714	0.278	0.007
	Cobalt	226	0.765	0.218	0.018
	Chromium	3206	0.843	0.154	0.003
	Barium	6110	0.832	0.167	0.001
	Manganese	15687	0.761	0.238	0.000
Test 2	Copper	1221	0.938	0.036	0.026
	Nickel	1171	0.904	0.049	0.047
	Cobalt	204	0.906	<0.053	0.041
	Chromium	2932	0.948	0.036	0.016
	Barium	6435	0.937	0.061	0.003
	Manganese	20741	0.958	0.041	0.001
Test 3	Copper	874	0.949	0.028	0.023
	Nickel	532	0.872	0.107	0.022
	Cobalt	150	0.941	0.047	0.012
	Chromium	1630	0.951	0.043	0.006
	Barium	4157	0.972	<0.026	0.002
	Manganese	11682	0.968	0.037	0.001

The U.S. EPA has concluded the test was successful based on the available data. Phase II of the SITE testing has proposed to demonstrate a 36-in. CBC at the Fullerton site in 1990.

TRANSPORTABLE CBC UNIT FIELD DEMONSTRATION TESTS

PCB Site Remediation Project

OES conducted a PCB-contaminated soil demonstration test burn at a Swanson River, Alaska remediation site project in September, 1988, in accordance with a test burn plan prepared by OES and approved by the U.S. EPA Office of Toxic Substances. The test burn was conducted under witness of the U.S. EPA and the Alaska Department of Environmental Conservation (ADEC) at the remote Swanson River Alaska site on the Kenai peninsula. All required performance criteria were met and in June, 1989 OES was granted a nation-wide PCB Disposal Operating Permit for its transportable 36-in. CBC unit.

The ARCO Alaska Inc. Swanson River site is located within the Kenai Wildlife Refuge. PCB contamination was identified during site soil sampling conducted by the U.S. Fish and Wildlife Service in 1984. The contamination was an indirect result of a compressor explosion which occurred in 1972. Remediation activities were initiated by a voluntary "Order by Consent" signed by the site operator. The remediation is being conducted under the direction of the U.S. Fish and Wildlife Service, the Bureau of Land Management, the Alaska Department of Environmental Conservation and the U.S. EPA, Region X.

OES was selected for the remediation project. OES' site remediation workscope includes mobilization, on-site demonstration testing, excavation, contaminated vegetation clearing, incineration, contaminated water treatment, concrete and metal surface decontamination, demobilization and site restoration.

The completion of the Swanson River project is scheduled for the end of 1991. Upon completion, over 70,000 tons of PCB-contaminated gravel/silt soil will have been treated. Figure 5 is a photograph of the Swanson River site. Soil is fed into the CBC at a rate of 4.5 tons per hr. The treated soil is analyzed for PCBs and then released by the on-site lab after the PCB level has been verified to be less than 2 ppm. The treated soil is placed into a clean discharge area.

OES has established a chemistry and analytical laboratory at the site that performs most required chemical and physical analyses required at the site, including analyses of PCB in pre-and post-treated soils, soil physical parameters, air quality and water quality. Samples can typically be prepared, analyzed and reported within 8 hr, substantially less time than required by an external laboratory and at considerably less cost. The laboratory has been audited and passed by the U.S. EPA on unannounced visits.

The laboratory equipment, which includes two Varian 3400 gas chromatographs with electron capture and flame ionization detectors, enables high sample throughput and rapid turnaround time. Decontamination verification on equipment and other pieces of machinery or buildings are analyzed in-house and reported quickly to provide real cost savings. The number of samples analyzed in a week has been as high as 200 samples following U.S. EPA Method 8080 and adhering to QA criteria.

The operating conditions during the two demonstration tests are listed in Tables 3A and 3B. Two sets of tests were conducted under different process conditions on PCB-contaminated soil in accordance with the Toxic Substances Control Act guidelines and a U.S. EPA approved demonstration test plan. Each test consisted of triplicate test burns. A continuous emissions monitoring system measured concentrations of oxygen, carbon monoxide, total hydrocarbons as methane, sulfur oxides, nitrogen oxides and carbon dioxide in a constant sample of cooled, desiccated flue gas. Monitoring equipment used in OES commercial CBCs are detailed in Table 4. Both tests surpassed all regulatory requirements.

As shown in Tables 3A, 3B and 5, the DREs were greater than the required 99.9999% and the purified soil PCB concentrations were significantly less than the regulatory limit of 2 parts per million. Combustion efficiency exceeded the regulatory requirement of 99.9%. Dioxin and furans were not detected in the purified soil. Stack gas emissions did not contain measurable levels of dioxins and furans above the U.S. EPA Office of Toxic Substances minimum quantitation limit of 10 ng/m³/coGENER. The results demonstrate that the OES CBC meets or exceeds all U.S. EPA-TSCA criteria for incineration of PCB con-



Figure 5
PCB Remediation at Swanson River Alaska Project Site, Aerial Photo

Table 3A
Swanson River Tests: Operating Conditions Tests 1 through 3

Test Conditions	Test 1	Test 2	Test 3
Combustor temp, °F	1620	1606	1620
Residence time, sec	1.68	1.68	1.67
Soil throughput, lb/hr	8,217	8,602	8,603
Soil PCB conc., ppm	632	615	801
Flue gas oxygen, dry %	7.1	7.4	6.9
CO emission, ppm	12	11	17.5
HC emissions, ppm	2	2	2
SO ₂ emissions, ppm	16	15	13
NO _x emissions, ppm	89	88	88
Carbon dioxide, %	8.8	8.7	8.6
HCl emissions, lb/hr	1.49	1.08	1.37
Particulate gr/dscf at 7% O ₂	0.0072	0.0065	0.0093
Combustion efficiency, %	99.980	99.990	99.985
DRE, %	>99.99993	>99.99992	>99.99997

Table 3B
Swanson River Tests: Operating Conditions Tests 4 through 6

Test Conditions	Test 4	Test 5	Test 6
Combustor temp, °F	1701	1693	1686
Residence time, sec	1.52	1.47	1.53
Soil throughput, lb/hr	8,194	9,490	9,555
Feed PCB conc., ppm	289	608	625
Flue gas oxygen, dry %	6.2	6.1	8.1
CO emissions, ppm	8.7	10	12.5
HC emissions, ppm	2	2	2
SO ₂ emissions, ppm	27	21	20
NO _x emissions, ppm	82	90	95
Carbon dioxide, %	8.8	8.9	8.8
HCl emissions, lb/hr	1.42	1.57	1.21
Particulate gr/dscf at 7% O ₂	0.0120	0.0190	0.0182
Combustion efficiency, %	99.990	99.990	99.990
DRE, %	>99.99996	>99.99994	>99.99993

Table 4
Transportable 36-in. CBC Monitoring Equipment

Name/Function	Principal of Operation	Range	Accuracy (% of Full Scale)	Sampling Method
Flue gas O ₂ Probe	Zirconia Cell	0-10%	2	In situ
Extractive Gas Analysis				
Oxygen	Paramagnetic	0-25%	1	extractive
CO	Infrared	0-250ppm	1	extractive
CO ₂	Infrared	0-25%	1	extractive
NO/NO _x	Chem Lumina.	0-500ppm	1	extractive
SO ₂	Infrared	0-500ppm	1	extractive
HC	Flame Ionization	0-200ppm	1	extractive
Combustor Pressure				
Various	Diaphragm	various	2	In situ
Temperatures				
Various	Thermocouple	0-2000 °F	0.2	In situ
Soil Feed Rate*	Correlation	0-100%	10%	n/a

* Soil feed rates are determined from a correlation of motor speed vs. feed rate.

Table 5
Swanson River Demonstration Test, Summary of Test Results and Performance Calculations

TEST NO.	DRE	PCB CONCENTRATION			DIOXIN CONTENT		FURAN CONTENT		CHLORIDES		VO**	SVO***
		FEED	ASH	STACK GAS	ASH	STACK GAS	ASH	STACK GAS	FEED	STACK		
		ppm	ppb	ug/min	ppt*	ug/min	ppt	ug/min	ppm	ug/hr	ug/hr	ug/hr
1	>99.99992	632	<9.0	<26.6	<68.1	<7.5E-5	<48.4	<4.3E-5	109	<11.0	35.1	492.3
2	>99.99992	615	<8.5	<32.1	<68.9	<6.0E-5	<59.4	<7.4E-5	230	<4.8	24.5	344.1
3	>99.99997	801	<9.1	<14.2	<93.7	<5.5E-5	<81.2	<5.8E-5	148	<8.9	39.0	6.8
4	>99.99994	289	<12.0	<74.2	<87.9	<8.3E-5	<84.2	<1.7E-5	228	<0.1	40.0	43.7
5	>99.99994	608	<9.9	<38.1	<101	<2.6E-5	<93.4	<2.6E-5	207	<10.4	41.9	34.0
6	>99.99992	625	<15.9	<31.5	<88.7	<3.3E-5	<76.9	<3.9E-5	253	<10.1	104	16.6

* ppt = parts per trillion
** VO = Volatile organics
*** SVO = Semi-volatile organics

taminated soil.

Swanson River DRE measurement was limited both by the size of the stockpile of contaminated soil and by the concentration of PCBs in the soil. OES was not allowed to bring any PCBs into the Kenai National Wildlife Refuge for any purpose, including feed spiking, even though the available soil concentrations and quantity were low. In all 6 tests, the DREs are based upon estimated maximum possible concentrations rather than detection limits or measured quantities since the measured quantities of PCBs in the flue gas were so low. The Swanson River DREs are the highest possible with these feed concentrations and current detection limits. Had OES been allowed to spike the soil to 10,000 ppm, as in the 1985 test at the research facility, higher DREs would have been possible as they were then. Soil was incinerated during four tests in August, 1985, three at 1800°F and one at 1625°F. The feed concentrations ranged from 9,800 ppm to 12,000 ppm and the DREs were all between 99.99998% and 99.999995%.

FUEL OIL SITE REMEDIATION

For more than 50 yr, a leaking underground storage tank at a cannery in Stockton, California contaminated surrounding clay soil with No. 6 fuel oil. OES was contracted by the site operator to remediate the site using one of its transportable 36-in. CBCs. OES developed and is now completing a remediation plan that encompasses site characterization, demolition of tanks and buildings, installation and operation of water intercept wells, water treatment, soil excavation, stockpiling, CBC treatment, placement of slurried purified soil and site and building restoration.

The excavation and backfilling is complete and the CBC thermal treatment of stockpiled soils is nearing completion (August, 1989). Upon completion of the project, over 11,000 tons of contaminated soil will have been treated. Following restoration, the site will have its full commercial value restored and it will be available for unrestricted use. Figure 4 is a photograph of the Stockton project site. Table 6A details the February, 1989 source test operating conditions performed at Stockton. The emissions are comparable to those from the other two CBC units. In July, 1989 a demonstration test was performed using naphthalene-spiked soil. Destruction removal efficiency data was the only preliminary information available in August. Table 6B lists the DREs from the three tests, all other results and operating conditions were similar to those recorded during the February source test detailed in Table 6A.

TREATMENT COSTS

Site remediation costs are divided into three categories. The first cost category includes both direct and indirect costs for engineering design, base equipment cost, materials, foundation and installation labor to erect a mechanically complete unit. The second cost category includes labor, materials, utilities, repair and maintenance and indirect costs. The third category includes material handling operations including excavation, feed processing and ash disposal. Costs for all three CBC soil remediation cost categories combined typically range from \$100-\$300/ton of soil depending primarily on soil moisture content and the quantity of wastes to be processed.

Table 6A
Stockton Source Test: Operating Conditions

Parameter	Test 1	Test 2	Test 3
Combustor temp, °F	1588	1588	1587
Residence time, sec	1.8	1.8	1.8
Soil throughput, lb/hr	4000	4000	4000
Soil TPH conc., ppm	2130	1160	3450
Flue gas oxygen, dry %	13.6	13.6	13.6
CO emissions, ppm at 7% O ₂	28.0	25.4	23.6
HC emissions, ppm at 7% O ₂	<2	<2	<2
SO ₂ emissions, lb/day	16.6	12.0	24.2
SO ₂ emissions, ppm at 7% O ₂	84	61	123
NO _x emissions, lb/day	7.4	7.3	6.7
NO _x emissions, ppm at 7% O ₂	52	52	47
Carbon dioxide, %	7.0	6.6	6.9
Particulate gr/dscf at 7% O ₂	0.045	0.046	0.045
Combustion efficiency, %	99.989	99.990	99.990

Table 6B
Stockton Demonstration Test: Preliminary Results

Naphthalene conc., ppm	4314	4730	4106
DRE, %	>99.9960	>99.99956	>99.99958

Conclusion

OES has developed a Circulating Bed Combustion waste treatment technology and demonstrated its applicability in private- and government-sponsored programs including the Superfund Innovative

Technology Evaluation program. Based on this development and testing program, modular CBC units have been designed, fabricated and deployed. CBC treatment is being utilized in two large remediation projects.

Treating contaminated soil in a CBC is cost-effective, highly efficient and meets all performance and operation criteria established by regulatory agencies. Ogden Corporation, OES' parent company, has made a major commitment to the site remediation business by building

four units, with two units now in operation and two ready for deployment.

REFERENCES

1. Young, D.T., "Process Demonstration Test Report for Trial Burn of PCB Contaminated Soils, PCB Destruction Unit: Circulating Bed Combustor" paper GA-C18051, GA Technologies Inc., San Diego, CA, Submitted to Office of Toxic Substances, U.S. EPA, Aug. 1985

Site Program Demonstration Test of the CF Systems Inc. Organics Extraction Unit

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ABSTRACT

The Superfund Innovative Technology Evaluation (SITE) Program demonstration of the CF Systems organics extraction technology was conducted at the New Bedford Harbor Superfund site in Massachusetts. The demonstration was conducted concurrently with pilot dredging studies managed by the U.S. Army Corps of Engineers, from which samples of contaminated harbor sediments were obtained for use in the demonstration. Several tests were conducted on a trailer-mounted, pilot-scale unit to obtain specific operating, analytical, and cost information that could be used in evaluating the potential applicability of the technology to New Bedford Harbor and other Superfund sites. The primary objective of this demonstration was to evaluate the developer's treatment goals for extracting PCBs from harbor sediments. Secondary objectives included an evaluation of (1) the unit's performance in terms of extraction efficiency and a mass balance, (2) system operating conditions, and (3) health and safety considerations.

The developer achieved an overall PCB concentration reduction of 89 percent for sediment samples that contained 350 ppm and 92 percent for sediment samples that contained 2,575 ppm. The unit generally operated within specified conditions for flow rates, pressures, temperature, pH and viscosity. Results of the demonstration tests show that the CF Systems technology is capable of reducing the PCB content of contaminated sediment by greater than 90 percent without a risk to operating personnel or the surrounding community.

INTRODUCTION

Through the SITE program, the U.S. Environmental Protection Agency (EPA) is assisting technology developers in the development and evaluation of new and innovative treatment technologies. The SITE program's objective is to enhance the commercial availability and use of these technologies at Superfund sites as an alternative to land-based containment systems that are used most often at Superfund sites. Part of the SITE program involves field demonstrations to gather real-world data on a technology. The developer is responsible for the cost of operating the equipment during the demonstration, while EPA is responsible for the analytical costs and evaluation associated with the demonstration. In most cases, the demonstration is performed at an actual Superfund site that provides appropriate site and waste characteristics for the specific technology to be tested.

PROCESS FLOW OF UNIT

CF Systems Inc., of Boston Massachusetts, developer of a liquefied propane extraction technology, was selected to demonstrate their pilot-scale system. New Bedford Harbor was chosen for the demonstration site for CF Systems technology. The harbor sediments are contaminated with polychlorinated biphenyls (PCBs), a complex

organic substance amenable to extraction with CF Systems' process.

The developer's pilot-scale treatment technology is a trailer mounted unit designed to handle pumpable soils, sludge, or sediments. The unit operates in the six basic steps shown in Figure 1, that can cover extraction, phase separations, and solvent recovery. A mixture of liquefied propane and butane was used as the extraction solvent.

In step one, pumpable (slurried) solid waste is fed into the top of an extractor. Then (step two), the solvent, a propane/butane mix, is condensed by compression and allowed to flow upward through the same extractor. In the extractor the solvent makes non-reactive contact with the waste, dissolving out the organics it contains. This is a somewhat non-specific organic extraction process, though it is based on the solubility of the organic waste in the extracting liquefied gas. Following this extraction procedure, the residual mixture of clean water or water/solids can be removed from the base of the extractor (step three).

In step four, the mixture of solvent and organics leaves the top of the extractor and passes to a separator through a valve which partially reduces pressure. The reduction of pressure causes the solvent to vaporize out of the top of the separator. It is then collected and recycled through the compressor as fresh solvent (step five). The organics left behind are drawn off from the separator.

The demonstration tests devised by CF Systems for their pilot-scale units (PCU-20 nominal capacity - 20 bbl/day) were designed to demonstrate the treatability of New Bedford Harbor sediments and to provide operating and scale-up data to assess potential commercial-scale applications. The demonstration included equipment setup; a "shakedown" stage to set process conditions; and daily start-up, operation, and shutdown. When tests were completed, the demonstration concluded with equipment decontamination and site closure. Thus, all of the major components of a full-scale cleanup of New Bedford Harbor were demonstrated.

TEST DESIGN

Sediments were dredged from five New Bedford Harbor locations and stored in 55-gallon drums for processing by the pilot unit. Drummed sediments were sieved to remove particles greater than one-eighth inch that could damage system valves. Water was also added to produce a pumpable slurry. The drummed sediments were blended to provide feedstocks for four tests. Measurements were also included on the decontamination of the equipment.

A test consisted of a number of "passes." When the sediment was treated or processed through the unit, the treated sediment became the feed stock for another "pass." The variation in the number of passes was to simulate a large full-scale unit, and to get additional design parameters on such a unit. The following are the test, concentration of the PCB's in the feed stock and purpose of the test:

1. Test 1 was run as a shakedown test to set pressure and flow rates in the PCU. The feed was a 50-gallon composite of sediments. The feed had a PCB concentration of 360 ppm. Three passes were run to gain experience with materials handling.
2. Test 2 was a 10-pass test. The feed was 350 ppm of PCB, and was contained in a 511-pound composite of sediments. Ten passes were run to simulate a high-efficiency process and to achieve treated sediment levels less than 10 ppm. A 350 ppm PCB concentration was chosen for this test since this represents an average, or typical, PCB concentration in the harbor.
3. Test 3 was a 3 pass test. The feed was 288 ppm, and was contained in a 508-pound composite of sediments. The purpose of this test was to reproduce the results of the first three passes to Test 2.
4. Test 4 was a 6 pass test. The feed was 2,575 ppm of PCB, and was contained in a 299-pound composite of sediments. The purpose of this test was to reduce a high-level waste to a lower level waste such as that used in Tests 1, 2, and 3. High-level wastes are found at several "hot spots" in the harbor.

Decontamination of the system involved running toluene through the PCU as a solvent wash. Samples were taken of the feed at the commencement of each test. Treated sediment products and extracts were planned for sampling at each pass. Additional samples were taken of system filters and strainers. The amount of PCB contained in these miscellaneous samples later proved to be small. The pilot unit's operating pressures, temperatures, and flow-rates were monitored throughout the tests. Field tests were conducted for feed viscosity, pH, and temperature.

TEST RESULTS

The objectives of this testing program were to evaluate: (1) the unit's performance, (2) system operating conditions, and (3) health and safety considerations.

SYSTEM PERFORMANCE

The evaluation criteria established for system performance were:

- PCB concentration in sediments before and after treatment
- PCB extraction efficiency with each pass of sediments through the PCU
- Mass balances established for total mass, solids, and PCBs.

These criteria are discussed with respect to analytical results below.

PCB CONCENTRATION REDUCTIONS

PCB analyses for feed sediments and treated sediment, conducted for samples collected at each pass, are shown in Table C-1. The data show that treated sediment concentrations of 8 ppm are achievable and that as much as 84 percent of the PCB contained in sediment can be removed in a single pass. In Test 2, feed containing 350 ppm of PCB was reduced to 8 ppm after 9 passes through the PCU. In Test 3, a 288 ppm feed was reduced to 47 ppm after just one pass. In Test 4, a 2,575 ppm feed was reduced to 200 ppm after 6 passes. The percent reductions in PCB concentration, based in a comparison of untreated feed to the final pass, for each test were:

Test	Percent Reduction in PCB Concentration	Number of Passes
2	89%	10
3	72%	3
4	92%	6

The data for each test show general reduction trends based on differences between initial feed and final treated sediment concentrations. However, these trends are not consistent on a pass-by-pass basis. For example, PCB concentrations in treated sediments increase at Test 2, passes 4 and 10, and at Test 3, passes 2 and 3. These anomalies are not related to the extraction process. Instead, they reflect cross contamination within system hardware, and partially attributed to the limited analytical precision and accuracy. Since the treated sediment collection tanks were under pressure, it was not

possible to clean out collection hardware and piping. Therefore, a pass-by-pass mass balance could not be established.

Data for each test show the potential number of passes required to reduce PCBs in harbor sediments to specific concentrations using the Pit Cleanup Unit (PCU). If data from Test 2, 3, and 4 are displayed side-by-side such that similar concentrations coincide, then a PCB reduction can be plotted. Data are displayed in table C.1 side-by-side so that similar concentrations overlap.

Table - C1
Pass-by-Pass PCB Concentrations

TEST 4	TEST 3	TEST 2
2,575	-	
1,000		
990		
670		
325	288	350
240	47	77
200	72	52
-	82	20
	-	66
		59
		41
		36
		29
	-	8
-		40

Based on the presentation of the data in Table C.1, it can be construed that harbor sediments containing 2,500 ppm of PCB could be reduced to 100 ppm after 6 passes through the PCU. A level less than 10 ppm may be achievable after 13 passes.

EXTRACTION EFFICIENCY

For each test, the first pass results in efficiencies greater than 60 percent. However, at later passes efficiencies range from negative values to 72 percent. This wide range is the result of cross-contamination of solids retained in the treated sediment subsystem.

Data show that the system irregularly retained and discharged treated sediments. For some passes, as much as 50 percent of the feed was retained in the system. That feed was treated sediment that clung to internal piping and tank surfaces. If discharged with a later pass, the combined discharge could have a higher concentration than feed for the later pass. For example, assume an extraction efficiency of 60 percent, a feed concentration of 350 ppm, and a carry-over of solids from the first pass to the second pass of 25 percent. Then, the treated sediment would contain 77 ppm, instead of 56 ppm if no cross contamination occurred.

Cross contamination did affect the interpretation of each test, but it does not invalidate the fact that treated sediment concentrations as low as 8 ppm were produced. Furthermore, the decontamination procedure showed that PCB which accumulated in system hardware was contained in the extract subsystem, not the treated sediment subsystem.

OPERATIONAL ISSUES

System operating criteria were set during the shakedown portion of the demonstration.

Extractor pressure was controlled at the unit's main compressor and

at the organics discharge from the extraction segment of the unit. Solvent flow rate and the solvent to feed ratio are set after laboratory bench-scale tests were run on various mixtures of solvent and feed.

The feed temperature represents the temperature of the material pumped into the feed unit. Feed in the extractor was maintained above 60°F to avoid the possibility of hydrate formation, which could have interfered with the extraction process. If the feed is above 120°F, it must be cooled to prevent vaporization of the solvent.

The feed flowrate represents the rate at which material is pumped from the feed kettle into the unit. Operational flow rates above the listed maximum can force segments of the system, such as decanters and control valves, beyond their effective hydraulic capacity.

The viscosity and solids content must be such that the feed material is pumpable. Feeds with a viscosity above the listed range were slurried with water to yield a pumpable viscosity. In order to prevent damage to the process equipment, the pilot-scale unit has a maximum limit for solids size.

OPERATIONAL MEASUREMENTS

Process controls, wastestream masses, and utilities were measured at various intervals during each test. Listed below are critical operational parameters and measurement frequencies:

- Feed temperature, viscosity, and pH—measured at each pass
- Feed sediment and treated sediment mass—measured at each pass
- Feed flow rate—measured every 10 minutes
- Extractor pressure and temperature—measured every 10 minutes
- Solvent flowrate—measured every 10 minutes
- Extracted organics mass—measured each test

OPERATIONAL RESULTS

The unit generally operated within the specifications with only several exceptions. Criteria were met for feed flowrates, solids content, maximum possible size, viscosity, and pH as well as extractor pressure. The solvent flow rate and solvent to feed mass ratios fluctuated above and below criteria throughout the tests but did not have an observable effect on pass-by-pass extraction efficiency. Temperature of the feed sediments fell below the minimum temperature criterion during passes 6, 7, 8, 9, and 10 of Test 2.

Commercial-scale designs for application of the technology should ensure that operating specifications are maintained. Feed materials are likely to be well below 60F throughout winter months and this could affect system performance. Therefore, heat must be added to sediments fed to a commercial-scale unit (or the unit could be located in an enclosed structure). Coarse solids removal will be required to maintain feed sediment particle sizes below one-eighth inch. Wide fluctuations in the feed to solvent ratio should be minimized. Extraction efficiency is directly related to the amount of solvent available for solubilizing organics contained in the feed.

HEALTH AND SAFETY ISSUES

The Health and Safety Plan established procedures and policies to protect workers and the public from potential hazards during the demonstration. Implementation of these procedures and health and safety monitoring showed that OSHA level B protection is necessary for personnel that handle system input and output, although only OSHA level C protection is necessary for unit operators.

Combustible gas meters indicated that levels at approximately 20 percent of the lower explosive limit for propane were encountered while samples were taken. Background air sampling and personnel monitoring results indicate that organic vapors and PCB levels were present at levels below the detection limit for the analytical methods. Site spoil samples taken before and after the demonstration indicate that demonstration activities did not result in increased PCB levels in the staging area soils.

Here is the CF Systems unit operating cycle for extracting and separating organics from liquid or solid waste.

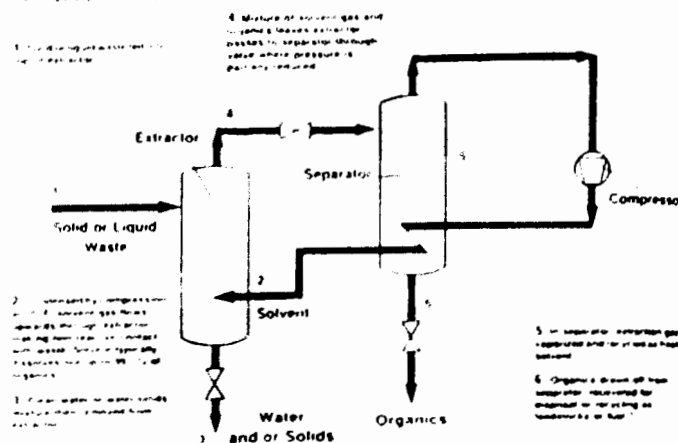


Figure 1
Simplified Flow Chart

DISCUSSION AND CONCLUSIONS

In the design of this treatability demonstration, and in many other cases, the demonstration plan is fraught by the reality of the field implementation. A perfectly good premise, even backed by previous field data, can go awry, and this was the case in this demonstration. The premise was that by recycling the material through the unit a number of times it would stimulate a full-scale unit. Even though there was a recognized deficiency in this method, it was felt that substantial data could be obtained on extraction rates and efficiencies. But the apparent cross-examination and retention of solids and PCB's in the equipment flawed the basic premise. There was a lack of consistency in the data as reflected in Table C.1, and there was an actual increase in PCB's in the process from one pass to another in some of the runs. In fact, if you review the last two passes of test 2 (the 350 ppm of PCB in the original feed with 10 passes), there is an increase from 8 ppm to 40 ppm of PCB's in the last pass. This last data point was in contrast to the general downward trend of the other passes, but this outlier data point was used for final determinant data point for this treatability test. If the 9 passes were used in the determination of the extraction rate, the total test extraction efficiency would have been 97% rather than the 89% with the use of pass 10.

Besides the possible issue of cross contamination, the precision and accuracy of the sampling procedures and the analytical methods for PCB's at the low ppm range, cause problems in the interpretation of the data. Even within limits set by QA/QC there is a wide variant in the 95% confidence range, thus making the data difficult to interpret at these low levels.

PCB Analytical Method 8080 precision criteria established for this project were plus or minus 20 percent and accuracy criteria were plus or minus 50 percent. Despite the occurrence of the cross contamination and its effect on each test, this does not invalidate the fact that treated sediment concentrations were as low as 8 ppm. Furthermore, the decontamination procedure (using toluene rinse) showed that the PCB's which accumulated in the system hardware were contained in the extract subsystem, not the treated sediment subsystem.

In contrast, the retention of solids in the pilot unit was a concern on the operating ability of the full-scale unit. The developer has indicated that the design of the full-scale unit will compensate for solid retention issue. This claim will be validated by the review of data from a full-scale unit (200 barrels/day) in December 1989. This evaluation should answer many of the questions associated with the on-line capacity of the full-scale unit.

A Field Evaluation of the UV/Oxidation Technology To Treat Contaminated Groundwater

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ABSTRACT

This paper presents the field evaluation results of the ultraviolet radiation (UV)/oxidation technology developed by Ultrox International, Santa Ana, California. The field evaluation of the technology was performed at the Lorentz Barrel and Drum (LB&D) site in San Jose, California, under the Superfund Innovative Technology Evaluation (SITE) program from Feb. 27 through Mar. 10, 1989.

The UV/oxidation technology uses UV radiation, ozone and hydrogen peroxide to oxidize organic contaminants present in water. At the LB&D site, this technology was evaluated in treating groundwater contaminated with volatile organic compounds (VOCs). The Ultrox system achieved VOC removals greater than 90%, and the majority of VOCs were removed through chemical oxidation. However, for a few VOCs, such as 1,1,1-trichloromethane (1,1,1-TCA), and 1,1-dichloroethane (1,1-DCA) stripping also contributed toward removal. The treated groundwater met the applicable discharge standards (NPDES) for disposal into a local waterway at 95% confidence level. There were no harmful air emissions from the Ultrox system into the atmosphere.

INTRODUCTION

The EPA is finding better solutions to hazardous waste remediation through its Superfund Innovative Technology Evaluation (SITE) program. The SITE program was created to demonstrate and evaluate technologies that may destroy or permanently change the composition of hazardous waste in the environment by significantly reducing the waste's toxicity, mobility or volume. The SITE program also generates reliable performance and cost data for these treatment technologies to be used in evaluating alternatives under the Superfund site remediation process.

In 1988, Ultrox International's proposal for its ultraviolet radiation (UV)/oxidation technology was selected by U.S. EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) under the SITE program. This technology was demonstrated at the Lorentz Barrel and Drum (LB&D) site in San Jose, California, through a cooperative effort between Ultrox International, ORD, OSWER and U.S. EPA Region IX.

UV/OXIDATION TECHNOLOGY: EQUIPMENT AND PROCESS DESCRIPTION

The Ultrox UV/oxidation treatment system uses UV radiation, ozone and hydrogen peroxide to oxidize organics in water. The major components of the Ultrox system are the UV/oxidation reactor module, air compressor/ozone generator module, hydrogen peroxide feed system and catalytic ozone decomposition (Decompozon) unit. An isometric view of the Ultrox system is shown in Figure 1.

The UV/oxidation reactor used in the demonstration (Model PM-150)

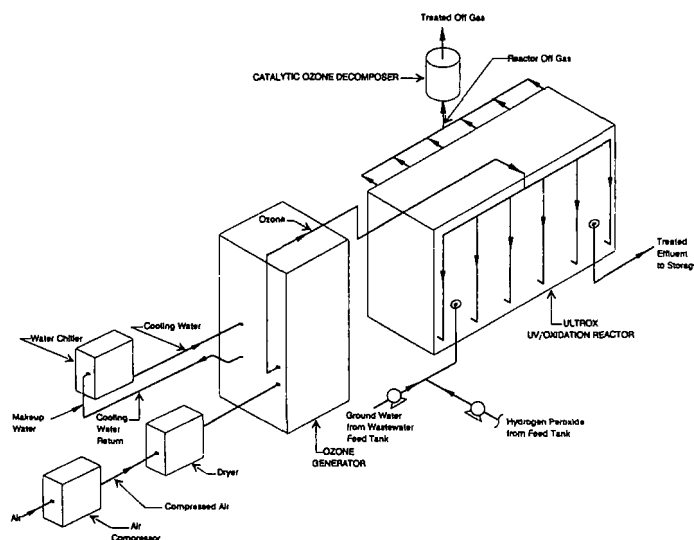


Figure 1
Isometric View of Ultrox System

has a volume of 150 gal and is 3 ft long by 1.5 ft wide by 5.5 ft high. The reactor is divided by five vertical baffles into six chambers and contains 24 UV lamps (65 w each) in quartz sheaths. The UV lamps are installed vertically and are evenly distributed throughout the reactor (four lamps per chamber). Each chamber also has one stainless steel sparger that extends along the width of the reactor. These spargers uniformly diffuse ozone gas from the base of the reactor into the water. Hydrogen peroxide is introduced in the influent line to the reactor from a storage tank. An in-line static mixer is used to disperse the hydrogen peroxide into the contaminated water in the influent feed line.

The Decompozon unit (Model 3014 FF) uses a nickel-based proprietary catalyst to decompose reactor off-gas ozone to oxygen. The Decompozon unit can accommodate flows of up to 10 scfm and can reduce ozone concentrations in ranges of 1 to 20,000 ppm (by weight) to less than 0.1 ppm.

During the Ultrox system operation, contaminated water first comes in contact with hydrogen peroxide as it flows through the influent line to the reactor. The water then comes in contact with the UV radiation and ozone as it flows through the reactor at a specified rate to achieve the desired hydraulic retention time. As the ozone gas in the reactor is transferred to the contaminated water, hydroxyl radicals (OH^\bullet) are produced. The hydroxyl radical formation from ozone is catalyzed by UV radiation and hydrogen peroxide. The hydroxyl radicals, in general,

are known to react with organics more rapidly than the oxidants ozone, hydrogen peroxide and UV radiation. They are also much less selective in oxidation reactions than the three oxidants. Ozone that is not transferred to the contaminated water will be present in the reactor off-gas. This ozone is subsequently destroyed by the Decompozon unit before being vented to the atmosphere. The treated water flows from the reactor for appropriate disposal.

LB&D SITE HISTORY

The LB&D site is in San Jose, Santa Clara County, California. This site was used for drum recycling operations from about 1947 to 1987. The drums contained residual aqueous wastes, organic solvents, acids, metal oxides and oils. A preliminary site assessment report for the LB&D site showed that the groundwater and soil were contaminated with organics and metals¹. In 1987, the LB&D facility ceased operation due to a restraining order issued by the California Department of Health Services. U.S. EPA Region IX assumed the responsibility for site remediation.

The shallow groundwater at the LB&D site was selected as the waste stream for evaluating the UV/oxidation technology. Groundwater samples collected in December, 1988, indicated that several volatile organic compounds (VOCs) were present in the shallow aquifer. VOCs detected at high levels included trichloroethylene (280 to 920 $\mu\text{L/L}$), vinyl chloride (51 to 146 $\mu\text{L/L}$) and 1,2-trans-dichloroethylene (42 to 68 $\mu\text{L/L}$). The pH and alkalinity of the groundwater were approximately 7.2 and 600 mg/L as CaCO_3 , respectively. These measurements indicated that bicarbonate ion (HCO_3^-), which acts as an oxidant scavenger, was present at high levels. Other oxidant scavengers such as bromide, cyanide and sulfide were not detected.

TECHNOLOGY DEMONSTRATION

The objectives of the technology demonstration were to: (1) evaluate the ability of the Ultrox system to treat VOCs present in the groundwater at the LB&D site at different operating conditions; (2) determine the extent of VOC stripping, if any, from the bubbling of ozone gas; (3) evaluate the efficiency of the Decompozon unit to decompose reactor off-gas ozone; (4) determine the operating conditions needed for the effluent to meet applicable discharge standards (NPDES) for disposal into a nearby waterway; and (5) develop the information required to estimate operating costs for the treatment system, such as electricity consumption and oxidant doses.

Testing Approach

Eleven test runs were performed to evaluate the Ultrox system under various operating conditions. After these runs, two additional runs were performed to determine if the system's performance was reproducible. The operating conditions for the runs are summarized in Table 1. All 13 runs were performed over a period of 2 wk.

The study was designed to evaluate the Ultrox system by adjusting the levels of five operating parameters: (1) influent pH, (2) retention time, (3) ozone dose, (4) hydrogen peroxide dose and (5) UV radiation intensity. The initial operating conditions (Run 1), given in Table 1, were based on the treatability study conducted by Ultrox on LB&D site groundwater.

During the demonstration, a preliminary estimate of the Ultrox system's performance in each run was obtained based on the effluent concentrations of three indicator VOCs. The VOCs selected for this purpose were trichloroethylene (TCE, a major volatile contaminant at the site), 1,1-dichloroethane (1,1-DCA) and 1,1,1-trichloromethane (1,1,1-TCA). 1,1-DCA and 1,1,1-TCA were selected because Ultrox's experience indicated that these VOCs are relatively difficult to oxidize.

In the first three runs, the influent pH was adjusted by adding sulfuric acid to evaluate the system's performance and to determine the "preferred" influent pH ["preferred" operating conditions are those conditions in which: (1) effluent concentrations of indicator VOCs are below NPDES limits and (2) the relative operating costs are the lowest]. Once the "preferred" influent pH was determined, it remained at that level for the remaining runs. The Ultrox system performance was then studied by varying other parameters, one at a time, as shown in Table 1,

Table 1
Operating Parameters Matrix for the Ultrox System Demonstration

Run No.	Retention Time	Ozone Dose	H_2O_2 Dose	UV Lamps	Influent pH
1	X ^a	Y ^a	Z ^a	All ON	Unadjusted
2	X	Y	Z	All ON	(Unadjusted - 1)
3	X	Y	Z	All ON	(Unadjusted - 2)
4	1.5X	Y	Z	All ON	Preferred ^c
5	0.5X	Y	Z	All ON	Preferred
6	Preferred	1.5Y	Z	All ON	Preferred
7	Preferred	0.5Y	Z	All ON	Preferred
8	Preferred	Preferred	1.5Z	All ON	Preferred
9	Preferred	Preferred	0.5Z	All ON	Preferred
10	Preferred	Preferred	Preferred	Only ON in the first three chambers	Preferred
11	Preferred	Preferred	Preferred	Only ON in the last three chambers	Preferred
12 ^b	Preferred	Preferred	Preferred	Preferred	Preferred
13 ^b	Preferred	Preferred	Preferred	Preferred	Preferred

Notes:

- ^a X = 40 minutes.
- ^a Y = 75 mg/L.
- ^a Z = 25 mg/L.
- (X, Y, and Z values were determined by Ultrox International to be the optimum conditions for treating ground water in the treatability study at the LB&D site.)
- ^c "Preferred" operating conditions are those conditions in which (1) the concentrations of effluent indicator VOCs are below their respective NPDES limits and (2) the relative operating costs are the lowest.
- ^b Verification runs performed to check the reproducibility of the Ultrox system's performance at the "preferred" operating conditions.

to determine the "preferred" values for those parameters. The criteria were the same as those used in determining the "preferred" value for the influent pH. After the "preferred" values were determined for all five operating parameters, two runs (12 and 13) were performed to verify the reproducibility of the Ultrox system's performance at the "preferred" operating conditions. By duplicating the "preferred" operating conditions determined during the previous 11 runs, the two verification runs served to ensure that the results could be based on repeated observations, with comparable findings.

Sampling and Analytical Procedures

Air and water samples were collected from the Ultrox system at the locations shown in Figure 2. For the critical parameters in this study (VOCs in water), six replicate samples were collected. Duplicate samples were collected for other parameters listed in Table 2. Sampling at the influent port began approximately 15 min after each run was started. At other locations in the reactor, sampling began after three retention times to allow the system to reach steady-state. All the air and water samples for off-site laboratory analysis were preserved as required before being shipped to the laboratory.

The analytical methods followed in this study are listed in Table 2. To obtain reliable data, strict QA/QC procedures were followed. Details on all aspects of the QA/QC procedures are presented in the Demonstration Plan and the Technology Evaluation Report^{2,3}.

RESULTS AND DISCUSSION

This section summarizes the results of the Ultrox system demonstration and also presents an evaluation of the UV/oxidation technology's effectiveness in removing VOCs from the groundwater at the LB&D site.

Summary of Results for VOCs

The purpose of the test runs was to evaluate the effectiveness of the Ultrox system in removing 44 VOCs present in the groundwater at the LB&D site. The removal efficiencies and concentration profiles of all VOCs are not presented in this paper. Instead, a summary of the results is given.

The mean concentration profiles and the discharge standards (NPDES) for the three indicator contaminants (TCE 1,1-DCA and 1,1,1-TCA) in

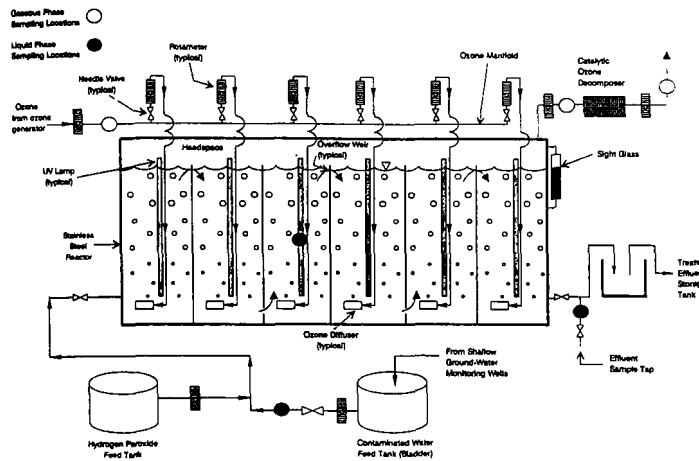


Figure 2
Ultrox System Sampling Locations

each run for each sampling location are plotted in Figures 3, 4 and 5. The VOC concentrations progressively decreased from the influent to the mid-point and from the mid-point to the effluent except for Run 3. In Run 3, the concentration of 1,1-DCA at mid-point was higher than that in the influent. It is believed that either the mid-point concentration or the influent concentration is just an outlier. This progressive decrease in containment concentration is due to the ozone and the UV radiation provided in the last three chambers (after the mid-point) and the increase in the retention time from the mid-point to the effluent port. Additionally, the effluent and mid-point VOC concentrations are comparatively high in Run 7, which appears to be due to the decreased ozone dose during that particular run.

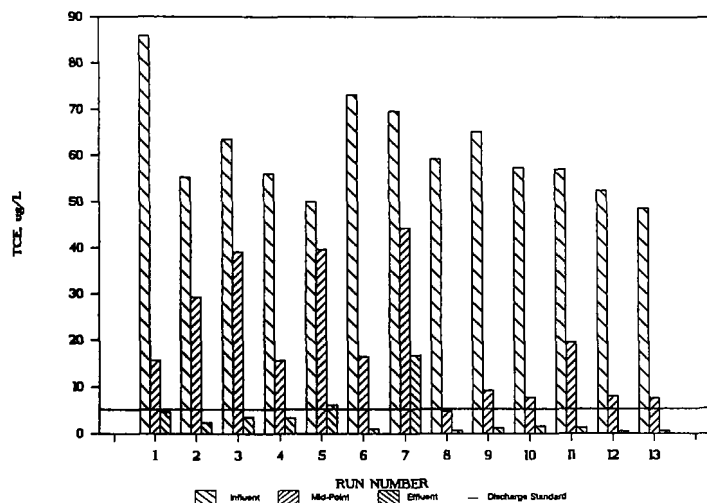


Figure 3
TCE Concentrations in Different Runs

The average effluent concentrations (determined during the demonstration by analyzing only two of the six replicates) for each indicator VOC with the discharge standard (NPDES) showed that the effluent met the discharge limits in Runs 8 and 9. Since a lower hydrogen peroxide dose was used in Run 9, compared to Run 8, Run 9 was chosen as the "preferred" operating run. However, based on a complete analysis of the six replicates performed after the demonstration, the mean concentration of 1,1-DCA was found to be slightly higher than 5 μ /L, the discharge standard for the VOC. Since Run 9 had the "preferred" operating conditions during the demonstration, the verification runs (12 and 13) were performed at those conditions.

A comparison of 95% upper confidence limit (UCL) values for the effluent VOCs in Runs 9, 12 and 13 with the discharge standards (NPDES) is presented in Table 3. The UCL values were calculated using

Table 2
Analytical Methods

Analyte	Matrix	Method Type	Method Reference
Alkalinity	Liquid	Field	MCAWW 310.1 ^v
Arsenic	Liquid	Lab	SW-846 7060 ^v
BNA (Semivolatiles)	Liquid	Lab	SW-846 8270 ^v
Chromium (Cr ⁶⁺)	Liquid	Lab	SW-846 7195 ^v
Chloride	Liquid	Lab	SM 429 ^w
Chromium	Liquid	Lab	SW-846 7191 ^v
Conductivity	Liquid	Field	Manual ⁿ
Hydrogen Peroxide	Liquid	Field	Boltz et al. (1979) ^w
Metals (Barium, Cobalt, Iron, Manganese, Nickel, Zinc, Potassium, Calcium, Magnesium, and Sodium)	Liquid	Lab	SW-846 6010 ^v
Ozone	Liquid	Field	Bader and Hoigne (1982) ^w
Ozone	Air	Field	40 CFR Part 50 ^x
pH	Liquid	Field	Manual ^x
Pesticides/PCBs	Liquid	Lab	SW-846 8080 ^v
Silica	Liquid	Lab	SW-846 6010 ^v
Sulfate	Liquid	Lab	SM 429 ^w
Temperature	Liquid	Field	Manual ⁿ
Total Organic Carbon	Liquid	Lab	SM 505A ^w
Turbidity	Liquid	Field	Manual ⁿ
Volatile Organics	Liquid	Lab	SW-846 8010 and 8020 ^v
Volatile Organics	Liquid	Lab	SW-846 8240 ^v
Volatile Organics:			
Vinyl Chloride	Air	Lab	NIOSH 1007 ^x
1,1-Dichloroethene	Air	Lab	NIOSH 1015 ^x
1,1-Dichloroethane	Air	Lab	NIOSH 1003 ^x
1,2-Dichloroethene	Air	Lab	NIOSH 1003 ^x
1,1,1-Trichloroethane	Air	Lab	NIOSH 1003 ^x
Trichloroethene	Air	Lab	NIOSH 1022 ^x
Benzene	Air	Lab	NIOSH 1500 ^x
1,1,2,2-Tetrachloroethane	Air	Lab	NIOSH 1019 ^x
Acetone	Air	Lab	NIOSH 1300 ^x

the one-tailed Student's t-test. Table 3 shows that the effluent met the discharge standards for all regulated VOCs at the 95% confidence level in Runs 12 and 13. In Run 9, the mean concentrations for 1,1-DCA and 1,2-DCA exceeded the discharge standards. Although 1,1-DCA and 1,2-DCA were present at levels slightly greater than the discharge standards, the difference in performance among the three runs is negligible.

The mean concentration profiles for total VOCs are given in Figure 6. A comparison of the VOC concentrations presented in Figure 6 with those in Figures 3, 4 and 5 indicates that the concentration profiles for total VOCs are similar to those for the indicator VOCs. For example, the peaks present at the mid-point and effluent for indicator VOCs are also present in the total VOC concentration profiles.

The percent removals for the indicator VOCs and total VOCs are presented in Figure 7. The figure shows that the removal efficiencies

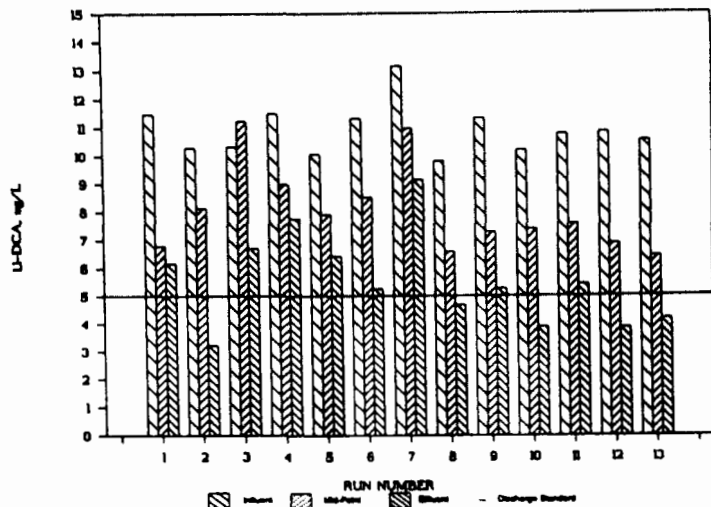


Figure 4
1,1-DCA Concentrations in Different Runs

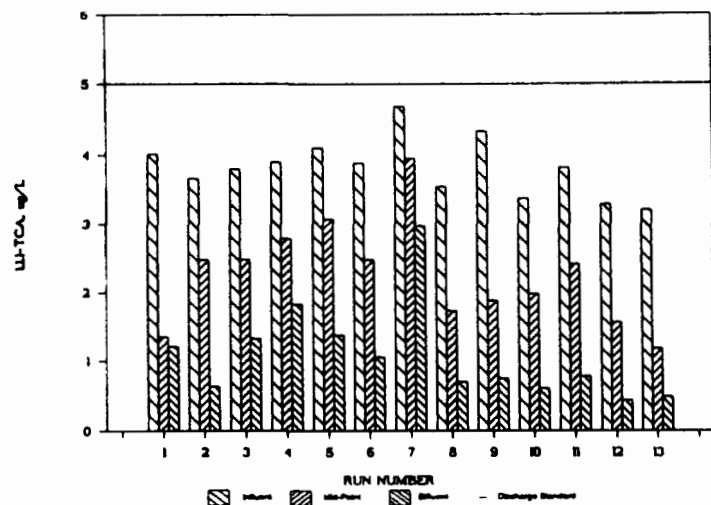


Figure 5
1,1,1-TCA Concentrations in Different Runs

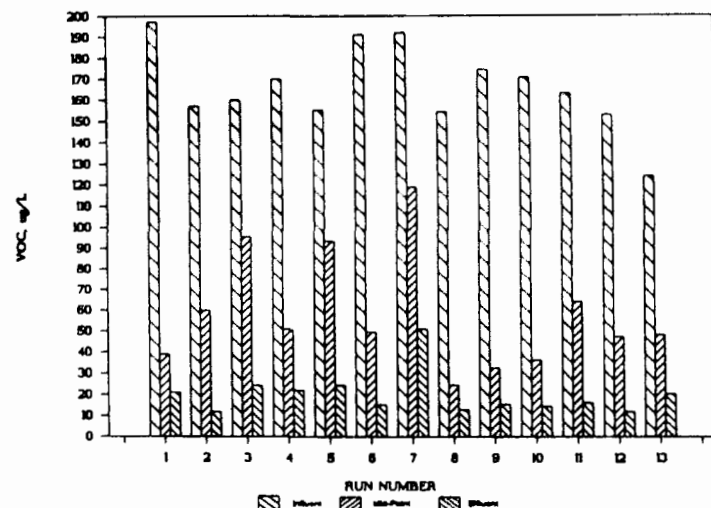


Figure 6
Total VOC Concentrations in Different Runs

Table 3
Comparison of Effluent VOC Concentrations in Runs 9, 12 and 13

	Mean, $\mu\text{g/L}$	95% UCL, $\mu\text{g/L}$	RT, $\mu\text{g/L}$	Conclusion
Run number: 9				
1,1,1-TCA	0.75	1.0	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	5.3	5.5	5	N
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	1.3	1.4	1	N
1,2-DCPA	3.3	3.4	5	OK
Benzene	0.023	0.026	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	1.1	1.2	5	OK
PCE	0.24	0.63	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	1.2	1.3	5	OK
Vinyl Chloride	0.11	0.11	2	OK
Run number: 12				
1,1,1-TCA	0.43	0.48	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	3.8	4.2	5	OK
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	0.92	1.0	1	OK
1,2-DCPA	2.6	2.9	5	OK
Benzene	0.023	0.026	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	0.74	0.82	5	OK
PCE	0.19	0.38	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	0.55	0.65	5	OK
Vinyl Chloride	0.11	0.11	2	OK
Run number: 13				
1,1,1-TCA	0.48	0.54	5	OK
1,1,2,2-PCA	0.045	0.045	5	OK
1,1-DCA	4.2	4.5	5	OK
1,1-DCE	0.000	0.000	5	OK
1,2-DCA	1.0	1.0	1	OK
1,2-DCPA	2.9	3.1	5	OK
Benzene	0.45	0.52	5	OK
Chloroethane	0.000	0.000	5	OK
Chloroform	0.81	0.87	5	OK
PCE	0.091	0.17	5	OK
T-1,2-DCE	0.000	0.000	5	OK
TCE	0.63	0.73	5	OK
Vinyl Chloride	0.12	0.12	2	OK

Notes:

95% UCL: Upper 95% Confidence Limit
 RT: Regulatory Threshold
 OK: Effluent met the regulatory threshold
 N: Effluent did not meet the regulatory threshold

Abbreviations:
 1,1,1-TCA: 1,1,1-Trichloroethane; 1,1,2,2-PCA: 1,1,2,2-Tetrachloroethane; 1,1-DCA: 1,1-Dichloroethane; 1,1-DCE: 1,1-Dichloroethylene; 1,2-DCA: 1,2-Dichloroethane; 1,2-DCPA: 1,2-Dichloropropane; PCE: Tetrachloroethylene; T-1,2-DCE: Trans-1,2-Dichloroethylene; TCE: Trichloroethylene.

for TCE were higher than those for 1,1-DCA and 1,1,1-TCA which is consistent with the rationale used in selecting the indicator VOCs. The percent removals for total VOCs and the indicator VOCs decreased considerably in Run 7, which appears to be due to the decreased ozone dose.

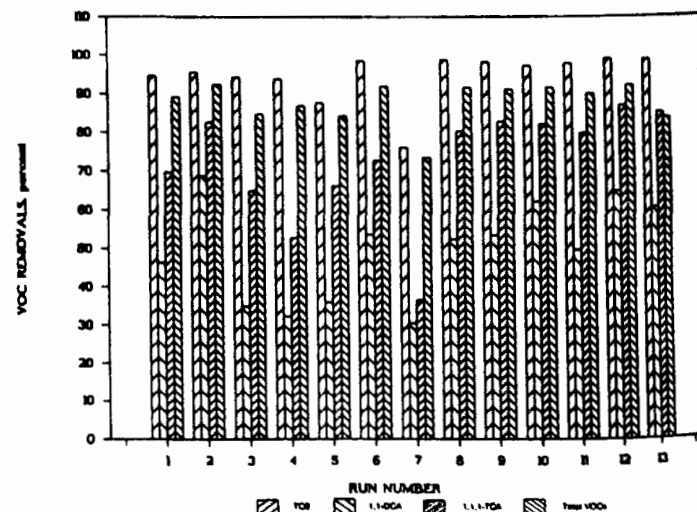


Figure 7
VOC Removals in Different Runs

Since ozone gas is bubbled through the groundwater treated by the Ultrox system, the VOC removal could be attributed to stripping in addition to oxidation. To determine the extent of stripping within the treatment system, VOC samples were collected from the reactor off-gas. Twenty-five samples were collected during the demonstration. Although 1,1-DCE, 1,2-DCE, benzene, 1,1,2,2-tetrachloroethane and acetone were present in two samples at concentrations close to the detection limits, TCE, vinyl chloride, 1,1,1-TCA and 1,1-DCA were detected more frequently. To determine the extent of stripping, the emission rates in the reactor off-gas for these latter four VOCs were compared to the VOC removal rates (estimated by difference between the VOC input rates at the influent and output rates at the effluent ports of the Ultrox system). The results are summarized in Table 4.

Table 4
Extent of VOC Stripping in the Ultrox System

Run No.	Air flow rate Water flow rate	Percent Stripping Contribution For			
		1,1-DCA 0.0043 ^b	TCE 0.0091 ^b	1,1,1-TCA 0.014 ^b	VC ^a 0.082 ^b
1	2.1	7.4	2.0	43	0.013
2	2.3	9.1	3.4	34	0.95
3	2.1	9.9	2.7	31	0.013
4	2.0	7.4	3.0	29	0.01
5	2.1	17	3.5	29	1.7
6	4.5	16	1.2	65	0.072
7	1.0	4.9	1.2	12	3.1
8	4.5	23	7.5	85	1.2
9	4.5	16	6.6	58	0.04
10	4.3	27	9.4	73	1.1
11	4.6	44	24	>99	13
12	4.4	34	7.0	76	8.9
13	4.3	37	26	75	1.8

Notes:

a VC: Vinyl Chloride

b Henry's law constant of the VOC, atm-m³/mol.

Since the extent of stripping for any particular VOC is expected to be proportional to the ratio of the air flow rate to the water flow rate, this ratio is presented in the table. The ratio for Runs 1 to 5 is approximately 2; for Run 6 and Runs 8 to 13, it is approximately 4.5; and for Run 7, it is 1. If stripping contributed to the total removal of the four VOCs, the extent of stripping should be the least in Run 7 and the most in Runs 6 and 8 to 13. The data presented in the table follow this trend for three of the four VOCs (except for the vinyl chloride in Runs 6, 7 and 9). However, a quantitative correlation of the extent of stripping cannot be made because the operating conditions were different in each run. For example, at a given air to water flow ratio, when oxidant doses are varied, the extent of oxidation also varies. Therefore, the extent of stripping will be indirectly affected.

Table 4 also presents the Henry's law constants for the four VOCs¹¹. By comparing these constants for the VOCs, their volatility is expected to increase from left to right:

1,1-DCA \rightarrow TCE \rightarrow 1,1,1-TCA \rightarrow vinyl chloride

However, a significant removal fraction for 1,1,1-TCA and 1,1-DCA were observed to be due to stripping. Conversely, the extent of stripping was low for vinyl chloride and TCE. This difference in stripping rates is because it is easier to oxidize vinyl chloride and TCE than 1,1-DCA and 1,1,1-TCA because there are double bonds between the carbon atoms

in TCE and vinyl chloride. In other words, in the UV/oxidation process, stripping is a significant removal pathway for compounds that are difficult to oxidize.

Performance of the Decompozon Unit

The ozone concentrations in the influent to and the effluent from the Decompozon unit were analyzed in each run. These concentrations are presented on a semi-log plot in Figure 8. The effluent ozone concentrations were low (less than 0.1 ppm) for Runs 1 to 8, approximately 1 ppm in Runs 9 and 10 and greater than 10 ppm in Runs 11, 12 and 13. The high ozone levels (greater than 1 ppm) in the effluent are attributed to the malfunctioning heater in the Decompozon unit. The temperature in the Decompozon unit should have been 140°F for the unit to properly function, whereas the temperature for Runs 11 to 13 was only approximately 80°F. The ozone destruction efficiencies greater than 99.99% were achieved in Runs 1 to 10.

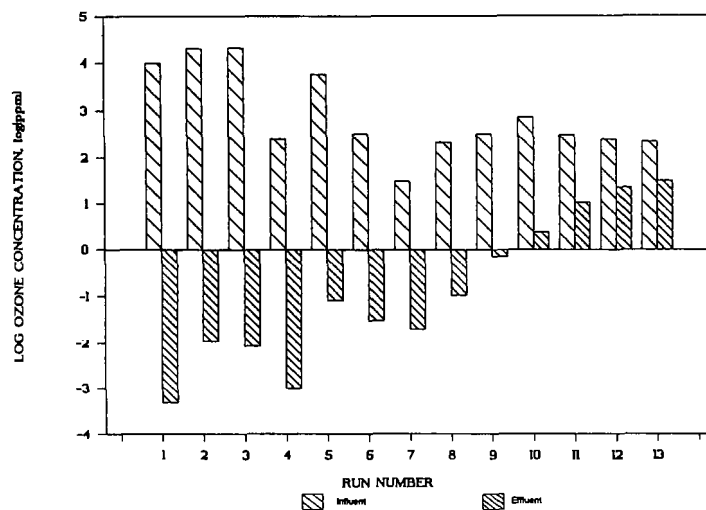


Figure 8
Ozone Concentration in Different Runs

Although the primary function of the Decompozon unit is to remove ozone, the data presented in Table 5 indicate that significant VOC removal occurred when the unit functioned as designed (Runs 1 to 8).

Table 5
VOC Removal in the Decompozon Unit

Run No.	TCE, ppm		1,1-DCA, ppm		1,1,1-TCA, ppm		Vinyl chloride, ppm	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	0.15	<0.15	0.1	<0.1	0.15	<0.1	0.002	<0.002
2	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.070	<0.002
3	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	<0.002
4	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	<0.002
5	0.15	<0.15	0.2	<0.1	0.1	<0.1	0.150	<0.002
6	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.003	<0.002
7	0.15	<0.15	0.15	<0.1	0.1	<0.1	0.517	<0.002
8	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.041	<0.002
9	0.15	<0.15	0.1	<0.1	0.1	<0.1	0.002	0.061
10	0.225	<0.15	0.15	<0.1	0.1	<0.1	0.064	0.078
11	0.55	0.325	0.25	0.2	0.2	<0.1	0.570	0.189
12	0.15	<0.15	0.2	<0.1	0.1	<0.1	0.271	0.006
13	0.45	<0.15	0.22	<0.1	0.1	<0.1	0.420	0.004

Summary of Results for Noncritical Parameters

In addition to the critical parameters (VOCs), many non-critical parameters also were measured. The non-critical parameters for organics included changes in semi-volatiles, PCBs/pesticides and total organic carbon (TOC); the non-critical parameters for inorganics included changes in pH, conductivity and alkalinity. Temperature, turbidity, residual oxidants and electricity consumption also were measured.

No semi-volatiles or PCBs/pesticides were detected in the influent

or effluent. TOC removal was achieved only at trace levels indicating that complete oxidation of organics to carbon dioxide and water did not occur. However, since no new VOCs were found by GC/MS analysis and GC analysis of the effluent, the oxidation products were not VOCs.

Metals such as iron and manganese were present at low concentrations in the influent and no significant metal removal occurred. No changes in alkalinity and conductivity were observed after the treatment. However, the pH increased by 0.5 to 0.8 units after the treatment. The increase in pH is probably due to the reaction between hydroxyl radicals and bicarbonate ion (the predominant form of alkalinity at the groundwater pH, which is 7.2) in which hydroxyl ions are produced⁹.

Turbidity increased by 1 to 4 units after the treatment. This increase may be due to the insignificant amount of metal removal by oxidation and precipitation. The temperature increased by approximately 4 to 5 °F after the treatment and was due mainly to the heat from UV lamps. The efficiency of ozone gas transfer to the groundwater was over 95%, with 5% remaining in the reactor off-gas. After the reaction, the residual ozone and hydrogen peroxide concentrations in the effluent usually were less than 0.1 ppm. The average electrical energy consumption to operate the Ultrox system was approximately 11 kwh/h of operation.

CONCLUSIONS

The groundwater treated by the Ultrox system met the discharge standards for disposal into a nearby waterway at the 95% confidence level at a hydraulic retention time of 40 minutes, an influent pH of 7.2 (unadjusted), an ozone dose of 110 mg/L, a hydrogen peroxide dose of 13 mg/L and with all 24 UV lamps operating.

There were no VOCs detected in the air emissions from the treatment unit into the atmosphere.

The ozone destruction unit (Decompozon unit) destroyed reactor off-gas ozone to levels less than 0.1 ppm (OSHA Standards) with destruction efficiencies greater than 99.99%.

The Ultrox system achieved removal efficiencies as high as 90% for total VOCs present in the groundwater at the LB&D site. The removal efficiencies for TCE were greater than 99%. However, the maximum removal efficiencies for 1,1-DCA and 1,1,1-TCA were approximately 65% and 85%, respectively.

The removals of 1,1-DCA and 1,1,1-TCA are due to both chemical oxidation and stripping. Specifically, 12 to 75% of the total removals for 1,1,1-TCA and 5 to 44% of the total removals for 1,1-DCA were due to stripping. However, stripping for TCE and vinyl chloride was observed to be less than 10%. For other VOCs, such as 1,1-dichloroethene, benzene, acetone and 1,1,2,2-tetrachloroethane, stripping was found to be negligible. VOCs present in the gas phase within the reactor at levels

of approximately 0.1 to 0.5 ppm were removed to below detection levels in the Decompozon unit.

Based on the GC and GC/MS analyses performed for VOCs, semi-volatile organics and PCBs/pesticides, no new compounds were discovered in the treated water. The organics analyzed by GC methods represent less than 2% of the TOC present in the water. Very low TOC removal occurred, a result which implies that partial oxidation of organics took place in the system but not complete conversion to carbon dioxide and water.

The Ultrox system's average electrical energy consumption was approximately 11 kwh/hr of operation.

ACKNOWLEDGEMENT

The authors sincerely thank Dr. Gary Welshans, PRC Environmental Management, Inc. for managing the field demonstration and for reviewing this paper.

REFERENCES

1. CH2M Hill, *Preliminary Site Assessment Report for the Lorentz Barrel and Drum Site*, 1986.
2. PRC Environmental Management, Inc., and Engineering-Science, Inc., *Demonstration Plan for the Ultrox International UV/Oxidation Process*, prepared for U.S. EPA, Feb. 1989.
3. PRC Environmental Management, Inc., and Engineering-Science, Inc., *Technology Evaluation Report SITE Program Demonstration of the Ultrox International UV/Oxidation Technology*, in preparation for U.S. EPA.
4. *Methods for the Chemical Analysis of Water and Wastes*, EPA-600/4-79-020, U.S. EPA Environmental Monitoring and Support Laboratory, Cincinnati, OH, 1983.
5. *U.S. EPA Test Methods for Evaluating Solid Waste*, Volumes 1A-1C: Laboratory Manual, Physical/Chemical Methods; and Volume II: Field Manual, Physical/Chemical Methods, SW-846, Third Edition, Office of Solid Waste, U.S. EPA, Document Control No. 995-001-00000-1, 1986.
6. Boltz, D.F., and Howell, J.A., *Hydrogen Peroxide, Colorimetric Determination of Nonmetals*, John Wiley & Sons, New York, NY, 1979, 301-303.
7. APHA, AWWA, and WPCF, *Standard Methods for the Examination of Water and Wastewater*, 16th Ed., 1985.
8. Bader, A., and Hoigne, J., Determination of Ozone in Water by Indigo Method, *Ozone Sci. and Eng.*, 4, 169, 1982.
9. The National Primary and Secondary Ambient Air Quality Standards, 40 CFR Part 50, Appendix D—Measurement of Ozone in the Atmosphere.
10. NIOSH, *Manual of Analytical Methods*, Third Edition, U.S. Department of Health and Human Resources, DHHS (NIOSH) Publication No. 84-100, 1984.
11. Operating instructions provided with the instruments.
12. *U.S. EPA Superfund Public Health Evaluation Manual*, EPA 540/1-86/060, Office of Emergency and Remedial Response, Washington, DC, 1986.
13. Hoigne, J., and Bader, H., Ozonation of Water: Role of Hydroxyl Radicals as Oxidizing Intermediates, *Science*, 19, pp. 782-784, 1975.

Evaluation of the Soliditech SITE Solidification/Stabilization Technology

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ABSTRACT

The Soliditech technology demonstration was conducted at the Imperial Oil Company/Champion Chemicals Superfund Site in Monmouth County, New Jersey. The primary contaminants at this site include PCBs and lead. Oil and grease and other metals are considered secondary contaminants.

The Soliditech process consists of mixing the waste material with proprietary additives, pozzolanic materials and water in a batch mixer. Methods used to evaluate the effectiveness of the process include: (1) batch extraction and engineering test, (2) long-term extraction and leaching tests, (3) petrographic examination and (4) structural integrity observations.

Three different waste types were treated: contaminated soil, waste filter cake material and a filter cake-oily sludge mixture. Pure sand was substituted for waste in one solidification batch to provide samples to evaluate the chemical constituents of process reagents.

The analytical results did not indicate the presence of PCBs and volatile organic compounds (VOCs) in the TCLP extracts of treated wastes. Metals concentrations were reduced significantly in TCLP, EP Toxicity and BET extracts of treated compared to un-treated wastes. Low concentrations of phenols and cresols were detected in some post-treatment TCLP extracts. Negligible release of contaminants was observed from all extraction and leaching tests performed on solidified samples. The pH of treated waste was near 12. Unconfined compressive strength of treated wastes was high; permeability was very low. Weight loss of treated samples after repeated wet/dry and freeze/thaw cycles was very low.

INTRODUCTION

The U.S. EPA's Office of Research and Development has been carrying out the Agency's formal program to accelerate the development, demonstration and use of new or innovative technologies which can provide permanent cleanup solutions for hazardous waste sites.

The Soliditech, Inc.'s waste solidification/stabilization process was the seventh technology to be demonstrated within this Superfund Innovative Technology Evaluation (SITE) program.

In cooperation with U.S. EPA's Office of Solid Waste and Emergency Response (OSWER), the Imperial Oil/Champion Chemical Superfund site in New Jersey was selected as the location to demonstrate the Soliditech SITE technology. This site currently is partially occupied by a private company involved in blending and packaging oil products. Technical staff of the New Jersey Department of Environmental Protection (NJDEP) provided data describing the characteristics and extent of contamination at this site and assisted U.S. EPA in public relations aspects of the demonstration.

This technology demonstration was conducted in early December,

1988. A batch-mixer, a supply of portland cement, Urrichem reagent, other additives for their formulation and accessory equipment were provided by Soliditech, Inc. The U.S. EPA's support contractor provided a sampling team. The demonstration was completed over a five-day period, resulting in nearly 14 yd³ of solidified material and over 300 individual samples for analyses of the numerous parameters applied to evaluate this technology.

PCBs and lead were the primary contaminants of concern on the Imperial Oil/Champion Chemical site. These contaminants were determined in TCLP and EP Toxicity extracts of untreated and treated wastes to assess chemical stabilization by the Soliditech process.

PURPOSE

The primary goal of the SITE program is to evaluate the effectiveness of a technology by conducting a field-scale demonstration of each technology, collecting samples of treated waste materials and analyzing data from a variety of laboratory tests.

TEST METHODS

The Soliditech SITE technology evaluation was based on the results of laboratory tests on samples of waste material before and after treatment. Physical tests included particle size analysis, water content, unconfined compressive strength¹, bulk density of treated waste, permeability of treated waste and wet/dry and freeze/thaw tests on treated waste². Extraction tests included TCLP extraction, EP Toxicity, Batch Extraction Test, American Nuclear Society 16.1³ and Waste Interface Leaching Test⁴. U.S. EPA SW-846 methods were applied for pH, Eh, total dissolved solids, total organic carbon, oil and grease, VOCs, semi-volatile organic compounds, PCBs and metals⁵.

Methods used in the evaluation of the Soliditech process were described in the Demonstration Plan, which was written and peer-reviewed prior to initiation of field activities⁶. This Demonstration Plan also included an approved Quality Assurance Project Plan which described all planned sample acquisition and analytical methods.

APPROACH

Contaminated soil was excavated from a pit approximately 5 ft wide, 3 ft deep and 8 ft long in off-site Area One of this Superfund site. Filter cake waste was collected from the open face of a waste pile (Fig 1). Oily sludge was scooped from an abandoned storage tank with a bucket and stored in steel drums until the waste was processed. A filter cake/oily sludge mixture was prepared for processing by mixing equal parts of filter cake and oily sludge. All waste feedstocks were screened to prevent large objects such as rocks, roots, bricks or other debris from being incorporated into the treated waste. Although this debris would not have interfered with the Soliditech process, it was removed to prevent inclu-

sion within samples taken for analytical testing.



A - Proprietary additives
B - Portland Cement supply
D - Drums containing oily sludge
F - Forms for treated waste monoliths
M - Mixer
S - Sample preparation
U - Urrichem supply
W - Filter cake waste pile

Figure 1
Soliditech Technology Demonstration Operations

Waste materials were mixed in a ribbon-blender shown in Figure 1. Water was added to the waste within the mixer to provide the proper mixing consistency. Portland cement, other specific additives formulated by Soliditech staff and Urrichem were then added and mixed. The mixture was discharged from the mixer into 1-yd³ plywood forms (Fig. 1). Aliquots of the slurried mixtures were taken from the forms and poured into waxed cardboard and PVC cylindrical forms, of several different sizes, to provide samples for various physical and chemical analyses.

All materials were allowed to set for 28 days inside a heated warehouse. Cylindrical samples were transported to the storage area of an analytical laboratory. Nearly 14 yd³ of treated waste were contained within the plywood forms to form the treated waste monoliths (TWM). These monoliths were placed in a two-tiered stack and covered with a plastic sheet for subsequent long-term examination.

Figure 2 illustrates the approaches used to evaluate the effectiveness of the Soliditech process. The Quality Assurance Project Plan, within the project's Demonstration Plan⁶, specified the details of sample collection and preservation, analytical protocols, matrix and surrogate spike procedures, blanks, replicate analyses and statistical procedures to be applied to data evaluation. Triplicate samples were provided for all analytical determinations on the treated materials. The Demonstration Report⁷ presents the complete data resulting from this technology evaluation.

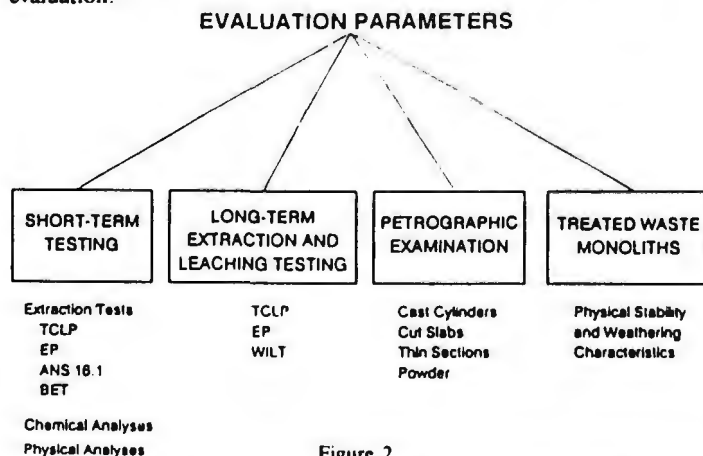


Figure 2

Evaluation Parameters Used to Evaluate the Soliditech Process

RESULTS

Table 1 shows the compositions of the waste treatment mixtures. The reagent mixture includes clean sand as a substitute for waste. The filter-cake/oily-sludge consists of filter-cake and oily sludge because Soliditech preferred not to treat the oily sludge in its original liquid form.

Table 1
Soliditech Treatment Formulation

	Reagent Mixture	Filter Cake/ Oily Sludge	Filter Cake	Off-Site Area No.
Waste Material (lb)	50	60	50	50
Type II Cement (lb)	31	51	16	39
Urrichem (lb)	0.0	0.0	0.0	0.0
Additives (lb)	1	1	0.0	0.0
Water	11	7	16	12
Total Weight (lbs)	1,420	9,700	19,100	15,700

Table 2 shows that, after treatment, the bulk density increased and water content decreased in all cases. These results are attributed to the effects of cement in the treatment process. In fact, bulk densities, permeabilities and UCS were directly related to the amount of type II cement added in the process (Table 1). The permeabilities of treated waste were very low with values below 1×10^{-8} cm/sec. The unconfined compressive strengths ranged from 390 to 860 psi.

Table 2
Physical Properties of Waste Materials

	Filter Cake		Filter Cake/Oily Sludge		Off-Site Area No.	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
Bulk Density (g/cm ³)	1.16	1.43	1.19	1.60	1.20	1.39
Loss on Ignition (g/kg)	560	610	700	560	560	560
Permeability (cm/sec)	NA	6.5×10^{-7}	NA	6.9×10^{-9}	NA	3.4×10^{-7}
Unconfined Compressive Strength (psi)	NA	390	NA	860	NA	860
Water Content (%)	20.7	21.0	650	16.7	22.5	12.6

NA Not Analyzed

Total chemical analyses, shown in Tables 3 through 5, for untreated and treated wastes indicate a variable effect from adding process reagents to untreated waste. PCBs varied from no observable change to over one-third less in the treated waste. Analyses of pure sand solidified with the Soliditech process showed that arsenic was present at 59 mg/kg. Chromium, copper, lead, nickel and zinc were noted to the extent of a few tens of mg/kg in this sand plus reagent mixture. A few mg/kg of phenols and cresols were detected in analyses of the treated wastes for semi-volatile organic compounds. Although the origin of these

Table 3
Chemical Analysis of Untreated and Treated Filter Cake Wastes and Their TCLP and EP Extracts

	Total Analysis		TCLP Extracts		EP Extracts	
	Untreated Waste (mg/kg)	Treated Waste	Untreated Waste (mg/L)	Treated Waste	Untreated Waste (mg/L)	Treated Waste
pH	3.4	11.8	4.6	10.0	3.8	10.0
VOCs	ND	ND	0.17	ND	NA	NA
SVOCs	ND	36	ND	1.2	NA	NA
PCBs	28	16	ND	ND	ND	ND
Oil and Grease	170,000	77,000	1.4	4.6	40.4	4.0
Arsenic	26.6	28	0.003	ND	0.01	0.00
Chromium	4.7	30	ND	0.06	ND	0.05
Copper	19	28	0.04	0.02	ND	0.04
Lead	2,200	600	4.3	0.002	0.20	0.00
Zinc	26	23	0.30	ND	0.03	40.00

Table 4
Chemical Analysis of Untreated Filter Cake/Oily Sludge Wastes and Their TCLP and EP Extracts

	Total Analysis		TCLP Extracts		EP Extracts	
	Untreated Waste (mg/kg)	Treated Waste	Untreated Waste (mg/l)	Treated Waste	Untreated Waste (mg/l)	Treated Waste
pH	3.6	12.0	4.8	11.6	4.8	11.8
VOCs	50	ND	1.3	ND	NA	NA
SVOCs	63	17	0.38	0.97	NA	NA
PCBs	43	15	ND	ND	ND	ND
Oil and Grease	130,000	60,000	1.6	2.4	<0.4	3.1
Arsenic	14	40	0.01	ND	0.01	0.002
Chromium	5.7	28	ND	ND	ND	0.04
Copper	34	43	0.02	ND	ND	ND
Lead	2,500	850	5.4	0.01	0.55	0.015
Zinc	150	54	1.3	ND	0.86	<0.02

Table 5
Chemical Analysis of Untreated and Treated Off-site Area One Wastes and Their TCLP and EP Extracts

	Total Analysis		TCLP Extracts		EP Extracts	
	Untreated Waste (mg/kg)	Treated Waste	Untreated Waste (mg/l)	Treated Waste	Untreated Waste (mg/l)	Treated Waste
pH	7.9	12.0	5.1	11.5	4.8	11.7
VOCs	10	ND	0.87	ND	NA	NA
SVOCs	79	16	0.12	0.32	NA	NA
PCBs	43	40	ND	ND	ND	ND
Oil and Grease	28,000	46,000	1.9	12	2.6	11
Arsenic	94	92	0.20	0.02	0.18	0.028
Chromium	11	29	ND	0.04	ND	ND
Copper	33	43	ND	0.04	ND	0.06
Lead	650	480	0.50	0.01	0.12	0.012
Zinc	120	95	0.60	ND	0.26	<0.02

phenolics is uncertain, laboratory contamination and contribution by the Soliditech additives and reagents have been ruled out. Volatile organic compounds were detected in levels up to 30 mg/kg in the off-site Area One soil and filter cake/oily sludge mixtures. Volatiles were not found in the treated wastes and were not detected by monitoring the atmosphere above the mixer as waste batches were being processed.

Tables 3 through 5 show chemical constituents determined in TCLP extracts. Extracts of both untreated and treated wastes showed undetectable quantities of PCBs. Lead concentrations of 4.3 and 5.4 mg/L were found in TCLP extracts of untreated filter cake and filter cake/oily sludge, respectively. These levels were reduced to below 0.01 mg/L as a result of treatment with the Soliditech process. Arsenic in the extract from treated off-site Area One, at 0.020 mg/L and lead in the extracts from treated filter cake and treated filter cake/oily sludge mixture each at 0.010 mg/L, were the highest levels of metals of concern detected. Chromium was found at 0.060 mg/L in extracts from both treated filter cake and treated sand reagent mix.

Analyses of EP extracts showed no detectable PCBs from either untreated or treated wastes. Tables 3 through 5 show reductions in extractable lead and other contaminants after treatment.

The Batch Extraction Test (BET) consists of crushing a sample to pass an ASTM No. 100 sieve (150µm), followed by 7-day extraction with distilled water of separate samples at the three solid-to-liquid ratios of 1:4, 1:20 and 1:100². Data from this procedure provide an indication of the maximum solute concentration and the capacity of the sample (as a reservoir) to provide a source of leachable solutes. No PCBs were detected in any of these extracts. Lead was not found (<0.05 mg/L) in extracts at all three solid/liquid ratios. This immobilization occurred even where the untreated filter cake/oily sludge waste released 1.7 mg/L of lead into the 1:4 extract. Arsenic was present only at hundredth mg/L levels in all extracts of treated wastes and decreased with decreasing

solid/liquid ratio.

Data from the ANS 16.1 28-day leaching test indicated that PCBs, chromium, copper, lead, nickel and zinc were not leachable from any of the three treated wastes. Arsenic was present at 0.005 to 0.006 mg/L in all leachates from the treated off-site Area One waste. This analyte represented the only presence of a contaminant of potential concern and its concentration was quite low. Thus, no contaminants of concern were found in the leachate in amounts sufficient to allow calculation of a leachability index, as described by the ANS-16.1-1986 procedure.

The Waste Interface Leaching Test (WILT) includes submersion of 3 in and 6 in diameter by 18 in length monolithic cylinders in distilled water, with analysis of solutes at 2-week intervals over 6 mo. Cylinders of each size from each of the three treated areas were leached in triplicate. Data available after the first six drainage collections showed no detectable PCBs in the WILT leachate from any of the treated wastes. Arsenic decreased by factors ranging from 20 to 100, to as low as 0.001 mg/L from the first to the sixth leaching increment. Lead was not detectable (<0.05 mg/L) in any of the leachates from treated wastes. Total dissolved solids decreased by about a factor of three from the first to the sixth leaching. Calcium, a good indicator solute derived from the portland cement, also decreased by about a factor of three from the first to the sixth leaching.

Petrographic examination of the solidified, treated wastes was planned in order to characterize the homogeneity of mixing, extent of curing of the concrete-like matrix, mineralogic composition of the solidified mass, voids within the solid matrix and potential long-term weathering effects. In addition, morphologic examination of the treated waste monoliths (TWM) provides long-term data which describe how well these large blocks withstand environmental exposure. Preliminary observations show that the oil and grease appear widely dispersed in globules throughout the cast cylinders prepared for laboratory study and in the TWMs. The millimeter-size globules appeared to be isolated and not contained within a continuous pore system. Detailed characterization data will appear in later reports.

Morphologic examination of the TWMs after 28-day initial curing showed a few large masses of oil and grease, suggesting that the first batch of waste processed in this technology demonstration may not have been thoroughly mixed. A few stress-relief cracks were noted along corners of some of the TWM blocks. Observations after 6 mo showed several of the large blocks contained distinct fractures that appeared to penetrate at least 10 cm in depth from the surface. Observers were unsurprised by fracture development in view of: 1) the richness of added portland cement in the treatment mixture; 2) the rapid setting time after mixing; and 3) the absence of any reinforcing bars or wire mesh within the large block masses. No distinctive color changes were evident on any of the blocks. Several of the blocks contained light salt deposits in surface trails suggestive of either weeping from the blocks or surface flow of condensation which may have developed under the cover over the stack of blocks.

CONCLUSIONS

The high unconfined compressive strength, very low permeability and high resistance to wet/dry and freeze/thaw deterioration indicate a high degree of physical stability of the three treated wastes. Since the concentrations of all contaminants found in the EP Toxicity and TCLP extracts of treated samples were below levels of concern, the Soliditech process stabilized contaminants in the waste from the site of this demonstration. It is significant that, as measured by TCLP, EP Toxicity, BET, ANS 16.6 and WILT procedures, lead is barely detectable in extracts of treated wastes. This result indicates a high degree of physical and chemical stability. The BET data confirm the stability of the treated wastes against aqueous leaching of lead and arsenic. The extremely low amounts of contaminant solutes found in the WILT leachates support the parallel findings in the shorter-term extraction tests.

Morphologic observations, both immediately after curing and after 6 mo, confirm the necessity to evaluate large masses of cement-solidified waste over an extended time.

The absence of any mechanical equipment problems during the demonstration illustrated the reliability of the Soliditech treatment

system. After the equipment operator gained familiarity with waste materials at this site, the process mixed all components into a homogeneous solidified product.

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REFERENCES

1. ASTM. *Annual Book of ASTM Standards, Vol. 4.03*. American Society for Testing and Materials, Philadelphia, PA, 1987.
2. Cote, P. (Draft) "Investigation of Test Methods for Solidified Waste Characterization (TMSWC)." Wastewater Technology Centre, Burlington, Ontario. Prepared for RREL, U.S. EPA, Cincinnati, OH, 1986.
3. American Nuclear Society. *ANS 16.1 Laboratory Test Procedure*. American Nuclear Society, LaGrange Park, IL., 1986.
4. Jackson, D.R. "Comparison of Laboratory Batch Methods and Large Columns for Evaluating Leachate from Solid Wastes." Prepared for RREL, U.S. EPA, Cincinnati, OH, 1988.
5. U.S. EPA. *Test Methods for Evaluating Solid Waste (SW-346)*, Vols. IA, IB, IC and II, Third Edition. U.S. EPA Doc. Control No. 944-001-00000-1, 1986.
6. PRC Environmental Management, Inc. "Demonstration Plan for the Soliditech, Inc., Solidification Process." WA 0-5, Contract No. 68-03-3484, U.S. EPA, Cincinnati, OH, 1988.
7. U.S. EPA. *Technology Evaluation Report SITE Program Demonstration Test*. Soliditech, Inc., Solidification Process, U.S. EPA/540/x-89/xx. RREL, U.S. EPA, Cincinnati, OH, (in press).

Concurrent Application of RCRA and CERCLA at a Unique Federal Facility: The Hanford Site

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ABSTRACT

A goal of the U.S. EPA is to integrate RCRA and CERCLA at hazardous waste sites where both laws may apply. On May 15, 1989, the U.S. EPA, the Washington State Department of Ecology (Ecology) and the U.S. Department of Energy (DOE) entered into an Interagency Agreement to provide a legal and procedural framework for cleanup and regulatory compliance at the numerous hazardous waste sites at DOE's Hanford Site. This document is entitled the Hanford Federal Facility Agreement and Consent Order. Hereafter, it is referred to as the Tri-Party Agreement or the Agreement.

The objective of this paper is to describe a creative approach to integration of the RCRA and CERCLA programs and to explain the development of an efficient, productive working relationship between the joint regulatory agencies; the U.S. EPA, Ecology and the owner of the Hanford Site, DOE.

INTRODUCTION

The Hanford Site is the largest CERCLA site in the nation, encompassing 560 mi. in Southcentral Washington. The site is bordered to the north and east by the Columbia River and is adjacent to the northern boundary of the city of Richland, Washington (Fig. 1). Four general areas of the Hanford Site were proposed for inclusion on the U.S. EPA's NPL on June 24, 1988. EPA anticipates that the proposal will be finalized in late FY-89. These four areas include over 1000 inactive waste disposal and unplanned release sites, ranging in scope from minor spill areas to burial grounds up to 100 ac. in size. The areas also contain 55 RCRA treatment, storage or disposal (TSD) groups which contain over 300 individual RCRA units that will be closed or will be permitted to operate in accordance with RCRA.

The areas include significant amounts of contamination. Estimates of the extent of soil contamination exceed a billion cubic yards, and there are known plumes of contaminated groundwater totaling over 230 mi. The contamination is in the form of RCRA hazardous waste, radioactive mixed wastes (hazardous waste mixed with either high-level or low-level radioactive waste, the hazardous component of which is subject to RCRA regulations) or CERCLA hazardous substances (such as radioactive waste which is not regulated under RCRA).

The State of Washington has received authorization from the U.S. EPA to implement the state's dangerous waste program in lieu of the federal RCRA program. In addition, the state has received authorization to implement the U.S. EPA's radioactive mixed waste program. The state currently is planning to apply for authorization to implement the Hazardous and Solid Waste Amendments of 1984 (HSWA). Therefore, an argument could be made that all of the hazardous or mixed waste units could be investigated and remediated under either RCRA/HSWA authority, eventually to be delegated its CERCLA

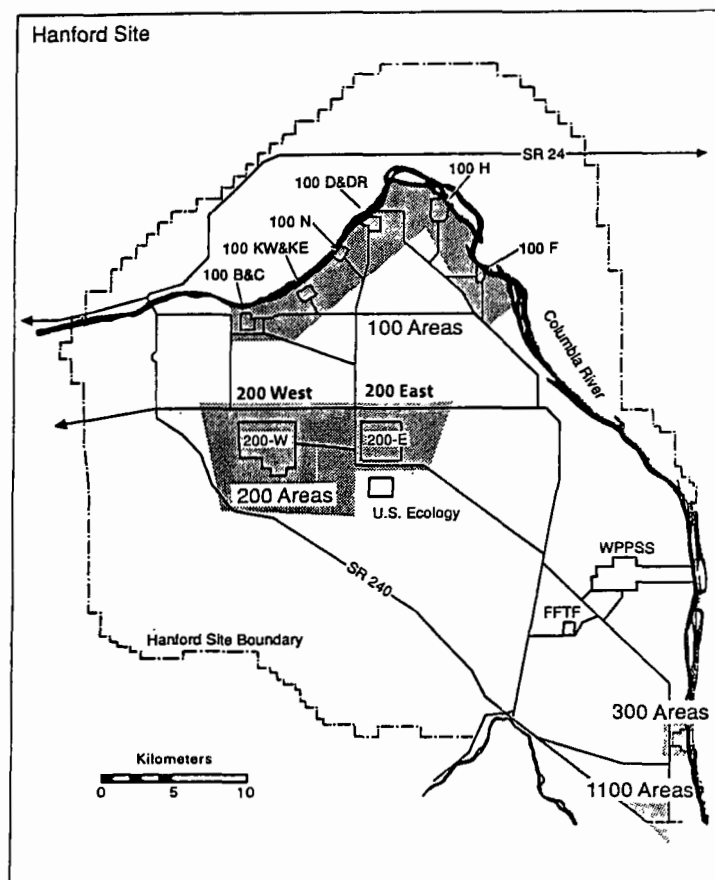


Figure 1
Proposed Aggregate National
Priorities List (NPL) Areas

authority to the state. There also was a concern about how to deal with contaminated groundwater plumes which contained contaminants from both CERCLA and RCRA regulated units. The DOE was very concerned that only one regulatory agency direct the investigation and remediation at each unit and that cleanup standards be consistent under the RCRA and CERCLA authorities. These potential sources of conflict and confusion were recognized early in the process of the Tri-Party Agreement negotiations and were primary topics and underlying themes throughout the negotiations.

SCOPE AND OBJECTIVES OF THE TRI-PARTY AGREEMENT

Section 120 of CERCLA requires the U.S. EPA to enter into Inter-agency Agreements with Federal Facilities which are listed on the NPL. The U.S. EPA encourages its state counterparts to be involved with such agreements since, in many cases, the states' cleanup standards will be applicable or relevant and appropriate to be a CERCLA action. In this case, Ecology had an ongoing RCRA program at the Hanford Site, and the need for an active state role in the Interagency Agreement was even more evident. The formal negotiations for the Tri-Party Agreement began in February, 1988, resulting in a draft document which was issued for public comment in February, 1989. The final Agreement was signed and became effective on May 15, 1989.

The three parties recognized the need to incorporate the CERCLA program, the federal RCRA/HSWA program and the state's Dangerous Waste program into the Tri-Party Agreement. As such, the scope of the Agreement includes all actions leading up to CERCLA remedial actions and RCRA/HSWA corrective measures. The Agreement also includes activities related to RCRA interim status compliance, RCRA permitting and RCRA closure activities—all of which apply to TDS units that last received waste after Nov. 19, 1980.

There were numerous specific objectives that the parties intended to meet through the Tri-Party Agreement. A major objective was to bring the Hanford Site into full RCRA compliance and to achieve full cleanup within 30 yrs. The parties considered this a reasonable period of time based on the extent of contamination, complexity of the site and wastes involved, need for development of new technology and realistic expectations for funding. Another objective was to create a clear picture of the work that needs to be done by specifying detailed schedules and milestones. This type of planning is necessary to support the large amounts of money that DOE will have to request over the next 30 yrs. Another specific objective, as noted above, was to provide specific roles and a plan of interaction between the regulatory agencies. All three parties considered this to be an essential element in order to minimize potential conflicts and disputes as the Agreement is implemented over the years. Another objective focused on a coordinated RCRA-CERCLA public involvement process in order to maximize available resources, to avoid duplication of effort and to provide a consistent format for the public.

RCRA — CERCLA INTEGRATION

Because of the large number of sites or units to be investigated and remediated at Hanford, the CERCLA "operable unit" concept was deemed necessary. The parties agreed to divide the site into 74 operable units (Fig. 2) plus four groundwater operable units. Each operable unit will undergo a separate investigation and remediation process on a priority basis. The criteria used to assign specific waste management units to operable units are identified in the Tri-Party Agreement, as are the criteria used to prioritize operable units for scheduling purposes.

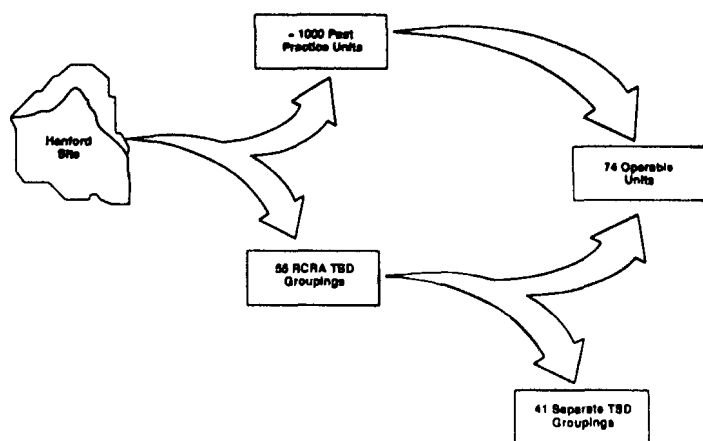


Figure 2
RCRA / CERCLA Integration

There has been a recent effort by the U.S. EPA to provide better coordination between the RCRA and CERCLA programs, specifically in regard to remedial actions or corrective measures. Some of the primary examples of this effort are the requirement to adhere to applicable or relevant and appropriate requirements as part of CERCLA remedial actions, elimination of RCRA permitting requirements for certain activities during CERCLA remedial actions, significant enhancement of quality assurance provisions to RCRA laboratory protocols (SW-846), the U.S. EPA's corrective action rule which contains significant parallels to the CERCLA approach and the U.S. EPA's evaluation of a RCRA "de minimus rule" (yet to be proposed) which would consider cleanup standards for listed wastes as something other than background concentrations. In short, there is a recognition of the need to draw these two statutes closer together, whenever possible, to eliminate conflicting procedures and requirements. The U.S. EPA's general approach to the private sector (i.e., non-federal facilities) is that if RCRA applies at a facility, the U.S. EPA will not pursue that facility through the CERCLA NPL ranking process. All of the cleanup or corrective actions would be taken under RCRA authority. At federal facilities, both the RCRA and CERCLA statutes apply and, therefore, a rational approach to integration is necessary.

The parties also have integrated certain administrative elements of RCRA and CERCLA in addition to technical elements. For instance, a single administrative record is being maintained by DOE and its contractors. As a federal facility, DOE is required to maintain the administrative record under CERCLA. Since many of the CERCLA activities are closely tied to RCRA work, the parties decided that DOE would maintain one overall administrative record, to include both RCRA and CERCLA. The system in place allows sorting of the data base in a number of different ways, allowing the user maximum utility by reviewing the entire record or by extracting specific components.

Another task that was viewed as a cost-saving, practical step was the consolidation of the public involvement activities under RCRA and CERCLA. A significant amount of time was spent developing the joint Community Relations Plan to merge the requirements of both programs into a single process. This joint Community Relations Plan will simplify the process for both the parties and the public and will maximize the efficiency of available resources used for public involvement.

RCRA AND CERCLA AUTHORITIES FOR PAST PRACTICE UNITS

The parties reached agreement that any of the operable units could be managed under either RCRA or CERCLA authority. This was a major step during negotiations. Accordingly, each of the first 20 operable units has been assigned to either the RCRA past-practice program or the CERCLA program for investigation and remediation. Additional assignments will be made annually, as the work schedule is updated. The Tri-Party Agreement requires the U.S. EPA and Ecology designate the regulatory process to be used at these additional operable units.

Most of the past-practice activities involved mixed waste. Therefore, the first area of agreement between the parties was that, in general, the radioactive component of mixed waste would be addressed as part of a RCRA corrective measure. This does not extend RCRA or state Dangerous Waste authority to regulate radioactive wastes; rather, it provides an understanding that DOE has agreed to address radioactive wastes as part of a comprehensive investigation and corrective action at an operable unit, whether the operable unit is being managed under RCRA or CERCLA. The Agreement states that "the corrective action process selected for each operable unit shall be sufficiently comprehensive to satisfy the technical requirements of both statutory authorities and the respective regulations" (Fig. 3). It is important to note that the authority for radioactive wastes remains under CERCLA. This agreement eliminates the potential for a worst-case scenario—the application of requirements of both programs at the same unit, a situation which would not serve the best interest of any party or the public.

The success of this approach requires flexibility in interpretation of the statutes and regulations by the U.S. EPA and Ecology and is predicated on certain assumptions and requires some concessions on the part of all parties. It also provides a solid framework under which the parties

can work cooperatively toward cleaning up the Hanford Site.

INCLUSION OF RCRA LAND DISPOSAL UNITS IN OPERABLE UNITS

Fourteen of the operable units contain significant RCRA land disposal units that received hazardous waste or mixed waste after Nov. 19, 1980. All of these TSD units are scheduled for closure under RCRA and, therefore, operational activities at these units will not be included in the Hanford RCRA permit. In some cases, the units will be covered in the Hanford RCRA permit for post-closure activities. The remaining 41 TSD groups contain only storage and treatment units. These storage and treatment groups have not been assigned to operable units, since the level of investigations required for storage or treatment Part B permit applications and closure plans is less comprehensive than that required for land disposal units (Fig. 2). Accordingly, the schedule for submittal of Part B applications and closure plans for these groups is separate from the operable unit schedule. The need for RCRA - CERCLA integration obviously centered around those operable units which contained the 14 RCRA land disposal groups. The parties agreed to the basic approach that the RCRA land disposal groups would be investigated concurrently with the past-practice sites within the operable unit and that the overall priority and schedule for the operable unit would drive the schedule for submittal of the closure plans and post-closure Part B applications. For this approach to succeed, the parties had to agree that a CERCLA RI/FS for an operable unit would yield a sufficient level of detail to develop a closure plan or post-closure Part B application. As with the integration of past-practice units, the worst case scenario, from an efficiency standpoint, would be a duplication of effort by the U.S. EPA and Ecology, using their different authorities.

In some cases, identically designed units located side-by-side may have received the same RCRA regulated waste streams, differing only in the date on which waste receipt ended. If that date was after Nov. 19, 1980, the unit would be a RCRA TDS unit. If the date was prior to Nov. 19, 1980, the unit would be regulated as a past-practice unit under either RCRA/HSWA or CERCLA. The parties concurred that a single investigation and coordinated timing for a remedial action and closure activity would be the most efficient method of dealing with this issue. For this reason, the parties agreed that only one investigative process—either RCRA or CERCLA—would be used within an operable unit. As stated earlier, this approach required agreement that the investigative procedures of CERCLA and RCRA as implemented at the Hanford Site would provide results that could be used to support technical decisions under either program.

LEAD REGULATORY AGENCY CONCEPT

The design of an efficient and comprehensive regulatory compliance and cleanup program for implementation under the Tri-Party Agreement incorporated numerous factors. One major factor, the integration of RCRA and CERCLA authorities, has been discussed above. Before this system could begin to work, the parties had to come to agreement on another major element—the roles of the two regulatory agencies. One can envision numerous logistical and efficiency problems that would be encountered if both regulatory agencies were to insist on full involvement with their respective authorities.

It became apparent early in the negotiations that a work-sharing approach for the regulatory agencies would be necessary. This approach was carefully crafted in the Agreement so that responsibilities were shared and clearly spelled out, but that authorities could not be transferred arbitrarily between the U.S. EPA and Ecology. In this way, the regulatory agency with the responsibility for oversight can fulfill its obligation to keep the projects running as efficiently as possible, obtaining the co-signature of the agency having authority, when necessary.

The concept of a lead regulatory agency was developed for the regulatory oversight of each operable unit. Its definition and use is restricted to that level. The U.S. EPA and Ecology will decide which agency will be assigned as the lead regulatory agency in each case. Such assignments have been made for the first 20 operable units, and additional assignments will be made during each annual update of the work

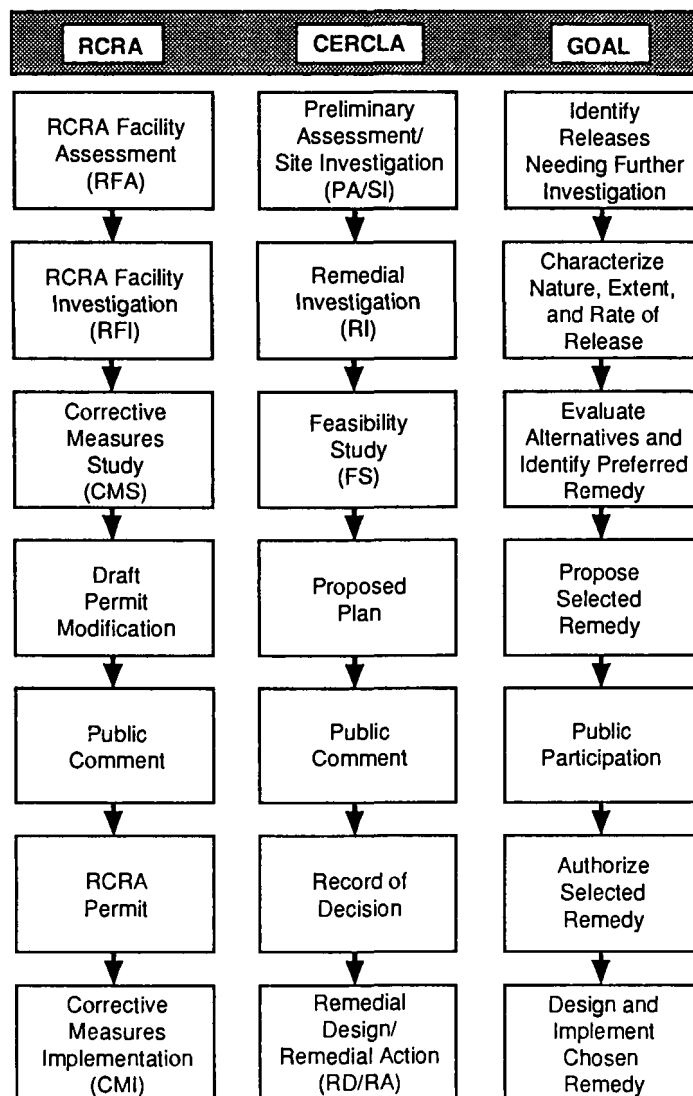


Figure 3
RCRA / CERCLA Comparison

schedule. The regulatory agency not designated as the lead regulatory agency will automatically be designated as the support agency. The roles are defined below.

Lead Regulatory Agency Responsibilities

The lead regulatory agency is responsible for overseeing all activities that are related to a given operable unit. This may include a combination of RCRA TSD and CERCLA work, RCRA TSD and RCRA past-practice work, or CERCLA work without any RCRA activity. The lead regulatory agency serves as the primary contact for DOE, the support agency or the public regarding any questions or issues at the operable unit.

Ecology may serve as the lead regulatory agency for an operable unit that has been designated under either the RCRA past-practice program or the CERCLA program. Likewise, the U.S. EPA may be the lead regulatory agency for such operable units. Ecology and the U.S. EPA have agreed to certain general criteria in the Agreement for designating the lead regulatory agency. Much of this agreement centers around whether significant TSD units are present in the operable unit. Such operable units generally would be assigned to Ecology, and the RCRA past-practice authority would be used. Since there are only 14 of these situations, as discussed earlier, this criterion will have no effect on the majority of the assignments. For those operable units involving only radioactive waste, the U.S. EPA generally would be the lead regulatory agency and the CERCLA process would be designated.

One important criterion for the designation of the lead regulatory agency is the availability of each agency's resources at any point in time to provide adequate oversight of the activities at the operable unit. Maintaining the proper balance of resources will be an ongoing effort by both regulatory agencies.

Support Agency Responsibilities

Both the U.S. EPA and Ecology believe that it is important that the support agency stay informed of the progress at every operable unit. In some cases, the lead regulatory agency and the support agency roles may be reversed at adjacent or nearby operable units. These situations will require close coordination of field activities and data, since technical information obtained at one operable unit may overlap to another. Certainly, the level to which the support agency can become involved will depend upon available resources and the issues at hand. The support agency may submit comments on work plans or other documents submitted by DOE for review. In such cases, the support agency will submit its comments to the lead regulatory agency in order to maintain a single point of contact and to avoid the potential for DOE to receive conflicting comments from the regulators.

CONCLUSIONS

The two processes described above for designation for the regulatory process and of the lead regulatory agency at each operable unit form a basic structure on which the Tri-Party Agreement is implemented. While the approach may seem simple from an overall view of efficiency and what makes sense, the construction of this approach into a working document was a complex task. It required a substantial amount of initial technical work to accurately identify the universe of waste sites and to design and prioritize the operable units. From the point, it required significant negotiations between the U.S. EPA and Ecology to determine appropriate regulatory processes and lead agency responsibilities for the operable units. This type of Interagency Agreement has been referred to as a "carve out agreement," since much of the workload distribution, has been determined prior to signature of the document. By expending a large amount of effort in initial planning, the parties believe that the total resource needs for this project have been established with some degree of accuracy. This makes it much easier for each party to identify and justify its resource needs over both the short and long-term.

One must keep in mind that this approach was developed specifically for the Hanford Site, due to its size; the number of units; the state's authorization status and its involvement and commitment to regulatory compliance and cleanup; and the number of situations which would require the integration of RCRA and CERCLA. This approach may not be appropriate for all sites at which RCRA and CERCLA integration is an issue. It can only work when all of the parties negotiate in a cooperative manner and when the U.S. EPA and the state are willing to place a significant amount of trust and confidence in each other.

The U.S. EPA and Ecology have included a dispute resolution process section in the Tri-Party Agreement that can be implemented in the event they can not come to agreement on certain integration issues. The DOE is not a party to that dispute resolution process since it involves only decisions between the regulatory agencies.

Present Status

The bottom line of any methodology can be simply stated as "Does it work?" The parties to this Agreement are now 3 mo. into implementation. At this point, we are still hiring staff and developing some of the detailed procedures necessary for efficient implementation. To date, work plans have been submitted for the first five operable units. Three of these are under the CERCLA process with the U.S. EPA as the lead regulatory agency and two are under the RCRA process with Ecology as the lead regulatory agency. One of the RI/FS work plans has been approved and field work has been scheduled. Overall, the process is running relatively smoothly, and we are optimistic that it will get better as to get over some of the hurdles for the first time.

Future

Many federal facilities currently are negotiating cleanup and compliance agreements with the U.S. EPA and/or state agencies. As these facilities are added to the NPL, some are faced with the potential conflicts of concurrent application of CERCLA and RCRA. To the extent that it may apply, the approach used by DOE, the State of Washington and the U.S. EPA could be used as a framework or model for negotiations between such federal facilities and the regulators. The experience gained at Hanford can be used to foresee and eliminate many of the conflicts and redundancies of the two regulatory programs, resulting in a streamlined approach to cleanup and compliance.

Hazardous Waste Decontamination With Plasma Reactors

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ABSTRACT

The use of electrical energy in the form of plasma has been considered as a potentially efficient means of decontaminating hazardous waste. Only a few attempts have been made to actually treat hazardous waste with plasma, however. This paper discusses both direct and indirect waste heating with plasma. Direct heating involves the direct injection of liquid waste into the plasma plume. Indirect heating involves using the plasma to create a bath of molten solid material which is used to heat and decontaminate solid hazardous waste. This paper summarizes the experience to date with plasma based hazardous waste treatment and discusses the implications of the limited data available.

INTRODUCTION

A plasma is created when gases are ionized by passing through an electric field strong enough to strip electrons from the molecules of the gas. Even though the aggregate gas remains electrically neutral, this occurs only because it is made up of equal numbers of positively and negatively charged particles. These charged species contain a high level of energy. When the ionized species in the plasma recombine with the stripped electrons, significant amounts of energy are released. This energy can be used in a variety of ways. Plasma torches have been used in the metals industry and have been considered for use in wood gasification, glass manufacturing and in radioactive waste nitrate reduction^{1,2,3}. Because of the large amounts of energy that can be delivered by plasmas, plasma torches have been considered as a possible means of decontaminating hazardous wastes.

Relatively little data are available on the use of plasma to treat hazardous waste. Basically, there are two ways in which plasma can be used to decontaminate hazardous wastes. One way is to inject the waste directly into the plasma. In this way, plasma energy is used to break apart molecules of various hazardous substances into their constituent atoms. The other way is to feed waste into either a molten metal bath or a bath of molten soil. While direct heating has been shown to treat only liquids and gases, indirect heating can also treat solids. The bath heats the waste feed, volatilizing the waste contaminants. Once volatilized, these waste contaminants are thermally destroyed in the hot atmosphere of the reactor. The molten material solidifies into a vitrified mass which, if containing heavy metals, is non-leachable.

This paper discusses the relative advantages and potential disadvantages of the use of both direct and indirect heating with plasma as a means of treating hazardous waste. Since there are only limited data available on this use of plasma, more questions will be asked than answered. Hopefully, asking questions will stimulate discussion on this topic. The U.S. EPA is interested in obtaining as much information as possible on the use of plasma technology because the Agency currently is evaluating it for its potential use in hazardous waste decontamination.

The potential advantages of the use of plasma in this application include the following.

Plasma may be able to deliver high levels of energy to the waste.

When injected directly into the plasma plume, hazardous wastes are directly subjected to the high intensity plasma energy. This energy is believed to be sufficient to break the molecular structure of the individual waste compounds into their atomic constituents and is far in excess of what is possible with conventional incineration.

Upon recombination, carbon dioxide, water and other common and relatively innocuous end products of combustion are formed. Products of Incomplete Combustion (PICs) are not believed to be formed in significant quantities. PIC formation can be a problem with conventional incineration and the use of plasma could eliminate it.

Plasma may be able to treat metal contaminated solids.

When plasma is used to create a molten bath of soil, metals or glass, a very uniform, high temperature environment is created. While the temperatures achieved are far below plasma temperatures, they are hot enough to ensure the thermal destruction of organic waste constituents treated in this way. Cold spots where PIC formation may be exacerbated are eliminated in this environment. In addition, it may be possible to entrap metal contamination in the melt. Upon cooling, this would result in a non-leachable solid residue which would not require further treatment. Fluxing agents could be added to the melt to adjust its properties (i.e., melting point and residue leachability).

If enough energy is provided through the plasma, the process could be very versatile and would be able to treat waste with any physical characteristics including entire waste-filled drums. This capability would eliminate the need for waste pretreatment. Combined with the production of non-leachable organic-free residues, the use of indirect plasma heating could eliminate the need for either pre- or post-treatment. This capability would reduce the overall costs associated with plasma treatment and may compensate for the likely additional energy costs for this process.

Both oxidizing and non-oxidizing atmospheres can be used while still achieving very high temperatures.

Since the only requirement for creating a plasma is that the gas used be ionizable, plasma can be used in the absence of oxygen in situations in which high temperature pyrolysis is desirable. Since the ionization potential of gases varies, torch efficiencies will vary with the torch gas used^{2,7}.

Two instances in which plasma is being used or is being developed for use in hazardous waste treatment will be discussed. One instance involves direct heating by plasma and the other concerns indirect heating.

DIRECT HEATING WITH PLASMA

Waste decontamination through direct heating by plasma has been studied more than indirect heating. For direct heating, non-transferred torches are used. Figure 1 is an illustration of a non-transferred plasma torch in which both positive and negative electrodes of the torch are contained in the body of the torch itself. An electric arc is created between the two electrodes. Gas passing between the terminals passes through the electric arc and is ionized, thus forming the plasma.

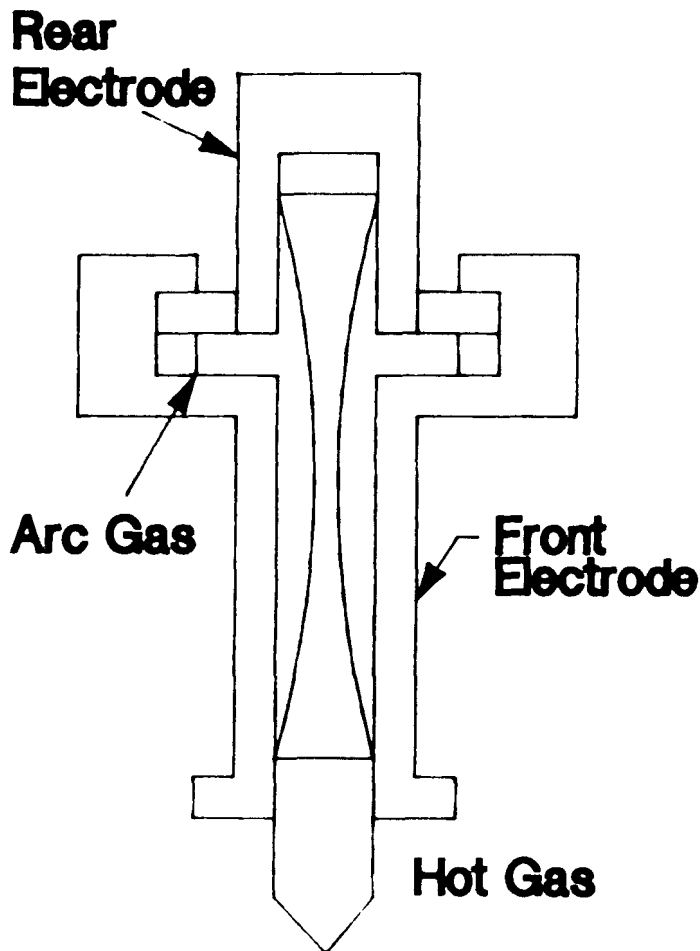


Figure 1
Non-transferable Torch

The Westinghouse Pyroplasma unit, originally developed by Pyrolysis Systems Inc., of Ontario, Canada, was tested for possible use at Love Canal by the New York Department of Environmental Conservation (NYDEC) and the U.S. EPA. A schematic diagram of the Mobile Pyroplasma Unit is provided in Figure 2⁴. The entire system, including the analytical laboratory, is contained in one trailer and operated as follows.

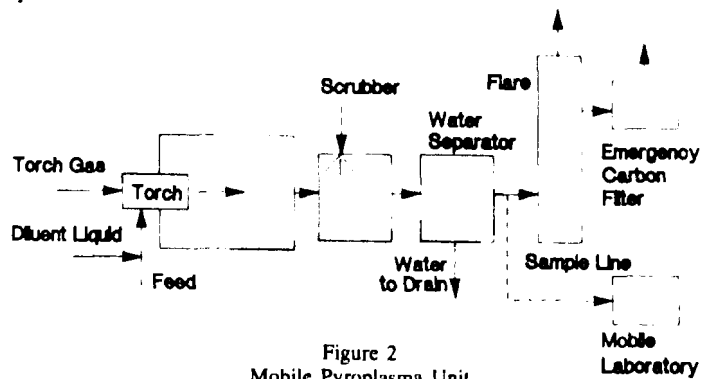


Figure 2
Mobile Pyroplasma Unit

Up to 1 gpm of solids-free liquid feed was injected into the plume of a 350-kw non-transferred electric torch. Air was used as the torch gas. Exhaust gas from the plasma torch was treated by aqueous scrubbing and water separation prior to being released into the atmosphere via a flare. Exhaust gasses were sampled upstream of the flare and were analyzed on-site through the use of continuous emission monitors and an on-line gas chromatograph⁴.

Two tests took place from 1982 to 1986. Both tests involved the treatment of simulated liquid wastes consisting of chemicals diluted in a mixture of methanol and methyl ethyl ketone. The first test treated carbon tetrachloride diluted in MeOH/MEK. The second test treated a mixture of PCBs also diluted in MeOH/MEK. These liquids contained no suspended solids and were free of water. Table 1 shows the Destruction and Removal Efficiencies (DREs) achieved.

Table 1
DREs Achieved During the CCl₄ and PCB Trial Burns⁴

Chemical	Test 1	Test 2	Test 3
CCl ₄	99.99995	99.99996	99.99996
Monodecachlorobiphenyl	99.99999	99.99994	99.9999
Tridecachlorobiphenyl	99.999999	99.99997	99.999999

A few parts per trillion of Dioxins and Furans were discovered in the stack gases during the PCB trial burns.

In use, the Mobile Pyroplasma Unit was quite sensitive to changes in waste feed or operating conditions. Virtually no solids could be present in the feedstream without causing operational problems. Cost data are not available from either study. Torch efficiency was 80%¹.

Recent data made available by Westinghouse Environmental Systems and Services confirms the very high DREs achieved earlier (and shown above). These tests involved the treatment of 300 gal (at 1 gpm) of transformer oil containing 70-80% PCBs by weight⁷. These data are shown in Table 2.

Table 2
Recent PCB Destruction Test Results⁷

	Test 1	Test 2	Test 3
DRE %	99.999999	99.999999	99.999995
HCl lb/hr	0.941	0.972	0.343
Particulate Gr/DSCF	0.00837	0.00845	0.00441

The results of the operating experiences with the Mobile Pyroplasma Unit raise several questions.

Question 1.

Is injecting waste directly into a plasma hazardous waste "overkill" since the energy delivered is far in excess of that normally needed to thermally destroy most waste compounds?

Question 2.

Is injecting waste directly into a plasma really worth all of the precautions necessary to assure solids-free and uniform feed since PICs can still form from the recombination of fragmentary molecules during the decay of the plasma?

Even though the levels of PIC material produced were relatively low, the presence of PICs in the exhaust suggests that the waste chemical molecules are not completely broken down into their constituent atoms when injected into a plasma plume. The free radical chain reactions of conventional fossil fuel/air combustion result in the formation of some

PICs when the free radicals and/or fragmentary molecules recombine. Is it possible that these recombination reactions still occur even in a very high temperature plasma environment?

Evidence that this can happen is provided by Drost, et al.⁵, in a study of the effect of recombination reactions on the formation of products from reactions at plasma conditions in shock tube experiments. Conditions in the pressure waves of shock tubes are similar to plasma conditions and so were used to study the effects of hydrogen ions on the formation of products produced when hydrogen was used as a plasma gas. Hydrogen decreased the formation of acetylene from methane, presumably by recombining with methyl radicals initially created in the plasma. Hydrogen also decreased the formation of soot from these reactions as a result of recombining with methyl radicals. These results contradict the previously held notion that the torch gas used to create the plasma acted only as a medium for the transfer of energy and did not react with the waste. They also suggest that PICs can be formed from the use of plasma gas just as they can be in conventional combustion.

These studies, in combination with the observed results, suggest that not even the intensive energy of plasma is sufficient to guarantee that waste compounds will be completely oxidized without forming any undesirable side products. If this is true, yet another question is raised.

Question 3. Is the type of torch gas used very important in determining the types and levels of any PICs formed? Or, is it merely necessary to use air or oxygen?

Question 4.

Finally, can real waste streams be treated in this device given the need to filter out all solids and the overall sensitivity of the process to the properties of the waste materials fed?

INDIRECT HEATING WITH PLASMA

For indirect heating, a transferred torch is used. Figure 3 is an illustration of a transferred torch. As the name implies, transferred torches strike an electric arc between the torch and a conductive body external to the torch. That body can be the heat conducting medium used in the case of indirect heating.

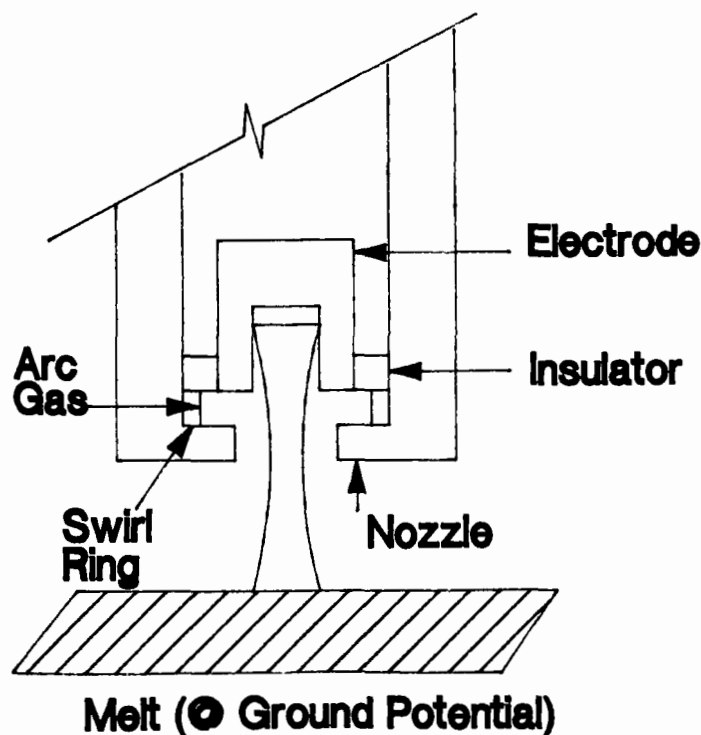


Figure 3
Transferred Torch

There is less experience with indirect heating. The Centrifugal Reactor developed by Retech Inc. of Ukiah, California, uses a transferred torch to melt soil and debris. Figure 4 is a schematic diagram of the Centrifugal Reactor⁸. The system operates as follows. Waste is fed through a screw feeder and enters the rotating tub in the upper chamber. There the rotating tub retains the solid waste for sufficient time to allow the 500-kw torch to melt and vitrify the soil. The torch fuses the solid matter into a slag, presumably trapping less volatile metals. The hot environment helps to oxidize the organic material volatilized from the slag. Air pollution control devices downstream of the reactor's secondary chamber remove particulate and acid gases from the exhaust gas stream.

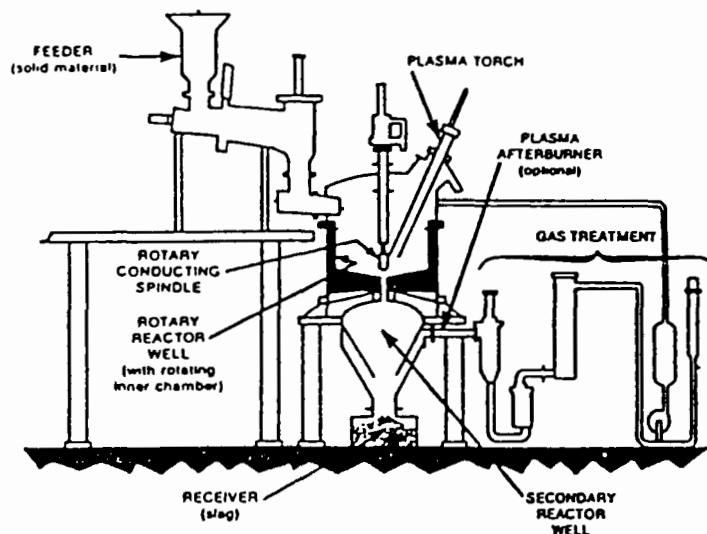


Figure 4
Centrifugal Reactor

The reactor currently is being evaluated under the Superfund Innovative Technology Evaluation (SITE) program at the U.S. Department of Energy's (DOE's) Magnetohydrodynamics Component Development Integration (CDIF) in Butte, Montana. The demonstration of this device will begin as soon as development work is completed which will optimize the performance of the reactor. DOE is interested in evaluating the reactor for its potential use in consolidating Transuranic waste currently stored at the Idaho National Engineering Laboratory (INEL). DOE has planned a 6-mo study to evaluate its potential usefulness in this application. The study will take place at the CDIF and will occur in conjunction with U.S. EPA's performance evaluation under the SITE program.

Even though there are no results yet, several questions can be raised about the applicability of indirect plasma heating to the treatment of hazardous waste.

Question 1.

How energy intensive is indirect plasma heating relative to conventional incineration? Is added energy input worth it in order to form a non-leachable solid residue that will require no further treatment? Or, is it cheaper and less risky to incinerate the organics and treat the ash?

Question 2.

How sensitive is indirect plasma heating relative to changes in waste properties such as water content and heating value. Indirect heating with plasma is presumed to be less sensitive to changes in waste properties. Since plasma is capable of melting rocks etc. the belief has been that treatment processes based on indirect heating with plasma were omnivorous and required very little, if any, waste pretreatment. Is this true or just a myth? Given the potential difficulty of providing sufficient energy to these processes, so much energy might be used to heat rocks and water that not enough would be available to thermally destroy hazardous wastes.

Question 3.

How efficient is the use of plasma in the heating of solid material when compared to the use of other forms of electrical heating?

Question 4.

Is plasma, therefore, useful only for certain types of waste such as high BTU low water content wastes?

Question 5.

Can fluxing agents be used to enhance melt properties and residue quality? How would the use of such agents affect the economics and practicality of the process?

CONCLUSIONS

Only limited data are available on the use of plasma to decontaminate hazardous waste, although the idea of doing so has been considered for a number of years. Although some of the results achieved thus far are promising, a number of questions remain about the usefulness of plasma in this application. Until more data become available, it will be impossible to answer these questions and to determine how plasma might best be used in this application. Information from future tests on the Retech Centrifugal Reactor and the Westinghouse Pyroplasma Unit will provide needed information to further assess the use of plas-

mas in hazardous waste treatment.

REFERENCES

1. Joseph, M.F., Barton, T.G. and Vorndran, S.C. "Incineration of PCBs by Plasma Arc," *Proceedings of the 33rd Ontario Industrial Waste Conference*, June, 1986. Toronto, Ont. 201-206.
2. Johnson, A.J., Arnold, P.M., Deitesfeld, C.A. and Morales, L.M. "Waste Generation Reduction-Nitrates FY 1984 Status Report. U.S. Government NTIS Report PBDE85102067. Apr., 1985.
3. Dolenko, A.J., *Research on Gassification of Wood in a Plasma Pyrolysis Unit*, Canadian Forestry Service NTIS PB 84901566. Jan., 1984.
4. Lee, C.C. and Huffman, G.L., "Update of Innovative Thermal Destruction Technologies" EPA/500/225 PB89118541/AS U.S. EPA, Cincinnati, OH, 1988.
5. Drost, H., Klotz, H., Schultz, G. and Spangenberg, H., "The influence of Hydrogen on the Kinetics of Plasma-pyrolytic Methane Conversion" *Plasma Chemistry and Plasma Processing*, 1 Mar. 1985 55-65.
6. Lee, C.C. and Huffman, G.L., "Innovative Thermal Destruction Technologies," *Handbook on Hazardous Waste Incineration*, CRC Press, Boca Raton, FL, July, 1988.
7. Reed, W.S., Sales Manager, Westinghouse Environmental Systems. Madison, PA, Personal Communicator, Aug 1, 1989.
8. Eschenbach, R.C., Hill, R.A. and Sears, J.W. "Process Description and Initial Test Results With the Plasma Centrifugal Reactor" Forum on Innovative Hazardous Waste Treatment Technology. Atlanta, GA, June, 1989.

Evaluating the Cost-Effectiveness of SITE Technologies

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ABSTRACT

The goal of the U.S. EPA's Superfund Innovative Technology Evaluation (SITE) Program is to develop reliable performance and cost data for unique and commercially available hazardous waste treatment technologies. A major challenge which faced the SITE Program was how best to insure that the cost evaluation process produced cost projections which would be useful to Superfund decision-makers. In this evaluation process, several impediments to the collection and analysis of cost data were identified. This paper discusses the four most important problems encountered and then offers a set of five cost guidelines which address those problems.

INTRODUCTION

Among the programs created by Congress through the passage of SARA was the Superfund Innovative Technology Evaluation (SITE) Program. The goal of the SITE Program is to help the Superfund decision-making process through the formation of reliable performance and cost data for unique and commercially available hazardous waste destruction and treatment technologies.

Interestingly, of all the language contained within SARA, the following section is the only one which specifically requires the Agency to collect and report cost data for those technologies being demonstrated. Section 311.e. states that the SITE Program will prepare an annual report for Congress, in which shall be "...an evaluation of each demonstration project..., findings with respect to the efficacy of such demonstrated technologies in achieving permanent and significant reduction in risk from hazardous waste, the cost of such demonstration projects, the potential applicability of, AND PROJECTED COST FOR, such technologies..." (emphasis added). While other language within the legislation indirectly speaks to the cost issue, either by specifying the need to select technologies for the Program that "are likely to cost-effective and reliable" (Section 311.b.7.B.), or by stating that the demonstrations will determine "whether or not the technologies used are effective and feasible" (Section 311.b.5.A.v), no specific guidance is offered on the scope or content of the economic analysis.

Within the Agency, implementation of the SITE Program is handled jointly by the Office of Research and Development and the Office of Solid Waste and Emergency Response. As stated in the SITE Program's first "Report to Congress", its goals are fourfold:

- To identify and, where possible, remove impediments to the

development and commercial use of alternative technologies

- To conduct a demonstration program of more promising innovative technologies to establish reliable performance and cost information for site characterization and cleanup decision-making
- To develop procedures and policies that encourage selection of available alternative treatment remedies at Superfund sites
- To structure a development program that nurtures emerging technologies

In order to participate in the SITE Program, interested technology developers first are asked to submit a detailed proposal to the Agency. This proposal should highlight the innovative aspect of their process, offer any preliminary test results and provide proof that they can commercialize the process. From those proposals submitted, the Agency selects roughly 10 technologies per year. Those accepted are invited to enter into a cooperative agreement with the U.S. EPA. Under the terms of that cooperative agreement, the government's primary financial commitment is to cover those costs involved with the collection and analysis of data. The developer, on the other hand, is responsible for all costs associated with the actual operation of the equipment. After the demonstration results have been analyzed, the engineering and cost evaluations for each SITE technology are then presented within one of a series of outputs; a report entitled "SITE Technology Application Analysis." This document is designed to provide the reader with an in-depth overview of the process including a report on the demonstration, an analysis of the test results, cost projections, case studies and comments by the developer. Draft versions of the cost analysis are prepared by the U.S. EPA Project Manager and his support contractor in consultation with the SITE Program's staff economist. Before publication, this draft version undergoes an extensive review. In the case of the cost projections, this review is performed in order to examine the soundness of the analytical approach and to insure conformity to the generalized cost protocol described later in this paper.

Thus, one effect of the SITE Program is to create a limited partnership between the U.S. EPA and the technology developer; between the public and private sectors. Nonetheless, the Agency has a significant responsibility to provide the public with an impartial analysis of each technology. The ultimate challenge to the SITE Program is to balance the need to remain neutral while encouraging the adoption of promising new technologies.

As the details of the SITE Program were being formulated, the special nature of this public/private sector interaction suggested the need to design a method for projecting the costs of new hazardous waste treatment technologies. This paper examines four

issues which limit the ability of the SITE Program to establish protocols for the conduct of each technology's cost analysis. After this paper has explored these issues, it will describe the cost methodology currently in use by the SITE Program.

PROBLEMS

The first problem that limits the ability of the Agency to provide Superfund decision-makers with accurate cost projections for new technologies confronts everyone involved with Superfund cleanups. Every cleanup operation represents a mix of factors unique to that site; these variables include the waste matrix, the amount of waste to be treated, the physical characteristics of the site and the cleanup treatment goals. The way that these factors combine will vary from site to site. Thus, any data (engineering or cost) collected during a given demonstration speak directly to the conditions found on a particular site at a given point in time. The ability to extrapolate those data to other hazardous waste sites is constrained in large part by the degree to which similarities exist between the demonstration site and other sites. The more similar the conditions, the more confidently we can predict the outcome.

Layered on top of these individual site variations are those variables directly related to the operation of the SITE Program. These variables include regulatory restrictions, programmatic and budget constraints, the level of the developer's experience (both working with the technology and operating within the hazardous waste field) and the expertise of the SITE Project Manager and his support contractor. Once again, the data collected during a demonstration are a reflection of the interaction of all variables. The lesson to be learned here is that the costs observed during a demonstration represent nothing more than one of many scenarios possible under different operating conditions. The problem confronting the cost analyst is how best to capture and portray the most likely costs; to generate a base-case cost projection which will have broad appeal among Superfund decision-makers.

The need to collect and analyze engineering and performance data under rigorous QA/QC conditions presents the second limitation to the Agency's ability to project future technology costs. When the research objectives of each demonstration are coupled with a finite demonstration budget, the ability of the Agency to collect economic data is reduced. There are many reasons why this is so.

Each developer needs to finance all costs associated with the operation of his equipment during a demonstration. Contracting his services to a third party is a good way to do that. It is likely that the actual demonstration will be conducted during an ongoing site remediation. The developer's primary responsibility is to meet the dictates of his contract; to treat the waste. From his perspective, the SITE demonstration activities are at times an impediment to that remediation. The Agency's sampling and analytical plan will specify the number and nature of the samples to be taken. Typically, the collection of samples will occur during a very small subset of the equipment's total operating time. The benefits derived from this "snapshot" view of the process are that it limits both the sampling costs and the interruptions to the process. The downside is that this sampling period may be the only opportunity that the Agency has to closely observe the operator and the equipment, thus virtually eliminating the Agency's ability to gather long-term economic data.

It may be impossible to directly observe other operations and record the cost of those activities. These items range from periodic maintenance to the average on-line utilization rate. The cost implications of these activities must be obtained from secondary sources or be estimated. Even in those cases where the developer is prepared to provide regular access to the equipment, the ability to collect variable cost data can be hampered by normal sampling requirements. Continuous process operations may need to be rou-

tinely interrupted as sampling occurs. When this happens, observed costs must be adjusted to account for such activity. Finally, one-time factors that are inherent in the operation of any new equipment (particularly in equipment incorporating innovative designs features) further limit the ability of the Agency to collect real-time economic data. These include the need to separate startup and shakedown problems from normal operations, including unplanned field modifications, materials handling adjustments and scale-up problems.

Commercialization

One of the stated goals of the SITE Program is to encourage the commercialization of innovative technologies. As such, the SITE Program has had to cope with both the impact that market forces have on each participating firm as well as the impact the SITE Program itself has on the market. This concern is the genesis for the final two cost problems which confronted the Program.

Each vendor accepted into the SITE Program must have demonstrated the potential to commercialize his technology. To put this requirement in economic terms each vendor has represented himself as profit maximizer willing (and prepared) to operate within a competitive marketplace. As a profit maximizer, each developer has formulated a unique strategic view of that market; one which he believes will ultimately sustain long-term profitability. The SITE Program needs to be sensitive to each developer's strategic viewpoint, which is colored in large part by the underlying condition of his balance sheet.

Company Financial Strength

The SITE Program has seen great diversity in the financial condition of vendors accepted into the program. Many firms enjoy advantages made possible by some form of long-term financial commitment. With this, they have the ability to withstand cash flow problems inherent in the conduct of research-oriented engineering work. These firms, and their backers, recognize the benefit in deferring short-term profits in order to gain an opportunity to establish their presence in the market and position themselves for long-term benefits. At the other extreme are those developers who enter the program with pilot-scale equipment, a promising idea, but limited financial resources. Participation in the SITE Program provides a wonderful opportunity for a firm to establish a presence in the marketplace. However, the precarious financial position of some firms often limits the time they have available to enter the market. Engineering, operational or regulatory delays of any sort may severely hamper a company's ability to successfully commercialize its technology, much less remain a viable corporate entity. The firm's corporate strategy likely differs greatly from that of its better-financed counterparts.

Since one stated objective of the Program is to "identify and remove impediments to the development and commercial use of alternative technologies," it is important for the Agency to be sensitive to these corporations' financial positions. Each firm will use a different method for apportioning its research and development expenditures. Each firm will have its own marketing strategy which places emphasis on exploiting some niche within that market. Each firm's growth potential will be constrained by its ability to raise capital and attract (and retain) a competent technical staff. Each firm will have established target levels of profitability, with a pricing strategy to reflect this. These points combine to form a framework which guides corporate decision-making.

Finally, each firm understands the important distinction between "cost" and "price," a point which is easily lost on those in the public sector unconcerned with the profit motive. In simple terms, cost reflects expenditures by the firm and is inherently a function of accounting. Price, on the other hand, is the end product of negotiations between the firm and those wishing to obtain

its services. It is much simpler for the outside observer to project costs than it is to project price. In the end, the price which the developer charges becomes a direct function of both the firm's strategic view of the market and the interaction of supply and demand forces.

Confidential Data

Armed with an understanding of the central role that a firm's business strategy plays, and given the highly competitive nature of the hazardous waste treatment market, it is easy to see why any firm would have a strong incentive to withhold its cost data from the public record. Such information, if placed in the hands of a competitor, could severely undermine the firm's chance for long-term success in the market. In those cases where cost data are offered by a firm, one must ascertain the motivation of that firm in releasing such data. Are the data accurate? Do the data truly represent the firm's actual costs or do they represent costs which the firm would like the market to believe are true? The Agency must accept the proprietary nature of each firm's cost data, despite the problems it creates in trying to project future costs. Even SARA acknowledges the sensitive nature of a firm's cost information when it states in Section 311.b.8. that all data collected during a demonstration shall be made available to the public except for "trade secrets or other proprietary information." This secrecy provision leads to the unhappy conclusion that SITE technology cost projections may end up being conducted without input from the developer.

The final cost issue confronting the SITE Program is the Program's own impact on the hazardous waste treatment market. For better or worse, the U.S. EPA's evaluation of demonstrated technologies will carry significant weight among decision-makers in both the public and private sectors. Merely participating in the Program confers a special status to those who are in it. The judgments offered by the Agency on a technology's effectiveness are likely to be viewed by the public as a U.S. EPA "Seal-of-Approval," regardless of the Agency's intention to remain impartial. Opinions offered by the U.S. EPA regarding the engineering effectiveness of a given technology can be supported through reference to vast amounts of QA/QC data generated during the demonstration. Not so with the cost projections. By contrast, those projections are supported for the most part by the quality of the underlying economic analysis.

Cost Projections

As the SITE Program's ability to influence the market grows, the real danger for all parties concerned is to discover that the Agency's cost projections have been overly optimistic or pessimistic. If it turns out that the cost projections end up being significantly lower than true costs, Superfund decision-makers will be misled into concluding that the technology is exceptionally cost-efficient when compared to other alternatives. In turn, other technologies under consideration may be rejected out of hand for appearing to be too costly. Eventually, the developer may be faced with the difficult problem of trying to negotiate a fair price with a buyer who harbors false price expectations. At the other extreme, if the cost projections end up being much higher than true costs, potential users conducting a preliminary screening may exclude the technology as being too expensive. Rather than helping to promote new technology, the Agency will have inadvertently limited the developer's market. In either case, making a significant error in its cost projections is the best way to endanger the SITE Program's long-term credibility with Superfund decision-makers.

In review, there appear to be four problems which significantly limit the ability of the SITE Program to generate useful cost projections for the technologies it demonstrates:

- Each field demonstration represents a mix of unique factors

- The research and development aspects of each demonstration will impact observed costs
- Each developer is a profit maximizer operating within a competitive marketplace
- The SITE Program creates unique interactions between public and private sector forces

SOLUTIONS

After reviewing the four issues presented above, it became clear that a single, rigid cost protocol would not serve the goals of the SITE Program. With the potential for several dozen demonstrations to be conducted over the life of the SITE Program, the sheer number of independent variables involved with each demonstration made the usefulness of such an effort suspect. What was possible, however, was to establish broad rules to guide Project Managers and their support contractors as they worked through the cost projections. The idea was to create a high degree of uniformity among all the SITE cost analyses while allowing the conditions of the demonstration to dictate the basic approach used in each cost projection. Most importantly, insuring that all cost projections follow the same basic rules should enhance the ability of Superfund decision-makers to make relative cost comparisons between technologies. The remainder of this section will highlight four major cost guidelines which, when taken together, address the concerns set forth in the previous section.

Cost Categories

The first and most critical step was to establish a set of cost categories which would serve as a common framework for a base-case cost analysis. These 12 categories are listed in Table 1. While the descriptions of each category have been omitted from this paper, they are intended to encompass the range of activities which could occur during a demonstration or cleanup. It is recognized that these categories are but one combination of activities and, in the long run, other ways of classifying these activities may be more appropriate. Under the most ideal conditions, each demonstration would provide enough information to make cost projections for each of the 12 categories. However, each demonstration is a mix of unique factors, reducing the likelihood that any final cost estimate would be based on the sum of all 12 categories. When assigning costs to these categories, it is incumbent upon the analyst to leave empty those categories for which data are unavailable. In other words, if data are unavailable for three of the 12 cost categories, then the report should clearly state that fact so that the reader fully appreciates the underlying basis for the cost projection.

Aside from providing a common framework for all SITE cost projections, use of these categories should help reduce the temptation many have to compare the cost of technologies when the bases for each of the cost projections are not equivalent. For example, if technology A's cost projection is based on the sum of eight categories while technology B's cost projection is based on costs incurred in all 12 categories, comparing their projected costs without first compensating for the difference in their bases would lead one to reach a false conclusion about the relative cost-effectiveness of one technology over the other.

Order of Magnitude Estimates

The second rule simply requires all cost projections to be presented as "Order-of-Magnitude" estimates, a precision level established by the American Association of Cost Engineers (AACE). The expected accuracy of "Order-of-Magnitude" estimates is within +50% and -30%. The AACE defines this level of precision as being those estimates generated without the benefit of detailed engineering data.² AACE suggests that this type of estimate is appropriate for feasibility studies or to aid in the selection of alternative processes. This analysis is the intended use of

Table 1
Cost Categories
SITE Application Analysis Report.

1. Site Preparation
2. Permitting & Regulatory Requirements
3. Capital Equipment
4. Start-Up
5. Labor
6. Consumables & Supplies
7. Utilities
8. Effluent Treatment & Disposal
9. Residuals/Waste Shipping & Handling
10. Analytical Services
11. Maintenance & Modifications
12. Demobilization

the SITE cost projections. While decision-makers may desire greater precision in the cost projections, doing so would require the preparation of much more detailed design work than is currently possible.

Base Cost Projection

The third rule provides that each cost analysis will generate a base-case cost projection which presents the reader with a full disclosure of all assumptions and calculations. The key idea here is full disclosure. There should be no question as to how final cost projections are derived. Providing full disclosure not only means clearly stating the assumptions, but it also means providing the source of that information. Were cost figures based on direct observation of the process or were they derived from secondary sources? The Agency has an obligation to clearly indicate where data points were obtained, allowing the reader to make an independent judgment on their worth. Regardless of whether the data are taken from the developer, a standard reference source, a cost curve or are arrived at through an educated guess, the analysis should be forthright and state the source. Formulas must also be presented, and where calculations are complex, each step should be outlined. Using the 12 cost categories will help to insure that all relevant assumptions are covered.

Adherence to this rule will provide several benefits. At the minimum, it places the burden of proof upon the reader to examine the assumptions used to generate the cost projections and insure they are appropriate, given the details of his cleanup problem. Unfortunately, experience suggests that the tendency is for many decision-makers to seek out and focus upon a single unit-cost estimate. The result is that these unit-cost projections often are taken out of the context of their assumptions and, as noted, understanding the nature of the assumptions is critical to the usefulness of the projection. While this rule cannot hope to stop the inappropriate use of cost data, it will insure that if and when questions arise surrounding a cost projection, the answers will be readily available.

Full Disclosure

The full disclosure of assumptions and calculations also will produce an end-product which the reader can replicate on his own. Suppose the reader finds the basis for a cost projection to be

inappropriate. It is very likely to be the case. As was stated earlier, each Superfund site represents a mix of factors. Any attempt to set forth a "standard" Superfund site upon which to base each cost projection is an exercise in futility. Thus, the base-case cost projection offered by the U.S. EPA can only hope to represent the most typical outcome of an infinite number. By affording the reader the means to recreate the cost analysis it becomes a straightforward matter for him to recalculate the projection, substituting any assumptions deemed inappropriate with others more in line with his own situation. In this way, each reader is offered the limited ability to tailor the cost projections to fit the needs of his problem.

Engineering Parameter Variations

Having generated a base-case cost estimate, the next rule spells out the need for the analyst to examine the effect on cost from changes in key engineering parameters. In other words, what deviations from the base-case assumptions will lead to significant increases or decreases in final costs? At the minimum, this analysis should offer the reader a short narrative which details the effect these alternative assumptions can have on the base-case. When the opportunity presents itself, the analyst is encouraged to conduct a numeric sensitivity analysis which will demonstrate the degree to which these changes can impact costs. The identification of these key parameters is a task best left to the judgment of the Agency's Project Manager. His goal is to apply the insights gained from the demonstration to the question of cost so that the reader will have enough information to ask intelligent questions concerning cost.

Market Forces

The final guideline attempts to address the problems that are created by the Program's interaction with market forces. As earlier portions of this paper have pointed out, the Agency needs to be sensitive to the fact that corporations will employ different strategies as they pursue the goal of commercializing their technologies and maximizing profit. The U.S. EPA cannot (and should not) factor these strategies into its cost projections. How does the Agency assist the developer's attempts at commercialization when it needs to remain at arms' length from that developer? The solution is to provide each developer with a forum to present his own cost analysis. This process is accomplished by setting aside a chapter just for the vendor's comments within the "SITE Technology Application Analysis."

In practice, the developer is given a chance to review and comment on the draft versions of the "Application Analysis." While the developer is free to offer criticisms regarding any of the Report's findings, the Agency is under no obligation to change the results of its evaluation. Instead, the developer is asked to prepare a chapter for the "Application Analysis" in which he is able to state his case, free from the U.S. EPA's editorial control. This means that the vendor has an opportunity to present a cost analysis which should implicitly account for all the market forces he perceives to be significant. In other words, the strategic viewpoint from which the vendor approaches the market will form the basis for his cost projections. In the end, the "Application Analysis" presents the reader with two different perspectives on the technology's cost-effectiveness. By comparing the developer's cost projections with the U.S. EPA's, the reader should be in a better position to determine the true range of future costs.

Cost Analysis Summary

In review, the five rules which govern the conduct of each SITE cost analysis are as follows:

- Place each base-case cost analysis within a common framework of 12 cost categories
- Present each base-case cost projection as "Order-of-Magni-

tude'' estimates (+ 50% and - 30%)

- Provide full disclosure of all assumptions and calculations used in the base-case analysis
- Identify key operating parameters which are likely to have significant cost implications beyond the base-case
- Offer developers the opportunity to present their own cost analysis

CONCLUSIONS

No methodology will insure that projected costs can be calculated with the same degree of precision as engineering or chemical data can be. When one combines the imprecise nature of cost-estimating with the heterogenous condition of Superfund sites

and the unanticipated problems one is likely to encounter working with new technologies, one must be prepared to accept the fact that the cost projections will be imperfect. However, cost data which will give decision-makers meaningful insights into the relative cost-effectiveness of new and innovative Superfund technologies can be prepared.

REFERENCES

1. *The Superfund Innovative Technology Evaluation Program: A Report to Congress*, EPA 540/5-88/001, U.S. EPA, Washington, DC, February, 1988.
2. Humphreys, K.K., *Project and Cost Engineers' Handbook*, 2nd Ed., pp. 51-53, Marcel Dekker, New York, NY, 1984.

Use of a Geographic Information System in Selecting Residential Properties for Remediation at the Bunker Hill NPL Site

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ABSTRACT

A Geographic Information System (GIS) was used to rank and select residential properties for remediation in a removal project at the Bunker Hill NPL Site. This site encompasses a 21-mi² area surrounding a defunct primary lead-zinc smelter in northern Idaho. Approximately 5,000 people live in the area. More than 1,000 home yards are contaminated with soil lead levels exceeding 500 ppm. More than 75% of these home yard soils exceed 1,500 ppm.

The GIS served an initial inventory function. For each of 3,000 individual properties, basic data were encoded to a relational data base. The primary information included: (1) legal and ownership data obtained from county tax records; (2) childhood health and census data and (3) sampling data.

Each property attribute was location-coded and a base map of all properties was created from the tax records. Specific uses of the GIS in the removal ranking process included: notifying owner/resident and verifying data using mail-merge options; identifying populations at risk; ranking risk according to sampling results; characterizing neighborhoods according to aggregate risk and population characteristics; identifying candidate properties for removal; and preparing exhibits for public meetings and discussions. The GIS proved to be an efficient tool in performing a variety of tasks related to selecting and ranking properties for remediation.

INTRODUCTION

Site Background

The Bunker Hill NPL Site encompasses a 21-mi² area surrounding a primary lead/zinc smelting complex in Northern Idaho. Smelter operations shut down in 1981. The industrial complex has since been salvaged through unregulated activities and is rapidly deteriorating. Large waste piles, dilapidated buildings and defunct industrial process equipment litter the 365-ac smelter complex site. The study area is located in a deep narrow, sub-alpine river valley in the Northern Rocky Mountains (Fig 1). Years of sulfur dioxide abuse have left many of the hill-sides denuded and subject to severe erosion. On the valley floor, massive impoundments of mine wastes and major deposits of unconfined tailings dominate the flood plain and major hydrologic drainage system. Four incorporated cities, home to a population of more than 5,000, are found within the site boundaries.^{1,2}

This area was the scene of epidemic lead poisoning in children during the 1970s. More than 75% of the area's children exhibited excess blood lead absorption in 1974^{3,4}. These poisonings were largely associated with environmental lead contamination resulting from uncontrolled smelter emissions. More than 1,000 children experienced lead levels in excess of current Centers for Disease Control (CDC) health criteria during the 1970s⁵. In 1983, 2 yr after smelter closure, community-wide testing revealed that 25% of the preschool children in the most contaminated residential areas continued to have blood lead levels above the CDC criteria⁶.

Subsequent studies linked this excess absorption to contaminated soil and dust exposures in the community. More than 1,000 homes have yard soil lead levels exceeding 500 ppm. Seventy-five% of those yards exceed 1,500 ppm, with 47% greater than 2,500 ppm. Housedusts as high as 52,700 ppm lead have been measured and average 3,400 ppm in the most contaminated residential area.

As a result of these studies, the Bunker Hill Site was placed on the NPL in 1983. In 1985 a large multi-phase RI/FS commenced and several expedited response activities have been undertaken.

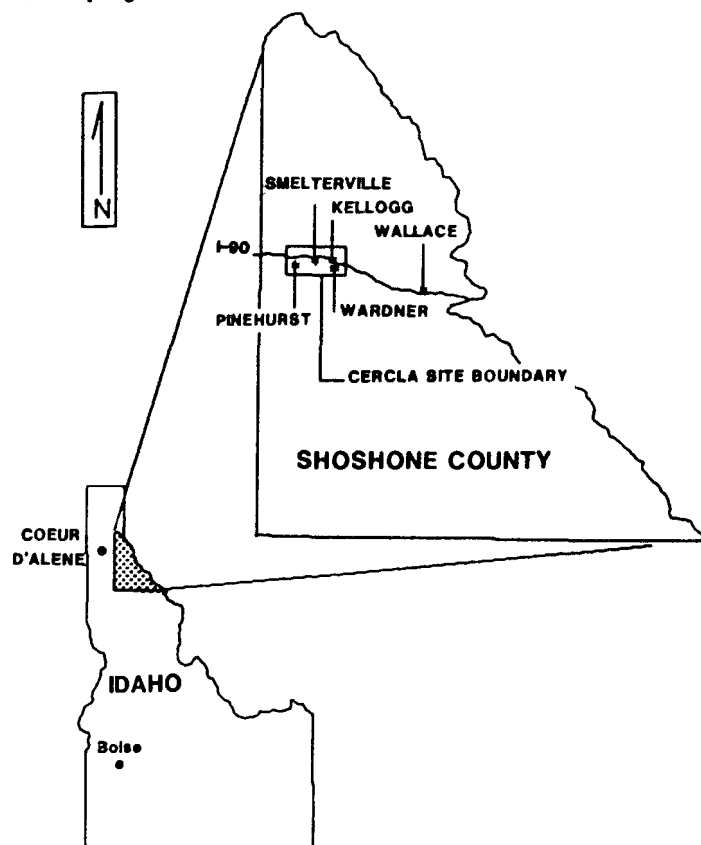


Figure 1
Bunker Hill NPL Study Area

RI/FS and Response Actions

The structure of the RI/FS and Response Action activities reflect the complexity of this site. The overall project is managed by Region X, U.S. EPA, with major investigation responsibilities delegated to the State of Idaho in the populated areas of the site and to the PRPs in the non-populated areas. The U.S. EPA exercises oversight responsibilities in both cases. The major portions of the PRP effort include the smelter complex, denuded hillsides, waste piles and tailings impoundments, groundwater problems and the river and floodplain system. The State's responsibilities encompass the health-related and private property-ownership issues. These include two major efforts: (1) an RI/FS to investigate contaminated soils, homes and features in the populated areas and (2) a health intervention program to reduce lead absorption through a combination of testing, followup and education response actions until source control measures can be implemented.

Several expedited response actions also have been implemented to reduce exposures. In 1985, an aggressive public health intervention program was undertaken to reduce excess absorption among young children in the community. The program included door-to-door testing of children for elevated erythrocyte-protoporphyrin (EP) levels, follow-up testing for blood-lead home visits and parental counseling for the families of children who had elevated blood leads. Additionally, public education programs were instituted with schools, community service organizations and health professionals. These programs stress the preventative hygiene, behavioral and home environment modifications that can effectively reduce lead absorption in young children.

In 1986, a removal action was instituted to reduce soil and fugitive dust exposures on publicly owned and accessed areas of the site⁷. Soil removal and replacement, seeding, sodding, cover and dust control efforts were instituted in parks, playgrounds, schoolyards and street berms. These efforts substantially reduced exposures in common areas accessible to community children. The combination of testing, education program and remedial measures was quite successfully reduced the prevalence of excess absorption. The percentage of children exhibiting excess absorption declined from 25% in 1983 to 2% by 1986. However, area participation rates for the important testing portion of the program had decreased by one-third in the 3 yr from 95% coverage in 1985 to 65% in 1987⁸. There was significant concern that the effectiveness of the screening program was compromised by the low participation rate. Informal community surveys revealed that the success of the program (i.e., individuals believing the problems had been solved) and public frustration regarding the pace of cleanup were

resulting in a growing complacency in the community. Of greater concern, was the fact that many of those who were dropping out of the program were from socioeconomic groups at higher risk of lead poisoning.

As a result, a decision was made to expedite cleanup of private properties where there was a high risk of lead poisoning to young children. A removal project was scheduled to begin in the summer of 1989. In addition to designing the remedial action, there were great logistic and informational challenges in initiating the removal. Those challenges included determining cleanup criteria; informing the public; contacting owners; determining which homes to remediate; securing access agreements with owners and residents; and implementing the project in the most health protective, efficient and cost-effective manner.

The Geographic Information System (GIS) data base management strategy developed for this project assisted the various agencies involved in accomplishing these tasks. This paper discusses the development of the populated areas data base and its use in helping to rank and select properties for expedited response actions during a 1989 soil removal project.

DATA BASE MANAGEMENT/THE GIS

In implementing such an involved project structure on this complex site, the U.S. EPA recognized the need for effective information management. At the beginning of the project, a determination was made to employ a GIS-based strategy. That system was briefly described in an earlier HMCRI conference⁹. This system has been used extensively in the populated areas to integrate health, population and property-related data bases for risk assessment, inventory and notification purposes.

Methods/Data Base Development

The GIS Data Base contains two principal components. The Base Map is the vector data base that provides spatial reference for each piece of information. The Attribute Files contain the scalar data or descriptive information about a location. Attribute files are maintained in a relational data base with a location-specific reference to the Base Map.

Base Map

The Overall Base Map encompasses the site as a 3 X 7 mi rectangle centered on the smelter complex (Fig 2). The populated portions of the study area are maintained as a series of sub-unit base maps representing each town. Each sub-unit serves as an inlay to the overall site base map. These maps were digitized from the County property tax inventories. Shoshone County properties are tracked by parcels assigned

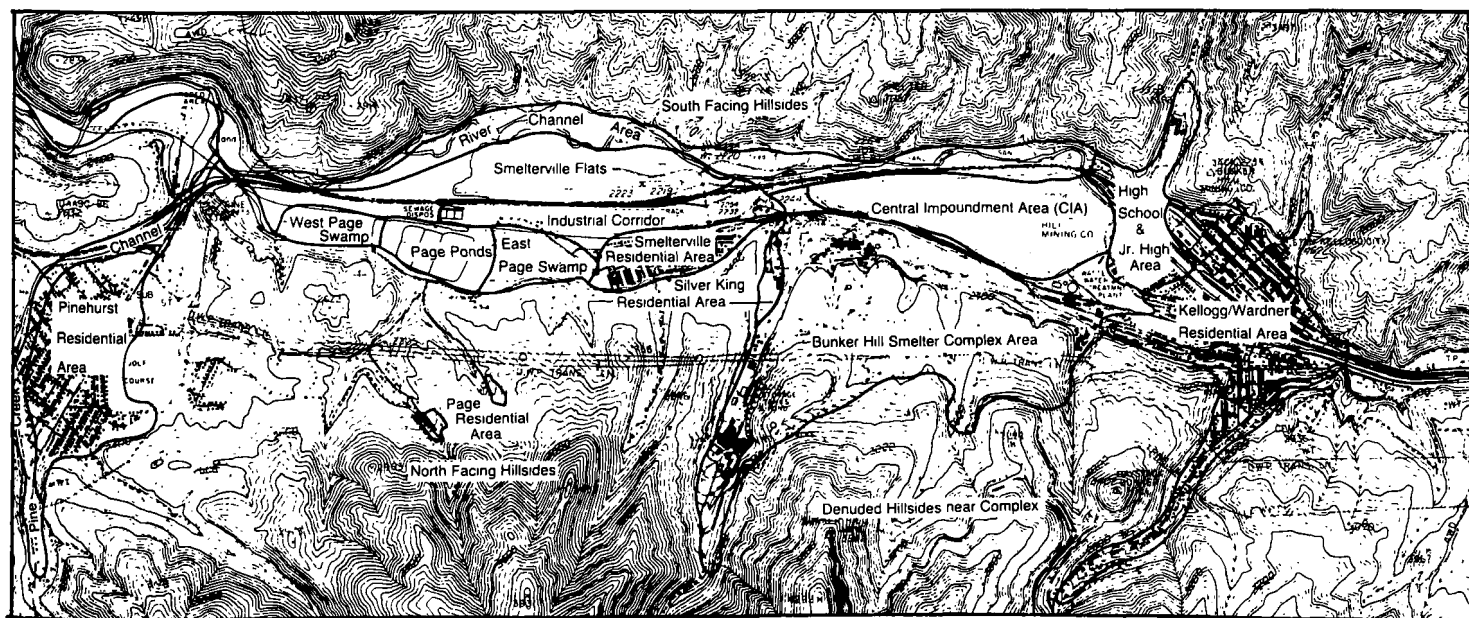


Figure 2
Bunker Hill GIS Base Map

unique identification numbers per a sub-division, block and lot hierarchy. All local government information pertinent to that parcel is indexed to the Property ID Number.

Attribute Files

Attribute files are maintained in ASCII format indexed to the Property ID Number. Three types of attribute files were developed for this effort. Those are County Tax Records, Health Census Data and Sampling Regime Results.

County Tax Records¹¹ provide ownership details and legal descriptions of the property. The County maintains these files by Property ID Number. Health Census Data¹² have been collected as part of the Health Intervention Program described above. All homes in the health surveys are coded by a Block*Lot* Unit hierarchy analogous to federal census techniques. These files were cross-referenced to the Property ID Number and converted to a property-specific data file.

Several Sampling Regimes^{11,12} have been undertaken at this site. The most extensive was the 1986 Residential Soil Survey effort in which surface soil sampling was offered to each property owner in four of the site's five residential areas. This survey was designed using the GIS data base.

A base map of each property was generated showing the Property ID Number. Fig 3 shows the map for the City of Smelterville. These maps were sub-divided into block maps (see inset Fig 3) used by field crews when interviewing residents and securing permission to sample yards. These data were merged with the County Tax Records and used to provide sampling assignments and track field crew progress. Information secured through questionnaires administered and protocols completed during the survey were then indexed with sample results to the Property ID Number. This resulted in attribute files containing the information shown in Table I.

Other, less extensive, sampling regimes have been accomplished at the site. These are indexed to the Property ID Number and can be accessed by the GIS and include: deep-core soil profiles; housedusts; historical health, environmental and garden vegetable surveys conducted in 1974, 1975, 1977 and 1983.

Table I
Data Base Attribute File Summary

Data Set	Description	Source
County Tax Records (1988 update)	Property ID Number, ownership name and address, lien holder, property address, zoning, landuse and legal description	Shoshone County Tax Assessor
Health Census Data (1974, 1975, 1983, 1986, 1988)	Property ID Number, resident's name, address and telephone number, number and ages of children, results of sampling (blood lead EP, Zn EP), household and yard conditions, parent education and income, smokers, child behavior (outdoor play time, dietary vitamins, oral behavior) and school attended	Parhandle Health District
Sample Records (1974, 1975, 1983, 1986, 1989)	Property ID Number, resident name and address, results of soil, litter and housedust metals sampling (Pb, Cd, Zn, As, Se, Mn, Cu, Sb), sample crew, resident response, sample date, bank date, lab sample number, sample type, and lab transfer	Parhandle Health District

GIS Capabilities

The combination of base maps and attribute files provides a complete and comprehensive summary of the information available for each property on the site. GIS utilizes these data to perform four key functions common to data base management: inventory, tracking, analysis and display. The principal advantages inherent in GIS are that each piece of information is systematically indexed in space and time. That requires that all data be reduced to a common format and meet minimum quality control criteria. That function, alone, is valuable for data inventory purposes in a project involving five major agencies and a dozen contractors compiling data and performing analyses.

The structure also provides for ease of updating and tracking. New data can be added by substituting or adding attribute files. For example, the County Tax Records are updated each year as the new tax roles are prepared. Residents are tracked annually through the Health Surveys and the data base is updated by substituting new information.

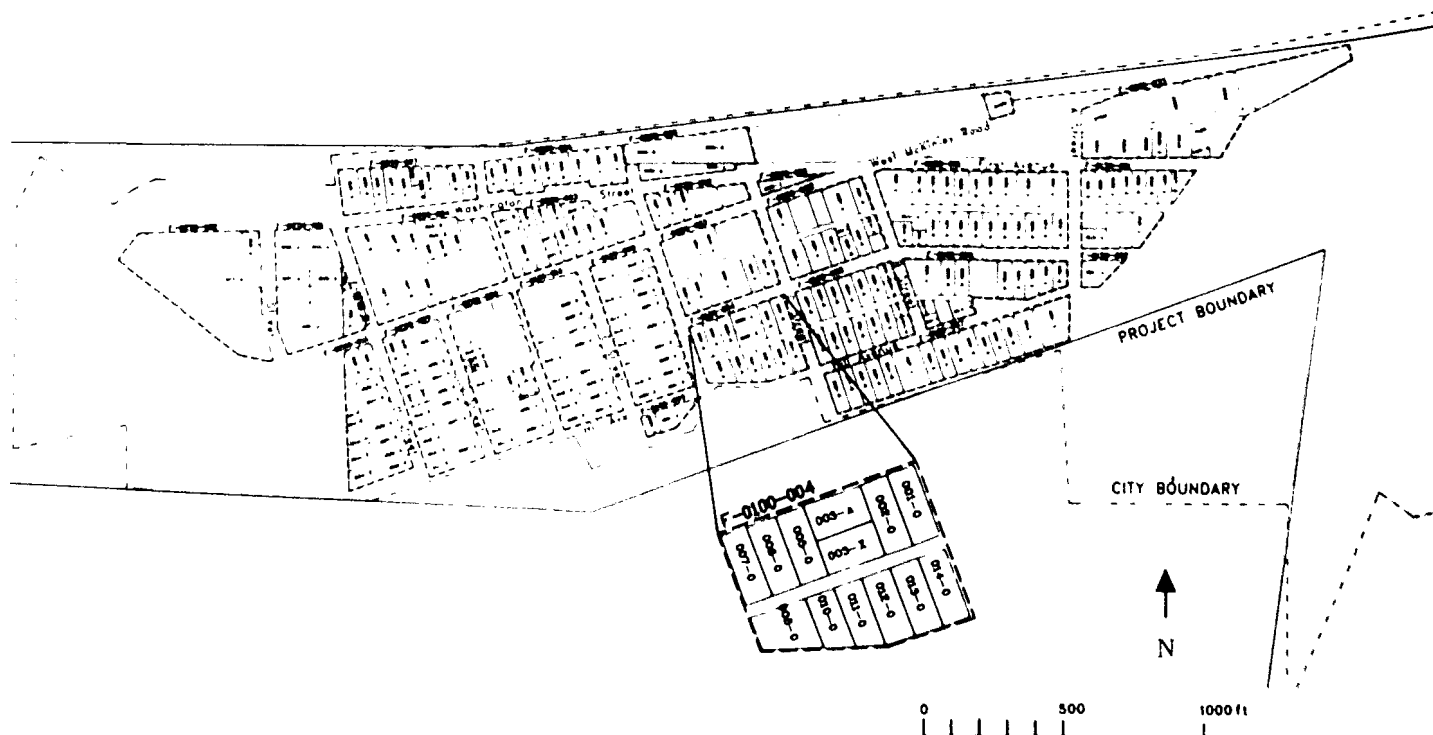


Figure 3
City of Smelterville Resident Property Map

New sampling regimes are appended as separately accessible files.

The greatest advantages associated with GIS, however, are analytical capabilities. The GIS offers a "tool box" of map analyses which may be grouped into the four categories described below:

- **Reclassification functions** create new maps by assigning new values to existing maps. Reclassification values can be based on the position, size, shape, or initial value of the original map's categories. For example, properties with soil lead levels less than 500 ppm could be reclassified into a map showing areas of "acceptable risk."
- **Overlay functions** are used to create new maps based on point-by-point or area relationships between independent maps of the same area. For example, a map delineating private properties with; (1) excess lead levels and (2) young children can be generated from individual maps representing each of the categories.
- **Distance and connectivity operations** include measurements of simple distance, perimeters, areas and volumes. These procedures are also expanded to include the concepts of proximity and connectivity (e.g., identifying equidistant zones of proximity to a smelter).
- **Neighborhood characterization** involves creating maps as a function of an independent value within a specific area or cartographic neighborhood of a location. The first step is defining the cartographic neighborhood. For example, the neighborhood might be all "downwind" locations within .5 mi of a smelter. Numerous maps then describe categorical values within the defined neighborhood such as mean childhood blood lead levels or number of children to exceed CDC health criteria.

By organizing these four general analytic processes sequentially, higher techniques of map analysis, called cartographic modeling, can be developed to perform more complex analyses. Cartographic modeling provides flexibility, "what if" analyses, rapid simulation of various strategies, optimization and effective communication through flow charting, while documenting the factors and assumptions used in the decisionmaking process.

GIS USE IN THE 1989 RESIDENTIAL REMOVAL

GIS analyses served five basic functions in the 1989 Home Yard Soil Removal Project. Each of those functions is briefly discussed below.

Data Verification and Owner/Resident Notification

Health agencies had a responsibility to notify homeowners and residents of the data collected, provide interpretation of sampling results and communicate the risk involved. Many of the data are confidential, requiring individual summaries and notification letters. As more than 1,500 homes were involved, this was an onerous task. The relational data base aspects of the GIS were exploited to prepare individual property summaries containing the ownership, childhood census, sample results and risk indices obtained for that property. Fig 4 shows a sample Property Summary Sheet.

Data were also extracted from the data base to provide name, address and key variable files for input to conventional mail-merge software. Individual data were substituted into mailing labels and master letters that explained the form and risk indices, asked recipients to provide updated information and invited them to attend public information forums.

Providing Master Lists and Maps for Project Managers

Each notification letter and summary form was tailored to the individual recipient. Several confidentiality issues were involved. For example, only owners and residents could obtain sample results, property owners did not receive confidential information about their tenants, individual data were not released publicly, etc. Owner-occupied residents received a different letter than renters. Owners, whose tenants had refused to have samples collected, were similarly notified.

Project managers and health response personnel, on the other hand, require complete summaries and maps of all results. Confidential Property Summary Sheets containing *all* data for each property were prepared for select project personnel. The reclassification functions of GIS were used to develop a number of maps for confidential project

CONFIDENTIAL: NOT TO BE RELEASED ¹									
BUNKER HILL SITE SUPERFUND REPORT									
PROPERTY SUMMARY									
DATE COMPLETED 01NOV88									
PROPERTY ID #		F-0100-007-013-0						14223	
OWNERSHIP / LEGAL INFORMATION									
OWNER:		JOHN SMITH							
ADDRESS:		100 MAIN STREET							
CITY:		DENVER, CO 55555							
LEGAL DESCRIPTION		LOT 13				INST 322789			
		BLK. 7 S.1. 35				FLG 0 0 0 0			
		SMELTERVILLE 1ST ADD				RES 00203 HILL			
		SMELTERVILLE				MKS 07/16/86			
LAST RESIDENCE CONTACTS									
CHILDHOOD CENSUS		NR		8/86					
RESIDENT		BOB DOE				# CHILDREN		2	
		203 HILL				# PRESCHOOL		1	
		SMELTERVILLE		ID 83868					
YARD SAMPLING									
RESIDENT		BOB DOE				RESPONSE		YES	
		203 HILL				SAMPLE COLLECTED		10/01/86	
		SMELTERVILLE		ID 83868					
COMMENT		WANTS GARDEN TEST							
SAMPLING INFORMATION									
DATE OF SAMPLING		10/01/86							
RESIDENT		BOB DOE							
		203 HILL							
		SMELTERVILLE		ID 83868					
SAMPLE TYPE		SOIL				LAB #		T 4321	
RESULTS		LEAD		ZINC		CADMIUM		ARSENIC	
MG/KG		5839		746		19		57	
								ANTIMONY	
								COPPER	
								PH	
								5.3	
SAMPLE TYPE		SOIL DUPLICATE				LAB #		T 4322	
RESULTS		LEAD		ZINC		CADMIUM		ARSENIC	
MG/KG		3780		629		15		64	
								ANTIMONY	
								COPPER	
								PH	
								5.1	
SAMPLE TYPE		LITTER				LAB #		M 5432	
RESULTS		LEAD		ZINC		CADMIUM		ARSENIC	
MG/KG		4070		1390		48		62	
								PH	
								5.6	
SAMPLE TYPE		LITTER DUPLICATE				LAB #		M 5433	
RESULTS		LEAD		ZINC		CADMIUM		ARSENIC	
MG/KG		3410		1277		42		70	
								PH	
								4.6	
SUB-CHRONIC HAZARD INDEX									
FOR LEAD IN YARD SOIL = 5.8									
¹ Fictional data for display only									

Figure 4
Example Property Summary Sheet

use. These maps were similar to Fig 5 except sample concentration and health survey attributes were substituted for lot ID #s. These maps included such items as:

- Top-inch Soil Metal Levels - As, Pb, Zn, Cd, Sb, Hg, Cu
- Litter Metal Levels - As, Pb, Zn, Cd, Sb, Hg, Cu
- Soil and Litter Lead Hazard Indices (Color Coded)
- Children's Blood Lead Levels
- Sample Status (i.e., whether sites had been sampled, owners contacted, etc.)

These series of summary sheets and maps allowed project managers to quickly access and evaluate individual data when dealing with residents and parents.

Public Display and Risk Communication

For public presentation it was necessary to use maps and displays that contained no identifiable individual results. GIS neighborhood functions were used to prepare non-confidential maps for risk communication purposes in public meetings. Neighborhoods were defined and summary statistics were developed. Fig 5 shows the results for Smelterville. Table 2 shows one of the inset summary tables from this map. There are 88 homes in this sub-division; 70 of these homes were sampled. A Sub-chronic Hazard Ranking (SHR), (soil lead level divided by 1,000), was developed to describe to residents how their soils compared to proposed national criteria. The average for this area was 3.7

(i.e., 3,700 ppm). Comparing data in Table 2 to the risk criteria shown in Table 3 shows that 3% of the homes had acceptable soil concentrations, 7% were recommended for individual consideration and 90% were candidates for remediation.

Table 2
Summary Table for Smelterville

F-0100	
Smelterville 1st Addition	
# resid	88
# sampled	70
Average SHR	3.7
SHR < 0.5	3%
SHR 0.5 - 1.5	7%
SHR > 1.5	90%

Ranking Properties for Remediation

The 1989 removal suggested that resources were available to remediate about 100 homes. Reclassification, overlay and neighborhood functions were used to help select which properties should be remediated.

Table 3
Sub-chronic Hazard Rank Criteria for Yard Soil Lead Levels (ppm)

SHR	Soil Lead (ppm)	Risk
< .5	< 500	Acceptable
.5-1.5	500-1500	Marginal
> 1.5	> 1500	Unacceptable

Pre-school children and pregnant women are those groups at greatest health risk from lead absorption. Reclassification functions substituting health census data were used to develop maps of homes where young children or pregnant women resided. Using overlay functions, these maps were then intersected with the risk indices maps to yield output maps of "high risk residences."

Neighborhood functions were then used to assess "cleanup zones." The original removal strategy was a zonal approach, where cleanup would be accomplished in particular areas of towns. Construction techniques that isolated entire blocks, kept equipment in single areas or accomplished block-long removals followed by replacements were among the several logistic considerations that made cleanup zones a favored approach.

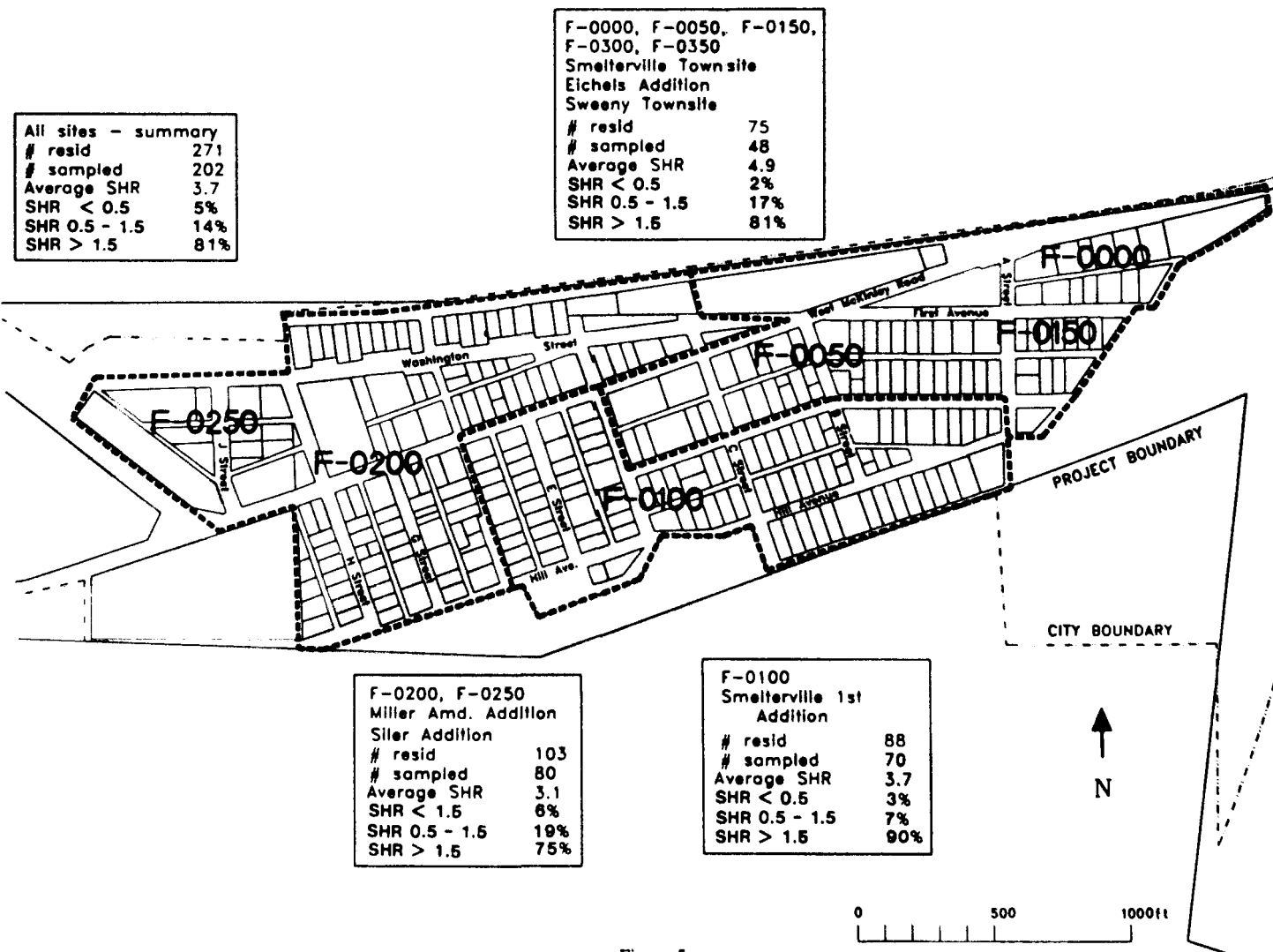


Figure 5
City of Smelterville Summary of Sampling and Sub-Chronic Hazard Ranking (SHR)

GIS neighborhood functions are particularly efficient in such analyses. Potential cleanup zones were defined as any 100 contiguous lots and summary statistics were produced for each possible combination. These analyses showed that no single 100 unit area would address more than 11 homes having preschool children. No more than 21 homes would be affected if the definition of the risk group were extended to children under 9 years.

Because of the small number of children impacted, zonal strategies were rejected. The second evaluation examined all possible combinations of non-contiguous blocks. This methodology resulted in a best combination including 20 homes (out of 100) having pre-school children present.

Based on these findings, the cleanup "zone" strategy was abandoned. U.S. EPA, Agency for Toxic Substances and Disease Registry (ATSDR) and State Health officials opted for a house-by-house strategy that targeted young children and pregnant women. This was precisely the "map of high risk residence" developed above. However, the problem of ranking these homes remained. In this case, that was accomplished by overlaying the high risk residence map over the soil lead concentration map and ranking the properties by lead concentration. An output file containing the information shown in Fig 6 was produced for all high risk homes. These data were used to contact homeowners and residents and initiate removal activities.

<u>Property ID</u>	<u>Owner Name</u>	<u>Owner Address</u>	<u>Owner City</u>	<u>Resident Name</u>	<u>Resident Address</u>	<u>Resident City</u>
D-1010-001-005-0	John Doe	1480 Main	Kellogg	John Doe	1480 Main	Kellogg
D-0010-018-002-A	Bill Smith	510 Howard	Kellogg	Fred Jones	115 Hill St	Kellogg
F-0550-001-015-0	Joe Willis	812 F St	Boise	Carol Miller	817 Main St	Smelterville

<u>Property ID</u>	<u>Blood Lead (ug/dl)</u>	<u>Sample Results Pb (ppm)</u>		
		<u>Soil</u>	<u>Litter</u>	<u>Dust</u>
D-0100-001-005-0	40	13400	9660	5240
D-0010-018-002-A	33	9820	8370	2480
F-0550-001-015-0	30	8330	10500	4550

(1) Fictional data for display only

Figure 6
Sample Listing of Prioritized High Risk Homes¹

Tracking Remedial Progress

Several steps are involved in accomplishing remedial activities on these properties. Both homeowners and residents must be contacted and permission must be obtained. The remediation must be negotiated and completed and there is provision for continued monitoring of both the environment and the residents. All of these functions can be easily tracked as attribute files in the GIS. This will aid in recordkeeping, providing progress maps and logistic assistance in future remediations.

CONCLUSIONS

GIS proved to be a valuable tool in several aspects of the 1989 yard soil removal project. The overall data base was accessed to provide a mechanism for contacting the nearly 3,000 affected homeowners and residents. These contracts served a dual notification and data verification purpose. The system was then used to produce non-confidential data displays for risk communication in public forums and detailed confidential maps and summaries for project personnel to use in individual consultations.

Cartographic analysis techniques were then used to rank properties for remediation based on land use, susceptible populations and soil contaminant levels. These results were used to assess and select remedial strategies based on health risk and logistic criteria. The GIS will also be used to track remedial progress. These multiple tasks and inventory functions demonstrate the utility and flexibility of GIS in projects of this type.

REFERENCES

1. Woodward Clyde Consultants and TerraGraphics, *Interim Site Characterization Report for the Bunker Hill Site*, EPA Contract No. 68-01-6939, Walnut Creek, CA, Aug. 4, 1986.
2. Dames & Moore, *Bunker Hill RI/FS: Data Evaluation Report*, Mar. 16, 1988.
3. Yankel, A.J., von Lindern, I.H. and Walter, S.D., *The Silver Valley Lead Study: The Relationship Between Childhood Blood Lead Levels and Environmental Exposure*, JAPCA 27, pp. 763-767, 1977.
4. Wegner, G., *Shoshone Lead Health Project Summary Report*, Idaho Department of Health and Welfare, Boise, ID, Jan. 1976.
5. Jacobs Engineering Group, Inc. and TerraGraphics, *Final Draft Endangerment Assessment Protocol for the Bunker Hill Superfund Site*, U.S. EPA Contract No. 68-01-7531, Feb. 1988.
6. Centers for Disease Control, *Kellogg Revisited—1983 Childhood Blood Lead and Environmental Status Report*, 1986.
7. Roy F. Weston, *Federal On-Scene Coordinator's Report Bunker Hill Initial Removal Action Kellogg, Idaho*, U.S. EPA Contract No. 68-01-6669, May 28-June 25, 1986.
8. Panhandle Health District, *Summary Report 1988 Lead Health Screening Program*, Silverton, ID, Sept. 1988.
9. von Lindern, I.H. and von Braun, M.C., *The Use of Geographic Information Systems as an Interdisciplinary Tool in Smelter Site Remediations*, *Proc. Natl. Conf. on Management of Uncontrolled Hazardous Waste Sites*, Washington, pp. 200-207, HMCRI, Silver Spring, MD, pp. 200-207, 1986.
10. Shoshone County Tax Assessor, *1988 Update of Property Owner Files*, Wallace, ID, June 1989.
11. TerraGraphics, *1986 Residential Soil Survey Status Report*, Contains Confidential Data, Dec. 31, 1986.
12. TerraGraphics, *Bunker Hill Site RI/FS, Soils Characterization Report*, Dec. 31, 1986.

Application of the Observational Method to an Operable Unit Feasibility Study—a Case Study

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ABSTRACT

The observational method, developed for application in the field of geotechnical engineering by R.B. Peck, has been applied to the Whittier Narrows Operable Unit Feasibility Study (OUFS). The observational method, a means of engineering under uncertainty, presents opportunity for potential savings in project time and costs. Recent U.S. EPA guidance has proposed implementing this "Streamlined Approach" as a way to improve the Superfund RI/FS process. The key components to the observational method are described and illustrated by case example in this paper.

The Whittier Narrows OUFS is part of the San Gabriel Basin Superfund site RI/FS. Groundwater is only known to leave the approximately 200 mi² San Gabriel Basin, located in northeast Los Angeles County, California, through the 1.5-mi-wide Whittier Narrows. The purpose of the Whittier Narrows Operable Unit is to control the migration of contaminated groundwater out of the San Gabriel Basin. Remedial alternatives presented and evaluated in the Whittier Narrows OUFS incorporate technologies for groundwater extraction, treatment, treated water use and monitoring.

Data from a limited site investigation were used to formulate a working hypothesis of the most probable site conditions and the maximum credible deviations to those conditions. Alternatives were developed to address both potential site conditions. In addition, general response actions to potential deviations are presented for each remedial alternative. Cost ranges based on the most probable case and the maximum credible deviation case are presented for each alternative.

The greatest challenge in applying the observational method to the Whittier Narrows OUFS revolved around developing response plans for the maximum credible deviation case. The maximum credible deviation case is not a "worst case" scenario. It is based on an evaluation of the uncertainty in the extent of contamination, the types of contaminants and their concentrations, and the hydrogeologic parameters that govern contaminant transport. However, if potential deviations to every parameter that affects a remedial alternative are considered to occur simultaneously (i.e., compounding uncertainty), the required response is unrealistic. For the Whittier Narrows OUFS, potential deviations to the three-dimensional extent of contamination and respective contaminant concentrations (the parameters with the greatest uncertainty and the greatest effect on potential remedial actions) are used as the basis for the maximum credible deviation case. That is, by developing response plans to address potential deviations to the nature and extent of contamination, it is expected, in this

case, that deviations to the other parameters that affect contaminant migration can be managed with the same response.

In applying the observational methods to an OUFS involving several parameters that could affect a remedial action (groundwater flow conditions, contaminant types and concentrations, extraction rates, etc.), it became apparent that a high number of possible combinations of deviations could occur. Thus, it is not practical to define specific responses to deviations for each alternative. Instead, general response actions for the main components of each alternative (e.g., extraction, treatment, water disposal and monitoring) are presented along with design considerations to facilitate modification. In the design phase, however, specific plans for monitoring to detect potential deviations and for subsequently modifying the remedial action will be developed.

INTRODUCTION

The Whittier Narrows Operable Unit is part of the San Gabriel Basin RI/FS. The San Gabriel Basin, a 170-mi² groundwater basin, is located in northeast Los Angeles County (Fig. 1). Groundwater is the primary source of drinking water for the more than 1,000,000 residents of the San Gabriel Valley. Extensive volatile organic compound (VOC) contamination prompted the U.S. EPA to place the San Gabriel Basin on the NPL.

Whittier Narrows is a 1.5-mi-wide gap in the hills which serves as the boundary between the San Gabriel Basin to the north and the Central Basin to the south (Fig. 1). Groundwater is only known to flow out of the San Gabriel Basin through Whittier Narrows. VOC contamination in and up-gradient of Whittier Narrows prompted the U.S. EPA to designate the Whittier Narrows area as an Operable Unit. The primary objective of the Whittier Narrows Operable Unit is to control the migration of contaminated groundwater from the San Gabriel Basin, through Whittier Narrows and into the Central Basin.

In accordance with the NCP, a Draft Operable Unit Feasibility Study (OUFS) for Whittier Narrows has been prepared. The Draft Whittier Narrows OUFS was released for public review in fall of 1989. A ROD is expected in early 1990.

APPROACH—OBSERVATIONAL METHOD

An approach to remediation that is demonstrated in the Whittier Narrows OUFS to be more efficient and timely than the current process for Superfund site remediation is proposed for the Whittier Narrows Operable Unit. This approach, referred to as the observational method (recently coined the "Streamlined Approach" by the U.S. EPA), has been adapted from similar

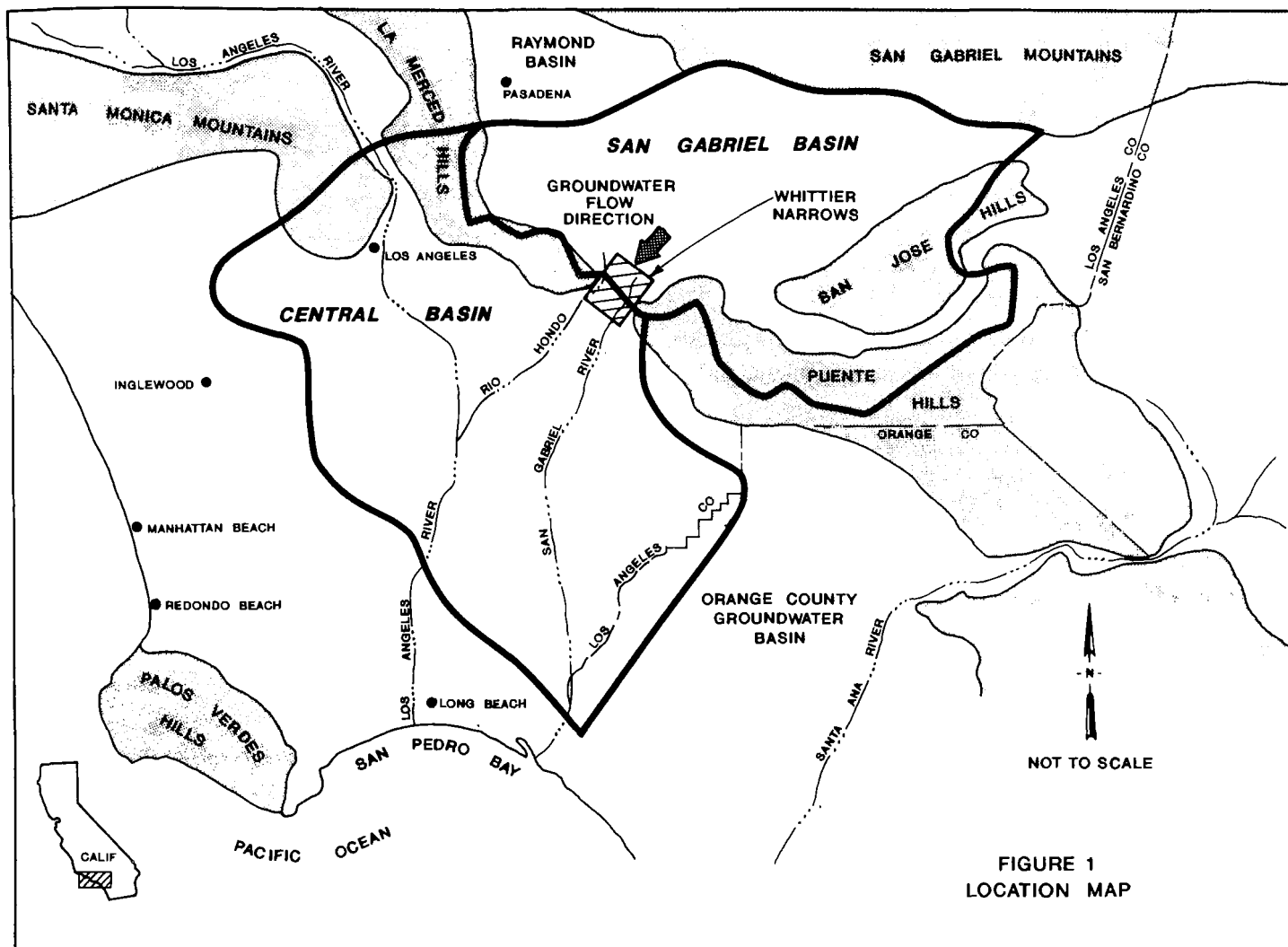


Figure 1
Location Map

methods developed for engineering under uncertainty in the geotechnical field. This application of the observational method is demonstrated in the Whittier Narrows OUFs to be consistent with CERCLA/SARA, the NCP and U.S. EPA guidance for remediation. The method provides a logical and consistent integration of the RI, FS, ROD, Remedial Design (RD) and Remedial Action (RA) process.

The current Superfund process of remediation is based on the traditional "study-design-build" engineering project sequence. This process assumes that after the RI/FS is complete, residual uncertainties at a site are reduced to manageable levels. The observational method recognizes that while considerable time, expense and effort can be devoted to attempting to characterize the complex subsurface, residual site uncertainties can be significant; and monitoring and modifications to the remedial action are to be expected. Using this approach, remedial action activities may be initiated more quickly than with the traditional approach.

The complete application of the observational method embodies eight general ingredients. The term "ingredients" is used because they are not necessarily followed in a sequential manner. And, in fact, several of the ingredients are conducted iteratively. The eight ingredients of the observational method (according to Peck¹) are as follows:

- Evaluate existing data and conduct investigation sufficient to establish the general nature, pattern and properties of the physical setting and contamination conditions. The level of site

characterization depends on the site and the expected general response actions.

- Assess the most probable site conditions and maximum credible deviations from these conditions. The most probable site conditions are working hypotheses based on interpretation of available data and are not necessarily based on a statistical evaluation. The maximum credible deviations from the most probable conditions do NOT represent worst-case scenarios or maximum conceivable conditions, but credible conditions based on interpretation of existing data. If a reasonable working hypothesis of the most probable site conditions cannot be developed, additional remedial investigation may be required (i.e., the ingredient above).
- Evaluate alternatives and establish a remedial design based on the hypothesis of the most probable site conditions.
- Calculate or estimate the physical and chemical conditions expected to be observed during implementation and operation of the remedial action, given the most probable site conditions.
- Calculate or estimate the same parameters for the remedial action given maximum credible deviations to the most probable conditions.
- Select a course of action based on the most probable conditions, and prepare contingent design modifications for foreseeable maximum credible deviations.
- Construct and operate the selected remedial action, monitor the selected parameters and evaluate the observed conditions with

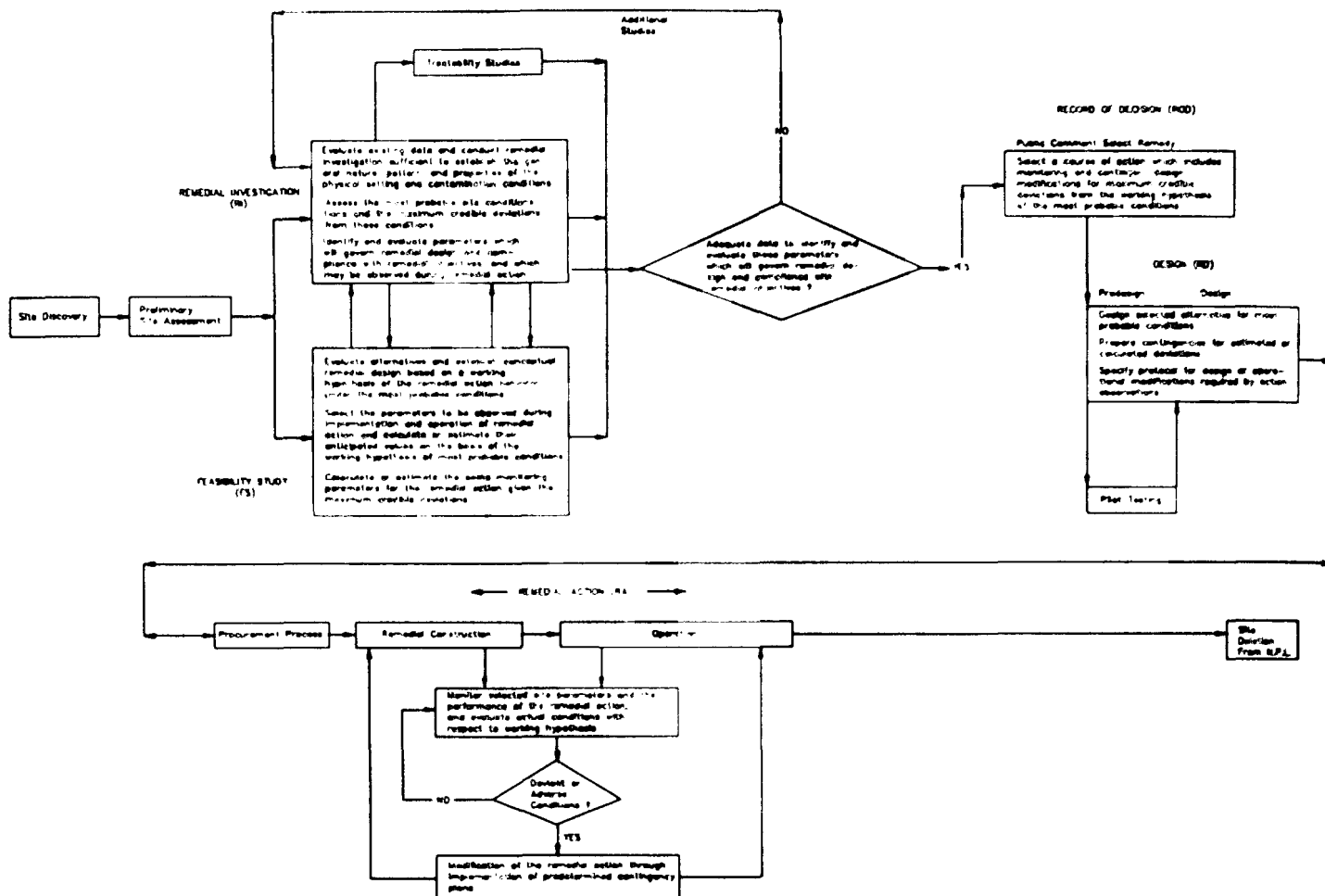


Figure 2
Application of Observational Method to
Superfund Remedial Process

respect to the working hypothesis of the most probable conditions and credible deviations.

- Modify the remedial action through the predetermined course of action to suit actual conditions, as required.

The general application of the observational method to the Superfund remedial process is illustrated in Figure 2.

The observational method offers distinct advantages to the timely and effective implementation of remediation in the presence of substantial uncertainty. In addition, by developing response plans, design modifications for deviations and a flexible initial design, required RA modifications resulting from observed deviations can be expedited.

The ramifications of using the observational method occur in almost every section of the Whittier Narrows OUFs. The site conditions and the nature and extent of contamination are described for most probable conditions and maximum credible deviations; and the uncertainty in developing these hypotheses is clearly spelled out. For the baseline risk assessment, a range of potential exposure point concentrations based on most probable conditions and credible deviations is estimated.

Remedial alternatives presented in the OUFs incorporate four main components: groundwater extraction, treatment, treated water use and monitoring. In this OUFs, these components are based on probable conditions. Also, modifications to the initial remedial action, in response to an observed deviation, are also presented for each component. For example, extraction options incorporate the estimated number and location of wells required to control contaminant migration given the most probable extent

of contamination. Additional wells and pumping rates are identified to respond to deviations, if they occur. For the treatment options, a required facility is determined from most probable conditions; and modifications to that facility to respond to potential deviations are identified. For example, in response to an observed deviation in influent VOC concentrations, a larger blower on an air stripping facility may be retrofitted to increase the air-to-water ratio and enhance the VOC removal rates. Such modifications are included in the cost estimate range.

Measures to facilitate implementation of modifications in response to deviations are also presented for the major components. For example, it is recommended that treated water distribution pipelines be sized and constructed with the capacity required for the maximum credible deviation case. It is expected to be more cost-effective in the long term to install the oversized pipelines rather than construct a smaller pipeline and have to tear up streets, remove the original pipeline and reinstall a larger pipeline, in, very possibly, the near future.

Remedial alternatives presented and evaluated in the OUFs are based on both most probable conditions and maximum credible deviations. Alternatives include initial remedial actions and modifications that may be required if maximum credible deviations occur. Thus, a range of cost estimates is presented for each alternative. As much flexibility as possible is incorporated into remedial alternatives.

The final section of the Whittier Narrows OUFs presents a generalized strategy for implementing the observational method. Specifically, a generalized approach for responding to observed

deviations, and flags that indicate modification to a remedial action component may be required, are presented. An implementation strategy is crucial to executing the observational method for several reasons. Primarily, deviations are likely to occur incrementally; and, thus, incremental modifications to some or all of the remedial action components would be expected to be required.

HOW THE OBSERVATIONAL METHOD IS INCORPORATED INTO THE MAJOR REMEDIAL COMPONENTS

There are four main components to potential remedial actions in Whittier Narrows:

- Groundwater Extraction
- Treatment
- Discharge of Treated Water
- Monitoring

How the Observational Method is incorporated into the evaluation of these components for the Whittier Narrows OUFS is discussed in the following sections. Applying the observational method, given the uncertainty in the numerous aspects of remediation, provided a significant challenge.

Groundwater Extraction

Factors affecting the groundwater extraction rate required to meet the remedial objectives are summarized as follows:

- Nature and Extent of Contamination
 - Types of contaminants
 - Horizontal extent
 - Vertical extent
- Groundwater Flow Hydraulics
 - Hydraulic conductivity
 - Specific yield (storage coefficient)
 - Porosity
 - Hydraulic gradient
 - Aquifer thickness
 - Pumping
 - Recharge (natural and artificial)
 - Basin boundary conditions (e.g., groundwater outflow)
- Contaminant Transport Parameters
 - Dispersivity
 - Retardation
 - Degradation

A working hypothesis of the most probable conditions with respect to the parameters listed above has been determined based on available data and numerical modeling.

A dilemma was encountered in estimating maximum credible deviations to the most probable conditions. Credible deviations are to account for uncertainty. However, compounding the uncertainty in a few of the parameters above, let alone all of them, results in conditions that are unrealistic (i.e., no longer credible). For example, the amount of extraction required to control contaminant migration, given combined maximum credible deviations to the extent of contamination and hydraulic conductivity, would result in extracting every single drop of groundwater that flows through Whittier Narrows (e.g., up to approximately 40,000 ac-ft/yr, or 25,000 gpm of continuous pumping 24 hr/day year-round).

Credible deviations to the parameters that have the greatest uncertainty and the greatest effect on required groundwater extraction schemes were evaluated individually (i.e., assuming most probable values for the remaining parameters). These parameters are as follows:

- Nature and extent of contamination
- Hydraulic conductivity
- Hydraulic gradient
- Storage coefficient
- Aquifer thickness
- Porosity

Of these parameters, the nature and extent of contamination and hydraulic conductivity have the greatest uncertainty and greatest effect on required groundwater extraction in Whittier Narrows. Deviations to contaminant concentrations, lateral extent and vertical extent have been evaluated. Hydraulic conductivity, which has the greatest effect of groundwater flow hydraulics, was evaluated using the mean absolute deviation to the over 100 calculated values of hydraulic conductivity for the area. Required groundwater extraction under the various conditions was evaluated using numerical modeling.

The estimated required pumping given maximum credible deviations to the nature and extent of contamination is approximately the same as the estimated pumping required under maximum credible deviations to hydraulic conductivity. And, as previously discussed, combining deviations to both parameters is unrealistic. For the Whittier Narrows OUFS, the required pumping given credible deviations to the nature and extent of contamination is used for a maximum credible deviation case. This increase in pumping due to deviation consideration represents up to a 41% increase in the required extraction over that required under most probable conditions.

Groundwater extraction schemes proposed in the Whittier Narrows OUFS are based on most probable conditions, with modifications (additional wells and/or higher pumping rates) for observed deviations. Observations that indicate modification to an extraction system may be required are discussed later.

Treatment

The following treatment technologies were incorporated into potential Whittier Narrows remedial alternatives:

- Stripping (packed tower, rotary and steam)
- Granular Activated Carbon (GAC) Adsorption
- Advanced Oxidation with Ozone/Peroxide

Influent flow rates (i.e., groundwater extraction) and contaminant types and concentrations were estimated for most probable conditions and the maximum credible deviation case. Each of the proposed treatment technologies would require modification for deviations. However, some technologies would require substantially more modification than others. A few examples of deviations, required modifications and design considerations to facilitate modification are briefly described below.

Treatment Technology	Deviation	Modification	Design Considerations
Stripping	Higher VOC concentration	Increase air: water ratio	Install variable-speed blower, or allow for replacement of blower
	Higher VOC concentration	Onsite carbon regeneration for off-gas	Oversize carbon beds on off-gas system, design for possible addition of facilities
	Higher Influent flow rate	Add stripping towers and carbon beds for off-gas	Design for additional towers to be added, adequate area at treatment plant site
GAC	Higher vinyl chloride concentrations	Replace GAC system (unable to adequately adsorb vinyl chloride)	Design alternate treatment system
Advanced Oxidation	Higher methylene chloride and/or carbon tetrachloride concentrations	Add post stripping with off-gas treatment (methylene chloride and carbon tetrachloride not adequately oxidized)	Design for additional facilities, adequate area at treatment plant site required

Observations that indicate modification to a treatment facility may be required are discussed later.

Water Discharge

Pipelines are proposed to distribute treated water to local distribution systems and/or points of recharge. Deviations to flow rates would be handled by expanding water distribution to additional local systems and/or by constructing injection wells.

Design considerations to facilitate modification to treated water distribution systems include oversizing pipelines where additional future capacity may be required. Constructing an oversized pipeline (i.e., sized for the maximum credible deviation case) would be less expensive than replacing a pipeline in the near future, especially in an urbanized area where pipeline construction involves digging up streets.

Monitoring Program

In applying the observational method, a monitoring program is crucial. In addition to performance monitoring of the RA, the monitoring program must be designed to verify most probable conditions and detect deviations. By initiating the monitoring program during the design process, an early indication of base conditions, relative to the most probable case or the maximum credible deviation case, is provided.

Parts of the monitoring program that provide information to the RD are highlighted in the Whittier Narrows OUFs. Those activities that are proposed for performance monitoring, but are not crucial to the RD, are not proposed for implementation as part of the RD.

As with the other components to remedial alternatives, devia-

tions to expected conditions may require modifications to the monitoring program. Modifications to the RA may require modifications to the monitoring program.

Estimating potential modifications to the monitoring program that may be required is difficult. For the Whittier Narrows OUFs, it is estimated that 33% additional monitoring wells may be required for the maximum credible deviation case.

Indications that modification to the monitoring program may be required are discussed below.

HOW THE OBSERVATIONAL METHOD IS MANIFESTED IN THE OUFs

The observational method is manifested throughout the Whittier Narrows OUFs. Description of the physical setting, which includes the nature and extent of contamination, is presented in terms of most probable conditions and maximum credible deviations. For the baseline risk assessment, two risk calculations are presented: one risk calculation was based on the most probable nature and extent of contamination and one was based on the estimated maximum credible deviation case. Remedial alternatives are developed for most probable conditions, and modifications are identified that may be required in response to deviations. Cost estimates for both conditions are included. The description of alternatives includes discussion on the actions necessary to respond to the deviations and design considerations to facilitate the timely modification if deviations are observed.

The detailed evaluation of alternatives in the OUFs addresses the following criteria (per U.S. EPA Guidance for Conducting an RI/FS Under CERCLA, October, 1988):

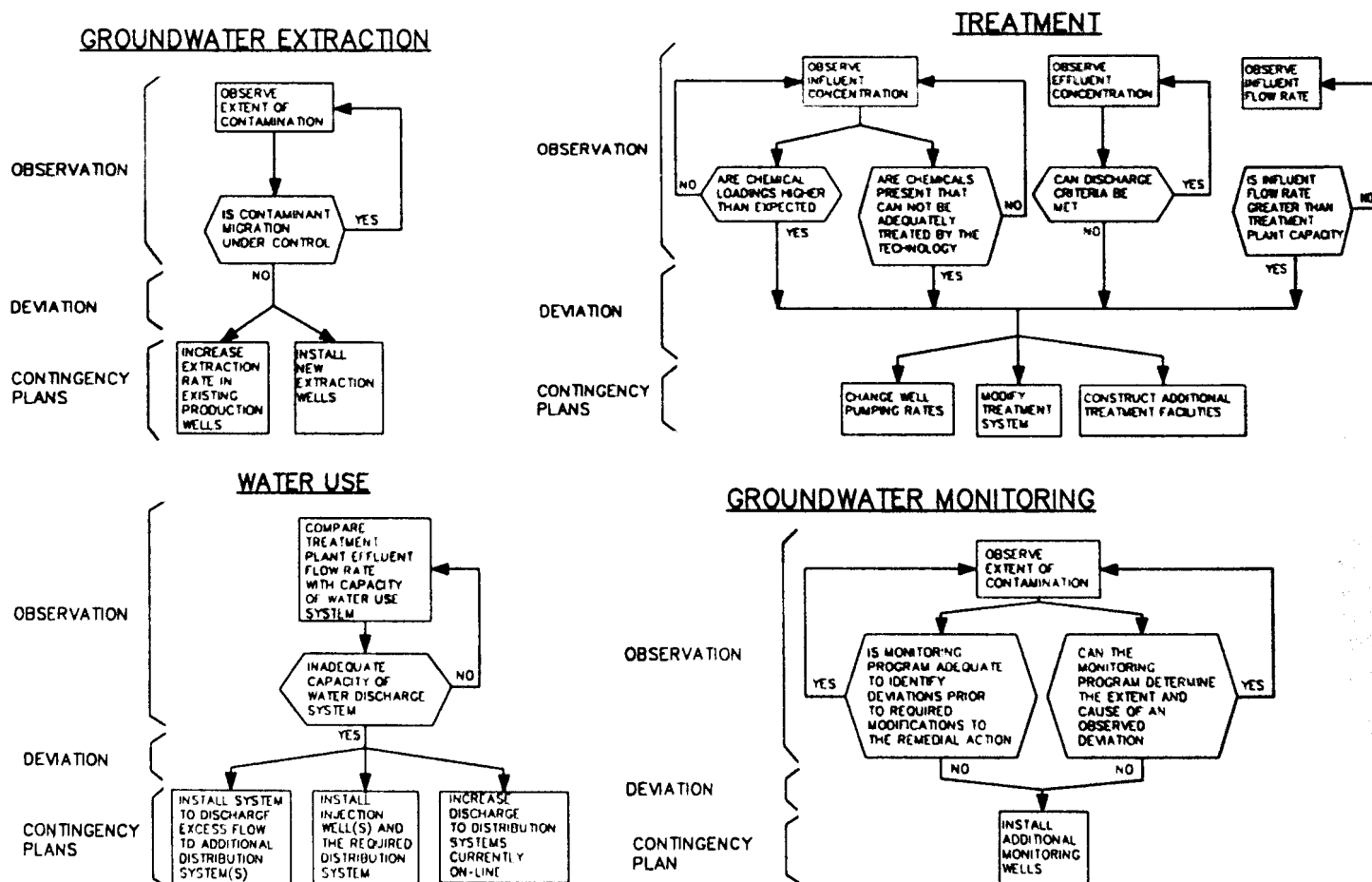


Figure 3
Observational Method Implementation Strategy for the Major
Components to Remedial Action Alternatives

- Overall Protection of Human Health and the Environment
- Compliance with ARARs
- Long-term Effectiveness and Permanence
- Reduction of Toxicity, Mobility or Volume Through Treatment
- Short-term Effectiveness
- Implementability
- Cost

A remedial alternative may undergo modification in response to observed deviations. Differences between the alternative designed for most probable conditions and that alternative as modified for the maximum credible deviation case are addressed with respect to the criteria listed above. For example, if a treatment plant is modified for on-site carbon regeneration, consideration is given regarding ARARs (e.g., requirements regarding transport and disposal of condensate) and cost.

Two cost estimates are presented for each remedial alternative: one estimate is based on most probable conditions and one is based on the maximum credible deviation case. For the Whittier Narrows OUFS, estimated costs for the maximum credible deviation case are based on the assumption that initial construction of all facilities is required. This assumption was made for ease of preparing cost estimates, and because it is possible that the maximum credible deviation case currently exists. Most likely, the cost of gradual or incremental modification would vary from this estimate.

Cost estimates for the most probable case include costs for measures that would facilitate modification (e.g., oversized pipelines). The greater up-front cost could be expected to result in a net future cost savings if deviations occur, as are expected.

The final section of the Whittier Narrows OUFS presents a summary of the general strategy for responding to observed deviations from: (1) the most probable site conditions and (2) the expected performance of an implemented remedial action. Given the high number of possible combinations of deviations that could occur, it is not practical to define specific responses to deviations for each alternative at the OUFS level. In the OUFS, general strategy for dealing with observed deviations, and indicators of a deviation that may require RA modification, are presented.

For the major components of the remedial alternatives (groundwater extraction, treatment, water use and monitoring), a general strategy for dealing with observed deviations is shown graphically in Figure 3.

Water quality parameters in Whittier Narrows to be observed in the monitoring program are presented in the OUFS. Table 1 summarizes the ranges of expected contaminant concentrations for most probable conditions and deviations to the nature and extent of contamination in the Whittier Narrows area.

Table 2 summarizes expected contaminant concentrations observed during performance monitoring.

Table 3 summarizes indicators of deviations and responses or modifications to the treatment technologies that may be required if deviations to treatment plant influent or effluent are observed.

Table 4 summarizes options for dealing with deviations in discharge rates. Indications that modification to the treated water distribution system may be required are straightforward in that the receiving distribution systems either do or do not have the capacity to take additional water.

An important point discussed in the Whittier Narrows OUFS is that careful reevaluation of the RA will be required prior to modification.

As more data on the nature and extent of contamination, aquifer properties and flexibility of the chosen treatment technology become available during remedial design and pilot testing, plans for response to observed deviations can be refined and specific modifications can be designed.

CONCLUSIONS

Applying the observational method is expected to result in

Table 1
Ranges of Expected Contaminant Concentrations Representing Most Probable Conditions and Deviations to the Nature and Extent of Contamination in Whittier Narrows

Well Number or Group	Ranges Expected For Most Probable Conditions (ug/l)	Ranges Representing Deviations (ug/l)
Central Basin production wells ^a	All contaminants <MCLs	Any contaminant >MCL
Proposed clusters near basin boundary ^b	All contaminants <MCLs	Any contaminant >MCL
Barrolo Wells ^c	TCE- to 8, others at or near MCLs	TCE- >8, any other MCLs
Proposed new wells in upgradient areas of Whittier Narrows ^d	All contaminants <MCLs	Any contaminant >MCL
Wells located between the two large areas of contamination ^e	All contaminants <MCLs	Any contaminant >MCL
01900001	PCE- MCL to 25, TCE- MCL to 10, all others <MCLs	PCE- >25, TCE- >10, any other > MCL
01900094	PCE, TCE- MCLs to 10, all others <MCLs	PCE, TCE- >10, any other >MCL
01900331	All contaminants <MCLs	Any contaminant >MCL
01901749	PCE- to 10, all others <MCLs	PCE- >10, any other >MCL
01902529	PCE- 50 to 200, TCE- MCL to 10, all others <MCLs	PCE- >200, TCE- >10, any other >MCL
01902579	All contaminants <MCLs	Any contaminant >MCL
08000004	PCE, TCE- MCLs to 10, all others <MCLs	PCE, TCE- >10, any other >MCL
08000049	PCE- MCL to 40, TCE- MCL to 15, all others <MCLs	PCE- >40, TCE- >15, any other >MCL
11900095	PCE, TCE- MCLs to 15, all others <MCLs	PCE, TCE- >15, any other >MCL
41900745	PCE- to 10, all others <MCLs	PCE- >10, any other >MCL
81902525	PCE, TCE- MCLs to 10, CTC- MCL to 4, all others <MCLs	PCE, TCE- >10, CTC- >4, any other >MCL
81902635	PCE, TCE- MCLs to 10, CTC- MCL to 4, all others <MCLs	PCE, TCE- >10, CTC- >4, any other >MCL
MP-1 and WC-1	PCE, TCE- to 15 (to 300 feet) PCE, TCE- <MCLs below 300 feet, all others <MCLs for all depths	PCE, TCE- >15 (to 300 feet) PCE, TCE- >MCLs below 300 feet, any other >MCL for any depth
WC-2, MP-4, and MP-7	PCE- MCL to 30, TCE- to 8 (to 200 feet) PCE, TCE- <MCLs below 200 feet, all others <MCLs for all depths	PCE >30, TCE- >8 (to 200 feet) PCE, TCE- >MCLs below 200 feet, any other >MCLs for any depth
MP-2	PCE- 40 to 100, TCE- MCL to 20 (to 300 feet) PCE, TCE- <MCLs below 300 feet, all others <MCLs for all depths	PCE- >100, TCE- >20 (to 300 feet) PCE, TCE- >MCLs below 300 feet, any other >MCL for any depth

Notes:

- ^aIndividual well numbers: 01900703, 01901419, 01901443, 01901593, 01901743, 01909173, 01909751, 01909774
^bIndividual well clusters: WC-3 through WC-7
^cIndividual well numbers: 01901430, 01901432, 01901434
^dIndividual well numbers: MP-3, MP-5, MP-8
^eIndividual well numbers: 01901745, 01901748, 08000071, 08000088, 08000090, MP-6

(Source: Draft Whittier Narrows OUFS, July 1989)

Table 2
Performance Monitoring of Extraction System—Expected Contaminant Concentration for Most Probable Conditions and Deviations, Whittier Narrows OUFS

Basin Boundary Objective^a

Well Group	Expected Ranges	Deviations
Wells downgradient of proposed extraction wells ^b	All contaminants <MCLs at all depths	Any contaminant >MCL at any depth
Proposed clusters near basin boundary ^c	All contaminants <MCLs at all depths	Any contaminant >MCL at any depth
Central Basin production wells ^d	Discharge below <MCLs	Water produced that exceeds MCLs

Central Basin Objective^e

Well Group	Expected Ranges	Deviations
Wells downgradient of proposed extraction wells	Some depth intervals may exceed MCLs	High contaminant concentrations or several depth intervals exceeding MCLs
Proposed clusters near basin boundary	Some depth intervals may exceed MCLs	High contaminant concentrations or several depth intervals exceeding MCLs
Central Basin production wells	Discharge below <MCLs	Water produced that exceeds MCLs

Notes:

- ^aBasin boundary objective refers to the objective which would prevent any groundwater exceeding MCLs from leaving the San Gabriel Basin through Whittier Narrows
^bIndividual well numbers: 11900095, 08000004, 01900094, WC-1, WC-2, MP-1
^cIndividual well clusters: WC-3 through WC-7
^dIndividual well numbers: 01900703, 01901419, 01901443, 01901593, 01901743, 01909173, 01909751, 01909774
^eCentral Basin objective refers to the objective that would prevent Central Basin production wells from exceeding MCLs

Table 3
Effect of Treatment Technologies on Varying Influent Conditions,¹
Whittier Narrows OUFs

- STRIPPING (PACKED TOWER AIR STRIPPING)**
- Increased 1,2-DCA and 1,1,2,2-TCA concentrations may require increased air to water ratios.
 - Methylene chloride concentrations above 500 to 1,000 ppb may require increase in the air-to-water ratio independent of any increases in 1,2-DCA and 1,1,2,2-TCA concentrations.
 - Air-to-water ratios will likely range between 20:1 to 75:1 as concentrations increase from probable design to credible deviation conditions.
 - Increases in flow rates will require additional units only if incremental changes are greater than 2,000 to 3,000 gpm. Changes less than this can be accommodated by distributing the increased load across available strippers.

- CARBON ADSORPTION²**
- Concentration increases of methylene chloride to greater than 200 to 500 ppb may cause carbon replacement costs to be prohibitive. Additional treatment by air stripping may be necessary.
 - Increases in vinyl chloride (VC) concentrations may limit ability to meet MCLs due to VC pass through. Additional treatment may be necessary at concentrations as low as 1 to 10 ppb.
 - Increases in flow rate that are greater than 1,000 to 1,500 gpm may require additional carbon beds to be added for each 1,000 gpm.

- ADVANCED OXIDATION (O_3/H_2O_2)³**
- Ozone/peroxide may not be effective in treating carbon tetrachloride (CCl_4) to MCLs. CCl_4 above MCLs may require additional treatment.
 - Assuming all compounds are treatable, increased concentrations may require increased reactor detention time and chemical consumption. The need for process modifications can only be determined during detailed design.
 - Increases in flow rate should be handled by the base design. Reactors should be capable of treating flows as high as 150 percent of the design peak flow rate.

¹Actual transition conditions will be determined after pilot testing or detailed design or both.

²Transition points must be determined by pilot testing.

³Effectiveness, transition conditions, and additional unit requirements can only be determined after pilot testing and detailed design.

Table 4
Water Use Options for Deviations in Discharge Rates
Whittier Narrows OUFs

Distribution Options	Capacity to Accept Excess Flow (gpm)	Distance (feet) from Proposed Treatment Facility to Connection		
		Whittier	Industrial	Residential
Purveyors				
City of Pico Rivera ^a	3,400	700	5,600	10,000
San Gabriel Valley Water Company - Central Basin	2,900	5,600	10,600	23,600
Wholesalers				
Cal Domestic	6,000	8,600	3,200	10,000
IND	Any Excess	24,000	22,000	6,750
Recharge ^b	Any Excess	1,400 ^c	6,400 ^c	19,400 ^c

^aFor Alternative 2, most of the base flow capacity is used for discharge under most probable conditions.

^bRecharge includes spreading basins and/or injection wells.

^cDistance to spreading basins. Distance to injection wells may be greater.

more timely implementation of remediation for the Whittier Narrows Operable Unit, and possibly at a reduced cost. Gathering data during the RD and RA as part of the monitoring program is expected to be efficient and timely. The observational method provides an acceptable means to expedite remediation and logically manage and minimize risk.

REFERENCES

1. Peck, R.B. "Advantages and Limitations of the Observational Method in Applied Soil Mechanics," in *Milestones in Soil Mechanics, The First Ten Rankine Lectures*, Thomas Telford Ltd., Edinburgh, pp. 263-279, 1975.
2. U.S. EPA. *Draft Whittier Narrows Operable Unit Feasibility Study, San Gabriel Basin, Los Angeles County, California*. Prepared by CH2M HILL, Santa Ana, CA. July 1989.

Advantages for the Regulated Business Community Through Compliance with SARA Title III

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ABSTRACT

SARA Title III has revolutionized the approach to managing chemicals within our communities. No longer can a company operate "behind closed doors." With the establishment of the State Emergency Response Commissions (SERCs) and the Local Emergency Planning Committees (LEPCs), the general public now has access to a wealth of information pertaining to a company's use of hazardous chemicals. Not only are the provisions of Sections 302, 304, 311, 312 and 313 demanding in their own right, but the Act also provides the LEPC with extremely broad authority to influence and implement the development of community emergency planning actions.

Fortunately, this Act puts the business community on equal footing with the rest of the community. Through the LEPC, the business community can play an integral role in the formulation of emergency response planning and LEPC policy. With a voice on such a committee, business leaders can help establish a constructive rapport between business, media, public servants and the general public. Involvement of the business community can also add a greater degree of technical competence to such a forum.

The focus of this paper is how industry's pro-active involvement with the community in the emergency response planning process can result in tangible benefits for industry as well as the community at large.

INTRODUCTION

The need for comprehensive emergency response planning was firmly established after the tragic chemical release in Bhopal, India. Since that time, efforts by the Chemical Manufacturing Association (CMA), public interest groups and concerned communities have resulted in the formation of awareness programs and local, state and federal laws and regulations, all addressing the concerns of chemical hazards in the community and the need to protect the public and environment from these hazards. In 1985, CMA developed the Community Awareness and Emergency Response program (CAER), designed to inform the public of hazards inherent in the chemical industry and ways to protect the public from these chemicals in the event of a spill or release. The U.S. EPA then introduced voluntary programs which included elements based upon the CAER program. These programs were the precursor to the Emergency Planning and Community Right-to-Know Act, also known as SARA Title III.

The intentions of SARA Title III are clear; to provide a comprehensive community emergency response plan to protect life, property and the environment in the event of a chemical spill or

accident. This act requires by law the formation of and participation in the LEPC by community officials, public agencies and community industries. Although the law provides for the levying of severe penalties on industries if they fail to participate in the LEPC, there are no provisions within the law that qualitatively measure the results of LEPC efforts.

In essence, the ultimate goal of SARA Title III is no different than that of CMA's CAER program. SARA Title III, however, now legally joins the community and industry at the emergency planning table. For the chemical companies that have already endorsed the CAER program, SARA Title III does not present new regulatory requirements except for inventory and emissions reporting. Many companies not previously involved in the CAER program are now faced with what they perceive to be just another regulatory burden absorbing more resources and requiring additional manpower. To the contrary, however, industry's involvement in the LEPC can provide industry with many distinct and tangible benefits.

ADVANTAGES OF INVOLVEMENT

Liability

Non-compliance with the minimal LEPC participation requirements of SARA Title III can result in the imposition of penalties of up to \$25,000 per day. Pro-active and energetic involvement by a company that goes beyond the minimal requirements, however, will not only avoid such penalties, but also will enable the company to realize significant advantages that are critical to a business' continued prosperity. One obvious advantage is the reduction in risk of liability a company may realize if it has invested the time and effort to ensure that its community's emergency response plan works. A workable plan can be achieved only through efforts on the part of the company that go beyond those steps required by law.

It is an undisputed fact that the liabilities associated with major spill response efforts are prohibitive. Cleanup costs alone can be staggering. Costs associated with property damage and economic losses add further to an already expensive bill. If there are injuries or even death as a result of an accident, the compensatory costs can exceed the physical cleanup costs. In addition, the poor public perception a company will receive if a spill response is mishandled is only too vivid in most Americans' minds. Damage control and recovery from these mishaps can be absorbed only by the largest conglomerates.

With the erosion of sovereign immunity, there could be some liabilities on the part of individual town officials or towns in the event of damages arising out of actions taken during an emer-

agency response. To avoid liability in the event of a spill or accident, a town must be able to defend that it has responded to the best of its ability. To do a good job, towns must have the resources, expertise and active cooperation of industries in their area. In instances where the town may be negligent or at fault, it is hard to imagine that some, or a good part, of the blame will not fall on industry's shoulders. Therefore, it behooves industry to ensure that their towns have the most effective and qualified emergency response capability possible.

Unfortunately, accidents and spills will occur, but the actions a community takes immediately following an event will dramatically affect the overall personal and environmental damage. If industry and the community together develop effective emergency response plans, the damage from accidents can be greatly mitigated. In effect, a competent response to spills or accidents can directly reduce industry's risk of liability.

Improved Public Relations Equals Smooth Operations

A poorly informed public is usually fearful, and this fear can significantly impact operations, perhaps forcing the closure of a facility. The public is becoming more educated through the media about the hazards of chemicals. They have a right to know what is going on in the chemical plant or warehouse down the street... and they know it! Industry must understand the public's fear and realize that it can be translated into operational difficulties.

The CMA recognized that this fear in people's minds concerning the hazards associated with chemicals could lead to over-regulation of the chemical industry. Thus, through the formation of CAER in 1985, the CMA took steps to attempt to reverse the public's perception of the chemical industry. This program stressed cooperation and interaction with the local communities. The fundamental goals of CAER were to make the public aware of the hazards and to take the protection necessary to minimize or eliminate these hazards. Large chemical industries, with plentiful resources, generally embraced the goals of CAER. Unfortunately, it proved to be very difficult to establish a rapport between the companies and towns. People still believed that the companies were trying to hide something and were not sincere. In addition, the plant managers did not have the knowledge and skill to communicate with the community and the media.

By the time SARA Title III was implemented, many companies had emergency response plans in place but had not integrated these plans effectively with the community. Following in the footsteps of CAER, SARA Title III was designed to open the door to effective communication between industry and the community through the establishment of the LEPC.

Through the LEPC, industry now has a legitimate conduit for access and dissemination of information to the community. The LEPC can be used as a forum to educate the public, reduce mounting fears associated with industrial practices and activities, and ultimately increase industry's profitability through the establishment of improved public relations and perceptions. At LEPC or similar meetings, industry groups can provide the public with information about the products they produce and the chemicals needed to produce such products in response to public demands. Through education, the public hopefully will understand that, as consumers of these products, they are partly responsible for the hazardous chemicals needed to produce these consumer goods. Once the public gains this awareness and sense of responsibility, the bridge between the public and the industry is established and effective communication between the two entities can take place.

Although the benefits to industry from better communications are improved public perceptions and relations, industry must take care to ensure that this effort is, in fact, a sincere effort. This effort on the part of industry must be focused upon educating and ultimately protecting the public while maintaining receptiveness to demands for consumer products. This effort

must not be, nor be perceived to be, a public relations campaign designed to serve the company's needs only. Public relations campaigns will lack credibility and must be avoided.

An industrial company with amicable community relationships may choose to expand or develop in that same community. When a good neighbor relationship develops, industry will receive its share of subtle benefits. The permitting process for new construction or development can be shortened because the public will support the endeavor or opposition to the project will be fragmented at best. Day-to-day operations also will be much smoother without unnecessary local interference.

The same public support can be beneficial when one-sided environmental groups attack a reputable community industry. Without support from the public, campaigns against the industry will be short-lived. In Springfield, Massachusetts, for example, local industries have put a tremendous amount of effort into helping their community develop an effective and workable emergency response plan. Through the development of this plan, the citizens of Springfield have been educated as to what industry does and why. The relationship between industry and the public is so strong in Springfield that consumer advocacy groups have been unable to justify to the local citizens efforts to campaign against industry operations.

Pre-emption of Possible Future Costs to Industry

During the implementation of SARA Title III, the chemical industry lobbied to make the Act a workable piece of legislation that would share the burden of responsibility between the towns and industry. This piece of legislation could have been far more burdensome for industry, and, in fact, it may become more burdensome if a method is not found to adequately fund the LEPC's efforts to implement emergency planning and provide adequate training. Industry is in a position to pre-empt the imposition of fees and additional regulation by filling this void.

The biggest impediment that most LEPCs must overcome is that of little or no funding. While some industries and states provide this funding for training first responders, funding is sorely lacking in many states. Bill Kremer of the Federal Emergency Management Agency (FEMA) explained that the federal government, through FEMA, has supplied some funding and expertise to assist emergency planning efforts. However, this funding is far less than is needed. In Massachusetts, for example, only \$70,000 of federal funds was available in 1989 to train all first responders throughout the entire state. In addition, seven emergency response vehicles which the federal government provided to the state cannot be used because no one is trained to use them. The situation in Massachusetts is not atypical. Without adequate training and equipment, the best emergency response equipment and plans are useless.

To combat this funding void that was not addressed in the Act, states such as Maine and New Jersey have levied a fee on industries that participate in emergency response planning pursuant to the Act. Public pressure will no doubt encourage the imposition of fees as long as chemical spills and emergencies continue to occur. To prevent levying of fees in states where the fee system is not yet established, or to prevent further increases in states where this fee already is in place, industry must share in the massive task of training both community firefighters and other responders and in-house personnel. Joint training exercises with industry, police and fire departments are essential. Joint exercises help alleviate the heavy burden on fire departments. In addition, they improve emergency response operations and help cement relations between the emergency responders.

Industry Resources

To reach the intended goals of SARA Title III, industry and the community should share resources. Communities typically have large equipment resources, town departments and evacua-

tion capabilities. Industry must be willing to provide the necessary expertise to complement town resources, as most local officials do not have the background required to address the complex issues associated with chemical management and safe, effective emergency response procedures. Industry also has many resources that are not available to the LEPCs or the local emergency response agencies.

In small towns, fire departments may not have the personnel or equipment to field a complete emergency response team. Equipment needed to evaluate and assess chemical dangers may not be available to the town departments. In these situations, industry should support the LEPC and the community by making available these resources and supporting them in the use of these resources. Equipment resources and an emergency response plan are useless in the hands of inexperienced responders.

Industry is a Member of the Community

A strong emergency response plan can reduce a company's risk of liability in the event of a spill or accident. However, the fact that a company helps prepare a worthwhile plan does not guarantee that the many benefits resulting from a good neighbor atmosphere will materialize. Good public relations and a good neighbor relationship will develop only if industry accepts that they too are a member of the community.

The industrial community must recognize that LEPC involvement must not serve only the public relations or marketing departments. Instead, industry must approach the emergency planning task with the same professionalism and expertise that they would devote to any internal endeavor.

As a member of the community, industry has the responsibility to protect its citizens. Industry does not have the unalienable right to operate. Industry must prove to the community that it can operate with minimal risk to the citizens of the community. Companies that fail to accept this responsibility face the risk of hostile public outcry and the detrimental ramifications it engenders.

Industry's pro-active involvement with the community can yield long-lasting and positive results. When industry does finally embrace the open door policy, it often is met with serious skepticism and concern from the public. A high level of cooperation and mutual trust does not develop overnight, but the rewards to both parties involved are well worth the effort.

CASE STUDY

The City of Springfield, Massachusetts, which received one of the first CAER awards for its superior efforts in emergency planning, provides us with a good case study. Jim Controvich, the Springfield Civil Defense Coordinator, has spent the past 5 yr developing a viable emergency response plan. Mr. Controvich said his program would not have been successful without the help of industry.

An example of this cooperation is help supplied by Monsanto Chemical Company of Springfield, Massachusetts. Monsanto provides many resources to the Springfield Hazardous Materials Response Team (Haz Mat) including Haz Mat responders, chemicals and equipment as needed.

When George Lemos, the Environmental Operations Manager of Monsanto, was asked how he justified such a commitment to the local Haz Mat team, he responded, "It is a symbiotic relationship. In many instances, the City does not have the chemical expertise and experience that we have. That's our business. On the other hand, we don't have the firefighting experience and equipment available to the police and fire departments. Take, for example, the heavy fire fighting trucks. Considering what is at stake in even the smallest incident, it would be downright foolhardy not to recognize each other's strengths and weaknesses, and then form a strong relationship to build a synergistic haz mat response capability."

Despite the strong support from Monsanto and other companies in the City, Jim emphasized that all of the planning and equipment is no substitute for practice. For this reason, Springfield has conducted monthly tabletop exercises. Explains Jim, "Only when personalities and response teams have worked together in a time of stress can they gain each other's confidence and recognize each other's capabilities. The tabletop creates a stressful situation in which we learn a great deal about our responsibilities and capabilities during an incident. And we made mistakes. Of course if we never make mistakes there would be no need to practice!"

This community is prepared! Others are not.

In some cases, emergency response planning is confounded by the public's belief that if industry cannot plan or is prevented from adequately planning for emergencies, industry should leave. This is evident in northeastern Massachusetts where several towns are protesting the operation of the Seabrook Nuclear Power Plant. Towns in this area have refused to submit emergency evacuation plans and cooperate with planning agencies. One community even dismantled a warning system in their town that was paid for and installed by the utility. Seabrook had to develop an emergency response plan independently of the communities that the plan was designed to protect. The fact that this plan was not a product of mutual cooperation raises serious doubts as to its effectiveness in the event of an emergency. The towns' failure to cooperate leaves their communities vulnerable to a disaster. Such actions also greatly increase industry's risk of liability in the event that an accident occurs.

To mitigate public opposition, industry must actively and sincerely attempt to develop a relationship with their community. It could take years for a relationship to develop between industry and the community which fosters effective planning and trust. Such a relationship, however, is absolutely crucial to protect the public and to minimize industry's exposure to liability in the event of a spill or accident.

WHAT INDUSTRY CAN DO

Chuck Losinger from HMM Associates, Inc. assisted CMA during the early development of the CAER program. Although Mr. Losinger agrees that the initial skepticism of the community toward industry is difficult to eliminate altogether, a sincere effort by industry will quickly destroy many misconceptions and counterproductive concerns. Mr. Losinger has highlighted the following items that industry can do that will help lead to mutually supportive and beneficial relationships between industry and the community.

- Industry must supply an interested and capable person to participate in the LEPC. The LEPC designee should not view the appointment as an assignment but rather as a challenging, exciting and worthwhile endeavor. The designee must appreciate the importance of the LEPC charter. This person should, of course, be trained in emergency planning.
- A company should be honest and forthright about its hazards and should be pro-active and reach out to community groups before being required or forced to do so. Conducting plant tours is a great way to facilitate community outreach programs.
- On a periodic basis, company emergency response training should be conducted in concert with local responders.
- If local responders do not have the necessary resources to effectively respond to emergencies, companies should help to augment these resources by providing emergency response equipment as required.
- A strong rapport with the local fire department should be established. Fire departments should tour the facility frequently and be aware of the company's operations and emergency response capabilities.
- Companies can help to make the paperwork burden on towns

more manageable by supplying emergency planning information (i.e., chemical inventories) in an organized format. The CAMEO program and/or a minicomputer can be supplied which will store data that can be recalled when necessary and aid a community in emergency planning. The expertise needed to operate the program also should be provided.

Mr. Douglas Forbes, from the Massachusetts Civil Defense Agency, also has ideas on what industry can do to facilitate effective emergency response planning. Some of these ideas include the following:

- Industry can increase awareness through the distribution of printed public information pieces (calendars, pamphlets, etc.) which address the need for various types of emergency planning.
- Industry can encourage emergency planning by hosting luncheons for tabletop exercises where industry and the community work together to respond to mock chemical emergencies.
- Industry can lend its management capabilities to emergency planning and practice efforts.
- Industry can offer services to the disabled public such as assistance in notification of the hearing-impaired.

CONCLUSION

SARA Title III provides an opportunity for industries and communities to work jointly to create a mutually beneficial, safer environment. Progress has been most effective where localities,

states and industry have worked closely together. States with strong county governments provide a natural structure to deal with the demands of emergency planning. On the other hand, states in the northeast have weak county governments and strong local governments which can impede regionalization and shared resources. These areas are particularly in need of industry's leadership and resources.

Industry is a part of the community. Let's all accept the challenge and make emergency planning a corporate goal.

ACKNOWLEDGEMENTS

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Superfund in Action: A Case Study in Planning a Successful Project

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ABSTRACT

Community relations (CR) activities have long been an important part of the Superfund program. The interactive process normally begins in a local community once a potential hazardous waste site is identified and targeted for investigative work and continues until the site has been remediated. During the course of the many phases of work at the site, the CR activities are quite varied and usually range from the simple preparation of informational materials to the time-consuming preparation and conduction of public hearings.

Many times the success or failure of a Superfund project depends on how well the CR activities are implemented. Successful remediation of the Superfund site in LaSalle, Illinois (a residential community with extensive PCB contamination of the soil) was totally reliant on the success of the CR activities that were planned and implemented in the area. Without the full cooperation and support of the residents and businesses in the neighborhood, complete remediation of the site was impossible.

This paper is a case study of the CR planning and implementation activities, both obvious and intangible, that are necessary at most Superfund sites and which were conducted at the LaSalle site. The paper has been prepared in conjunction with a video documentary that was produced in order to document the positive characteristics of the Superfund program and the role that CR activities play in that success. The goal of both the video and written documentaries was to capture the positive side of the Superfund program and to show that with careful planning, projects can be successfully implemented even under extremely difficult conditions within a community.

INTRODUCTION

The LaSalle Electrical Utilities (LEU) site in LaSalle, Illinois, was a former manufacturing facility of electrical equipment. The plant began operations prior to World War II, and in the late 1940s it began using PCBs in the production of capacitors. This manufacturing process was continued until approximately October, 1978. By May, 1981, operations at the LEU facility had ceased, and by September, 1983, the company's last operating facility in Farmville, North Carolina had filed for bankruptcy. In December, 1982, the LEU facility was included on the first NPL.

The now abandoned LEU facility is located on the northern outskirts of the City of LaSalle bordering a small residential community. Approximately 70 homes are located in this area, and nearly 190 people occupy those homes.

Information concerning the waste handling and waste management practices of the LEU company is limited. However, based on conversations with local residents and former employees, it appears that the company regularly engaged in the practice of applying PCB-

contaminated waste oil to parking lots, roads and alleys at the plant and in the adjacent areas to suppress dust. Following the Federal regulation of PCBs, LEU company manifests document the legal disposal of the contaminated material.

PROBLEM

Even though the LEU company altered its PCB disposal practices in order to comply with the new Federal regulations, its historic operating practices had already released PCBs into the environment both on the company property and in the surrounding residential area. The extent of contamination varied, but extensive investigations conducted by the Illinois Environmental Protection Agency (IEPA) defined the limits. The IEPA data revealed that the contamination did not stop at the company's gates. Rather, the results showed that the residential community directly adjacent to the plant contained extensive soil contamination at depths up to 3 ft. In addition, wipe and dust samples taken from the interiors of the residential homes revealed the presence of low-level PCB contamination.

REMEDY SELECTION

Based on the results of the extensive remedial investigative work at the site, the U.S. EPA and the IEPA determined that all soil in the residential area with PCB concentrations greater than 5 ppm should be addressed in the remediation project. The feasibility study evaluated numerous technical alternatives for alleviating the problem. Possible solutions ranged from capping the contaminants in place to excavating the affected soil and destroying the material in a permanent off-site incinerator.

Unlike most feasibility studies conducted at Superfund sites, this project was entirely within a residential area which meant that a great deal of weight had to be placed on resident concerns. The evaluation conducted during the project's feasibility study very seriously considered these concerns and regarded meeting them as an integral aspect of successful implementation. For this reason, many technically sound alternatives such as capping in-place or excavation and disposal in an on-site landfill were readily dismissed.

The final alternative chosen for implementation at the site called for excavating the contaminated soil and destroying the material in a mobile incinerator which would be temporarily located on the LEU property. In addition, the selected alternative included a thorough cleaning of all affected homes after excavation of the contaminated soil. Although this alternative best met the technical, financial and protective criteria established during the review, it was not without numerous potential barriers to implementation such as community acceptance of an on-site incinerator and residential consent for entry onto and into the affected property and homes.

COMMUNITY RELATIONS OBJECTIVES

In order to successfully implement the selected alternative, a thorough and comprehensive community relations plan was necessary. The primary objective of the plan was to aid project implementation through extensive communication. This meant sharing the details of the selected alternative with the residents, knowledgeably and patiently answering individual's questions to ease their fears and ultimately obtaining the full consent of the neighborhood so that the remedy could be implemented. Without the full participation and cooperation of the residents, the selected alternative could not be successfully implemented.

IMPLEMENTATION PLANNING

For the remediation project to be a success, all governmental agencies as well as all elected officials had to work jointly to reach the project objective. Government agencies included both the U.S.EPA and the IEPA, the City of LaSalle, the Illinois Department of Transportation and the Illinois Department of Public Health. Other interests included the prime contractor - Westinghouse/ HAZTECH, the IEPA oversight contractor—Ecology & Environment and the local labor unions.

Before beginning any site work and any on-site community relations activities, the primary contacts with both the U.S.EPA and the IEPA met on numerous occasions in both Springfield and Chicago to evaluate the community's needs and concerns and to plan activities that could be undertaken to address them. In addition, in order to optimize the evaluation and planning efforts, all primary contacts at both the U.S. EPA and the IEPA participated in 3 days of extensive community relations training in Dallas, Texas. That training focused on how to gain consent in difficult situations when a common concern is the objective. In this case, the common concern of the project was eliminating the PCB contamination.

Through the course of the planning meetings, countless problem areas and needs were identified. These included basic items such as the need for equal treatment of all homes and security in the area during the actual work, as well as more complicated matters such as maintaining access to the residential community while at the same time adequately protecting the health and safety of the residents and the workers.

Since it was necessary to temporarily relocate residents during the soil excavation and cleaning of the homes, the list of problems that could be encountered during implementation multiplied rapidly. During the planning meetings that were held, a great deal of time and effort went into brainstorming and generally trying to determine what the needs of the residents would be when the actual work commenced. The project coordinators in essence tried to picture themselves in the residents' position. Through this role reversal, the coordinators were able to determine what they would be concerned with and what they would like to see happen during the relocation and remediation period if they themselves were the homeowners.

As a result of the brainstorming sessions, many items which initially might have seemed trivial were identified as being issues that could ultimately determine the success or failure of the implementation. For example, the contractors' work schedules during the cleanup had to be carefully coordinated so that residents could be given adequate notice when cleanup activities would commence at their homes and so that the costs and the inconveniences associated with the relocation could be minimized. Arrangements had to be made at nearby hotels to account for the special needs of those who were being temporarily moved out of their homes. Special arrangements had to be made for transportation of children to and from school, of the elderly or sick to and from doctors and of the residents who normally did not depend on cars to get around the area. Normal day-to-day activities, such as bringing in the daily newspaper or mail, which are not generally given much thought also had to be addressed.

Ultimately, the issue that was the basis of the CR planning activities was the temporary separation of the residents from familiar settings and routines. The residents were being asked to hand over their homes and their possessions, to forgo their day-to-day security and to trust people that they had only recently met to take care of a part of their lives. This traumatic interruption in the lives of area residents required

special consideration and respect during both the planning and implementation.

The demographic makeup of the community was widely varied and as a result, no simple plans could fit all the residents involved. Even though meals were provided at the hotel, some elderly and infants had special dietary needs that had to be addressed. Some people also had pets that had to be relocated along with their owners. As part of the initial security plan, no residents were to be allowed back into their homes until all work was completed. However, since many of the residents had extensive collections of plants that needed special care and since some people ran small businesses out of their homes, arrangements had to be made to allow for daily entry into the homes without breaching the security that had been established.

Since the residents would be vacating their homes for extended periods of time and allowing virtual strangers into them to clean the structures while they were away, liability was a primary concern of both the residents and the contractors. Plans had to be drawn up to protect the residents' property while at the same time limiting the contractors' potential liability.

IMPLEMENTATION

Once most of the problems and their solutions were determined, the main issue was implementation of the plans and education of the community. Without the complete understanding, cooperation and consent of the community, there was no project.

The first step in the implementation process was to establish personal contact with all the residents who would be affected. This was accomplished initially through door-to-door visits to each home in the area. After sending out notices to all the homeowners, groups of two or three representatives from the IEPA and the U.S.EPA sat down with the residents in their homes and discussed the proposed project with the people on a one-on-one basis. This informal and small atmosphere allowed the residents to get to know the agency representatives, to learn about the project in the relaxed setting of their own homes and to feel comfortable asking questions and conveying concerns.

The person-to-person contact was a visible sign that the bureaucrats planning the project, a project that would totally upset resident's daily living, had enough concern to take the time to talk. It allowed the residents the opportunity to meet the bureaucrats, to get to know them as real people and concerned planners and to judge both the people and the project for themselves. The personalized discussions gave the residents an option to decide whether or not they thought the planners were confident and knowledgeable and whether or not these virtual strangers could be entrusted with their homes and their well-being.

In addition to the in-home meetings, large community meetings were held at various times to begin specific aspects of the project and to allow the residents to meet as a group and see that their neighbors had similar concerns. Prior to these meetings, information or fact sheets and letters were prepared to briefly summarize key aspects that were important and to reinforce information that was passed on during the meetings.

In order to successfully implement the project, both the residents and the local city and county officials had to concur. Therefore, in addition to formal and informal meetings with the residents, planned meetings were also held with the local government officials.

Another tool used to successfully aid implementation was a survey of the residents' needs during the project. Prior to the actual start of the remediation work, the IEPA distributed a detailed questionnaire to all the residents with a cordial cover letter explaining that its purpose was to gather specific information from each home so that arrangements could be made in advance of the relocation, thus minimizing the degree of inconvenience. The survey asked the people what needs had to be met in order to make them feel the most comfortable with the move. Additionally, the letter stated that all information collected would be treated as confidential and would be used solely for the purpose of implementing the project.

Once the project was actually underway, the needs of the residents became much more important. It was decided in advance that a com-

munity relations contact person from the IEPA would actually stay with the residents in the hotel throughout the course of the project. This person acted as both a counselor and a concierge who answered all questions and concerns and also made necessary arrangements for any specialized needs. The decision to station a CR contact in the hotel during the relocation period proved to be one of the most valuable decisions made during the planning and implementation processes. Not only did this decision act as a bridge and continuation of the initial contacts made, but it also physically showed the residents the high level of dedication to their needs.

VIDEO DOCUMENTATION

The LaSalle project was unusual because it directly involved a residential community. In addition, the proposed solution to the problem involved not only direct intrusion and interruption of the day-to-day lives of the area residents, but it also involved the temporary placement and operation of a hazardous waste incinerator directly adjacent to the community, a difficult proposal in itself to implement. The project also was unusual because of its high degree of success. For all these reasons, the U.S. EPA project coordinators felt that this project was ideally suited for documentation.

The medium selected to capture the project was a videotape documentary. The 22-min tape chronicles the project through the eyes of the affected people. It gives the residents a chance to say what they felt about the project and it records a successful implementation from their standpoint. The documentary also allows the planners to step out of their decision-making role to see how their ideas were accepted and integrated. This is accomplished through community feedback which

shows, from the residents' perspective, what their fears and concerns were and how these were addressed.

While the documentary focuses only on the LaSalle project, it can be used as an example for all Superfund projects to illustrate the necessity for thorough planning prior to the implementation of any remediation project.

The documentary was produced by the U.S. EPA, but it could not have been completed without the help and cooperation of all the people involved in the project, including the cleanup contractors, the local officials, the IEPA project planners who provided the lead role in implementation and who also provided copies of video footage from the IEPA's own tape library and, most importantly, the people of the City of LaSalle.

CONCLUSION

This project was successful because it was carefully thought out and implemented. The fact that all of the affected residents gave their consent for the work to be done on their property attests to this fact. While no two Superfund projects are alike, the fact of the matter is that regardless of the project and the associated degree of impact that the project may have on the nearby community, any project has a higher chance of successful implementation if careful pre-planning is undertaken and if the needs and concerns of the community are adequately addressed.

REFERENCES

1. Black & Veatch, *Final Report, Phased Feasibility Study For Remediation of PCB Contamination of the LaSalle Electrical Utilities Site*, Prepared for the Illinois Environmental Protection Agency, Aug. 13, 1986.
2. *Remedial Action Selection and Record of Decision for the LaSalle Electrical Utilities Site*, U.S. EPA, Aug. 19, 1986.

Appendix I Community Relations Responsiveness Summary August 19, 1986



Illinois Environmental Protection Agency 2200 Churchill Road Springfield IL 62706

August 1986

COMMUNITY RELATIONS RESPONSIVENESS SUMMARY ELECTRICAL UTILITIES COMPANY LASALLE, ILLINOIS

The Illinois Environmental Protection Agency (IEPA) conducted the community relations program at this site. Community relations activities continued throughout the remedial investigation and feasibility study.

During the phased feasibility study, a three week public comment period (July 8 -- July 29) was established to receive public comment about remedies for managing contamination found in residential areas. A public hearing was held on July 17 to discuss these remedies. This responsiveness summary documents citizen concerns expressed during the comment period and IEPA's response to those concerns.

Another public hearing and public comment period will be held to discuss remedies for managing contamination found on the Electrical Utilities property. The additional hearing and comment period will be held after the feasibility study for the EUC property is complete. A separate responsiveness summary will be prepared and distributed following that comment period.

Introduction

Polychlorinated biphenyls (PCBs), used in the manufacture of electric capacitors, are present in the soil of a portion of the residential area east of the EUC plant, in the commercial property south of the plant, and in a small portion of the farm field to the north. In addition, PCBs are in the soil north and south along St. Vincents Road.

Five remedies are proposed for managing this PCB contaminated soil: landfill; on-site incineration; off-site incineration (outside LaSalle County); temporary storage; and no-action.

Community sentiment is virtually unanimous in support of the remedy preferred by IEPA--mobile incineration. A question expressed by several in

the community, including city officials, regards the level of noise that will be generated when the incinerator is in operation. Residents are not opposed to off-site incineration, but are skeptical that USEPA would approve this remedy because of the high cost.

Two of the other remedies, landfill and "no action," received no support and would not be accepted by the community judging from verbal comments from residents during the remedial investigation and feasibility study.

Temporary storage was not supported by the community. However, this remedy might be acceptable if storage did not exceed six months. Primary community concerns are for residential property values and for attracting a new business to the EUC site. Landfill and "no-action" conflict with these community concerns.

Community Involvement

Community relations commenced with a joint presentation by IEPA and USEPA officials at a City Council meeting in January, 1984. Through personal interviews, "living-room meetings," and public meetings, the following issues were identified as concerns of the citizens during the remedial investigation.

Effect on business--Several small businesses are located in the immediate vicinity of the EUC site. Business owners are concerned about how present and potential customers are reacting to the news that PCB contamination exists in the area.

One businessman has been refused liability insurance. Insurance companies are citing PCB contamination and underground storage tanks as the reason.

Property values - According to residents, residential property values have diminished in one area near the EUC site. Residents feel that once cleanup at the EUC site is completed, property values will increase. Removal of approximately 260 fifty-five gallon drums containing PCB and drainage of a tank containing trichloroethylene in February, 1986, did not affect property values according to residents.

Health effects--PCB contamination in residential yards raised questions about potential health effects to both present and future generations. Officials from the Illinois Department of Public Health and the IEPA went door-to-door when PCB levels were identified to discuss the impact of the PCBs in residential yards.

During the public comment period, a public hearing was held to discuss each of the proposed remedies. The hearing was held on July 17, at the Howard Johnson Motor Lodge, Route 80 & 51, in LaSalle beginning at 7:00 p.m. A written statement was presented from the City of LaSalle. Approximately 15 of the 35 in attendance asked questions. Beginning two weeks before this hearing, six small group meetings were held with residents, elected officials, and the news media to discuss specific questions about the proposed remedies.

Summary of Comments and IEPA Response

Issue: Superfund Program

QUESTION: Are the residential yards considered part of the EUC site listed on the National Priority List?

RESPONSE: Yes

QUESTION: Who pays for the remedies implemented as part of the EUC cleanup?

RESPONSE: The federal government will provide 90% of the cost through the Superfund program and the State of Illinois will pay the remaining 10%. There will be no charge to homeowners and residents of LaSalle. The Electrical Utilities Company has filed bankruptcy, and no further assets exist.

QUESTION: Property values have decreased as much as 30% at some residences near the EUC site. Does the Superfund program provide relief for those who are trying to sell their property before the cleanup is completed?

RESPONSE: A home buyout, similar to the one in Times Beach, Missouri, is not likely. Furthermore, there is no language in the federal law that provides reimbursement for declining property values.

QUESTION: Once yard excavation begins would the project stop?

RESPONSE: No, when USEPA approves a remedy, it will allocate sufficient funds before the project begins to complete it.

QUESTION: When will Superfund money be available for the EUC project?

RESPONSE: Superfund is presently depleted. Superfund must be reauthorized by Congress before federal money would be available for the EUC site.

Issue: Soil Contamination

QUESTION: Is yard excavation mandatory?

RESPONSE: No. Each homeowner who has significant concentrations of PCB will be offered yard excavation and internal housecleaning as an option. IEPA encourages all affected homeowners to take advantage of this offer.

QUESTION: What is the smallest concentration of PCB that will be removed from residential yards?

RESPONSE: The IEPA and USEPA considered four different concentrations. Each concentration is measured in parts per million. These concentrations are 50, 25, 10 and 5 ppm. PCB concentrations that equal or exceed 5 ppm will be excavated.

QUESTION: How many tons of contaminated soil will be removed from residential yards?

RESPONSE: Approximately 29,000 cubic yards (equivalent to 36,000 tons) will be excavated.

QUESTION: Do any homes south of 23rd Street have excessive concentrations of PCB?

RESPONSE: No.

QUESTION: How did PCB contamination reach residential yards?

RESPONSE: PCBs were probably transported on the bottom of shoes worn by EUC employees and on tires of vehicles leaving the EUC property. Some PCBs were carried by the winds from the EUC parking lot. However, wind deposition alone does not account for the concentrations found in residential yards. The IEPA is not sure how all the PCBs reached residential yards. If oil was sprayed on roads, this may have contributed to the problem.

QUESTION: To what depths were residential yards sampled to determine the extent of contamination?

RESPONSE: Five feet, but virtually all measurable concentrations of PCBs were found in the top 10 inches of soil.

QUESTION: How were residents first notified about the results of PCB sampling in yards?

RESPONSE: Officials from the Illinois Department of Public Health and the IEPA went door-to-door in March, 1985, to inform residents about the results of PCB sampling.

Issue: Internal House Cleaning

QUESTION: How many homes are eligible for the internal house cleaning option?

RESPONSE: Approximately 20 homes. All homes that have soils excavated will be eligible for the cleaning.

QUESTION: If homeowners of each eligible home request internal house cleaning, what would be the total cost?

RESPONSE: The combined cost for all of the homes would be about \$80,000.

QUESTION: How did PCBs get into homes?

RESPONSE: Most likely from blowing dust and on the bottom of shoes.

Issue: Remedies

QUESTION: What will happen to dirt from residential yards if it is incinerated?

QUESTION: How did trichloroethylene (TCE) get into the groundwater?

RESPONSE: TCE was either spilled or dumped onto the ground when the EUC site was in operation. A tank on the EUC property contained TCE which was drained and hauled off-site in February, 1986, to prevent additional quantities of TCE from reaching groundwater.

QUESTION: Is our drinking water safe?

RESPONSE: Yes. Virtually all the residents in the vicinity of the EUC site have hook-ups to the LaSalle public water supply which is not endangered by TCE or PCB from this site. A survey conducted by the IEPA identified 3 wells on Edwards Street still used for drinking water. These wells, and any other wells within 1/2 mile of the EUC site, will be sampled. Residents living within 1/2 mile of the EUC site who still use their private well are urged to contact the IEPA.

QUESTION: If a deeper well is drilled, would it be safe from TCE contamination?

RESPONSE: A groundwater study is being conducted by Black & Veatch. When the study is complete we should know if deeper aquifers are protected or connected to shallow groundwater in this vicinity.

Remaining Concerns

IEPA anticipates a variety of questions and concerns to arise during yard excavation. Some of these questions and concerns may be resolved before excavation begins. For example, a particular bush may have sentimental value or special appeal, therefore, the IEPA should communicate this concern to the contractor so that plans can be made to protect this bush during excavation. In an effort to identify these special concerns, the IEPA is planning a door-to-door meeting with affected property owners during the design phase.

Some questions and concerns will arise unexpectedly during excavation.

These include access to homes, weather delays, transportation routes, and accommodations. News media coverage of the excavation may extend beyond LaSalle County, and is likely to involve video-taping for television stations as well as still photographs for newspapers. A news conference will be planned for the start of excavation. During the excavation, community relations staff will be in LaSalle to assist residents with special needs. A news release and personal letter will be distributed which provides the location and telephone number where IEPA staff can be reached in LaSalle.

Groundwater will continue to be sampled to determine the extent of contamination. The results of this additional work will be available at the LaSalle Courthouse after analyses of groundwater sampling is complete, and will be discussed at the next public hearing about remedies for on-site contamination.

Appendix II Household Relocation Survey

Revision 1

Household Relocation Survey
USEPA and IEPA
LaSalle Project

Last Name _____
Address _____
Home Phone _____
Work Phone _____

Household Number Name	Age	Need Transportation	If Staying Elsewhere There?	Any Special Dietary Needs?	Any Other Special Needs Handicap Access (E, C, ...)	Total Rooms Needed (Enter Number of Rooms of each type Needed)		
						1	2	King
1								
2								
3								
4								
5								
6								

(Rooms are available with 1 double bed, 2 double beds, 1 king bed.)

Do you have any pets that need accommodations? If so how many, and what type. If applicable have they had their shots?

1. _____
2. _____
3. _____
4. _____

Appendix III Consent Form For Entry and Construction



Illinois Environmental Protection Agency P.O. Box 19276, Springfield, IL 62794-9276

ZONE A

CONSENT FOR ENTRY AND CONSTRUCTION

The undersigned property owner ("property owner") is the owner of the property, including a residence, ("property") commonly known as _____ (address) _____, LaSalle, Illinois.

- A. The property owner, in consideration of having soil contaminated with polychlorinated biphenyls ("PCBs") removed from his property, does hereby authorize and consent to the Illinois Environmental Protection Agency ("IEPA") and the United States Environmental Protection Agency ("USEPA") and their respective representatives, employees, agents and contractors to enter upon the property and into the residence described above to conduct the following activities:
- Excavation and removal of soils contaminated with PCBs from the front, sides and back yard of the property, if necessary.
 - Cleaning of the inside and outside of garages and the inside and outside of the residence, including commercial removal, cleaning and return of draperies to the residence.
 - Placement of clean soils in excavated areas and restoration of vegetation.
 - Soil sampling prior to, during, and after the above described work.
8. The IEPA agrees that the following activities will be undertaken through its duly authorized contractors and the property owner recognizes and acknowledges the following activities in connection with the above described work:
- Soils located at the front, sides and back yard of the property which are contaminated with PCBs in the amount of 5 parts per million ("ppm") or more within the top 12 inches of soil and 10 ppm or more below the top 12 inches of soil shall be removed by excavation and replaced with clean soils, provided that the Illinois General Assembly and federal funding source shall appropriate or otherwise make available funds sufficient for the IEPA to undertake such activity.

- Residential lawns shall be replaced with sod.
 - Shrubs and ornamental vegetation shall be removed and replaced with average size nursery stock of like kind or quality.
 - Trees under 6" in trunk diameter measured 6" above the soil line shall be removed and replaced with nursery stock of like kind or quality having a trunk with a diameter of between 2" and 4" measured 6" above the soil line.
 - Trees of trunk diameter over 6" shall not be removed wherever possible and care will be taken to minimize any adverse impact or damage to them. If replacement is necessary, the tree shall be replaced with nursery stock of like kind or quality having a trunk diameter of between 2" and 4" measured 6" above the soil line.
 - Permanent structures, such as driveways, sidewalks, steps, and patios, shall, wherever feasible, not be disturbed or removed. If removal is necessary, the replacement shall be made of like kind or quality.
 - Fencing or similar items removed shall be reinstalled, wherever feasible, or replaced with comparable items of like kind or quality.
 - In the event the IEPA determines it necessary that for health and safety or logistical reasons that the property owner vacate the property, temporary accommodations and meals shall be provided for the property owner and the household members at the expense of USEPA/IEPA while the work described in paragraph A above is occurring at the property owner's property.
 - The property owner shall be notified seven to ten days prior to the anticipated date that excavation of the property will begin and relocation to a motel will be necessary.
- C. The property owner agrees that any claims which arise against the IEPA or other agency or department of the State of Illinois, or its respective officers, employees, and authorized representatives, or against any contractors for the IEPA or other agency or department of the State of Illinois shall be brought before the Illinois Court of Claims pursuant to the Illinois Court of Claims Act (Ill. Revised Statutes 1985, Ch. 35 Section 439 et seq., as amended).
- D. If the property is occupied by a party or parties other than the legal owner such as a tenant or contract for deed purchaser, please provide signature of the tenant, contract purchaser, or other, in addition to the property owner's signature.
- E. The undersigned property owner agrees that this consent shall become effective from date of signature for a term of one year.
- Dated this 5th day of November, 1987.

ILLINOIS ENVIRONMENTAL
PROTECTION AGENCY

By: [Signature]
Federal Site Management Unit
Remedial Project Management Section
Division of Land Pollution Control

Owner(s)
Signature(s) _____

Home Address _____

Non-Owner
Resident(s)
Signature(s) _____

Appendix IV Video Documentary

Copies Available Upon Request From:

Mary Ann Croce LaFaire
U.S. EPA Region
(312) 886-1728
1-800-621-8431

Communication Traps for Engineers

Melissa F. Shapiro

United States Navy
Washington, D.C.

George Hanley

U.S. Army Corps of Engineers
Kansas City, Missouri

INTRODUCTION

Engineers today are facing the complexities of hazardous waste cleanup. The process is not simply a technical one. They are increasingly aware that straight engineering, no matter how technologically advanced, is not enough to win public confidence. What is needed, in addition to traditional engineering skills, is an ability to communicate with the public on an ongoing basis about the risk and uncertainties of hazardous waste cleanup. There is a need to reach a consensus so that the remedy proposed by these engineers will be accepted. This goal demands that engineers be not only technological wizards, but also skilled communicators.

As we all know, engineers are not trained to be skilled communicators. They are trained to be engineers. What happens, more often than not, is that engineers find themselves walking into large, angry public meetings and facing hostile media interviews; they are generally confused and overwhelmed. Engineers have discovered it isn't enough just to be an engineer, and unfortunately they are not quite sure what to do about it!

In fact, if we look at the Superfund program, whether at U.S. EPA or at federal facility sites, we can see a emerging pattern of certain "communication traps" that engineers fall into time and time again. These "traps", which form the substance of this paper, in no way imply that engineers are not capable of being good communicators. Rather, this paper draws on the observations of community relations experts and seeks to illustrate these traditional communication pitfalls, briefly discuss them and, by pointing them out, make engineers aware of them so that they can develop strategies for coping with them in their site remediation plans.

COMMUNICATIONS TRAPS

Communication Trap #1

"Superfund/Installation Restoration is an engineering problem and will be solved through engineering."

One of the painful realizations long-term Superfund Remedial Project Managers have made is that factors impact on cleanup that have nothing to do with engineering. Factors such as concerns about health, property values, fear of the unknown (which comes into play when a new cleanup technology is proposed), and even fears about loss of control over aspects of community life and decision-making have, at one time or another, all been issues at Superfund sites. A technical solution may not address any of these factors. Yet each one of them, individually or collectively, can slow down or stop a cleanup.

An engineer's basic task is to study a problem, make a recommendation and take some remedial action. This task orientation by many engineers excludes as non-essential anything that is outside the realm

of engineering. The phrase that comes to mind is "... artists fall in love with their models, engineers fall in love with their projects."

An engineer, then, must know about these issues and take them into account when he or she communicates. To ignore these issues is to jeopardize the project and invite failure.

Communication Trap #2

"Those people who don't like my technically sound solution are extremists and I don't have to deal with them."

Almost nothing could be further from the truth. You do have to deal with them! Today in America, we have something called an environmental ethic. What this means is that everyone, regardless of background, income, education or politics, considers himself an environmentalist. Hazardous waste is seen as a personal health and safety issue and, therefore, have the highest priority to everyone.

Some pollsters have even gone so far as to suggest that the environmental movement of the 1990s will be just like the civil rights movement of the 1960s. What this means for engineers is that there is a much broader-based constituency of those people calling themselves environmentalists, and that same constituency represents a cross-section of the American public, not a radical fringe group. To ignore those interests in or in disagreement with the proposed alternative, may very well be to ignore the heart and soul of the public, the very group needed to build a consensus for remedy acceptance.

Communication Trap #3

"Everybody knows how somebody makes a reasonable, intelligent decision. They base it on facts and data, and they weigh risks in a scientific manner."

By virtue of the way engineers are trained, many of us have often make the erroneous assumption that with the right information, and enough of the right information, people will make the right decision. Unfortunately, what has happened, time and time again, is that getting the information out is only half the story. We have to find out what happens to the information once it is out there. We cannot relax just because we have inundated the public with facts and figures.

What comes to mind is the old joke about the child who asks his parents where he came from. They go into a long discussion of human reproduction. At the end the child says—"That's fine, but Johnny is from Cleveland, where did I come from?"

People make decisions differently and they use facts differently. We cannot be complacent just because we put out lots of information. We also cannot assume that people will make decisions the way we want them to or the way engineers do.

Communication Trap #4

"I am the expert. Therefore my judgment will be accepted."

Unfortunately, many engineers approach the public this way. What always comes as a surprise is that expertise is not enough and that sound engineering judgment will not necessarily be accepted. We have seen, many times, that the risk assessments have very little to do with the level of public involvement. As engineers, we often have told communities about what we perceive to be very minor threats to public health or the environment—only to be besieged by calls from the news media and from congressional offices asking if the rumors are true about evacuation. At the same time, we have told communities that a very real threat to public health does exist and we have been unable to arouse enough interest to get people to stop using their contaminated water supply. Our engineering credentials will not necessarily be validated by community support. We cannot expect background and training to carry the battle and make our message understood and accepted.

Communication Trap #5

"Remedial action must be explained accurately and in great detail. We cannot afford to simplify our explanations without sacrificing the quality of our response."

This communication trap is referred to as the "Watchbuilding Syndrome." Ask any engineer what the time is, and he will tell you how to build a watch! While it might be an oversimplification, it certainly is true of many members of the engineering profession.

There are many arguments between the technical staff and the community relations staff on this subject. This dilemma, more than any other, illustrates the tensions between the technical experts and the public. Unfortunately, what gets lost in the battle is the ability to understand the issues. If it is true, as has been suggested, that over half the American people do not know the difference between astronomy and astrology, why do we fight among ourselves over who can be most precise when the message is lost. If we explain difficult concepts in a non-technical way, using everyday examples, we may not get high grades from engineering professors, but we will get understanding and later reach a consensus.

Engineers have to find a middle ground—between being technically accurate and being understood. It might mean developing a whole new vocabulary for explaining some of these issues, a vocabulary that is very different from the one we have been using. Engineers do communicate well with each other, using the lingo of the trade, but the public is not part of the trade. Those who may have served as combat engineers know how far lingo can go. What they know as an E-tool, or entrenching tool, is commonly known as a shovel.

Communication Trap #6

"The public wants lots of information, so I'll tell them everything," or—"I'll only tell them what I think they need to know."

Either one of these approaches is fraught with problems. The major flaw is that this approach assumes what the public's need for information is without validation. It is as though someone asks for a briefing on the state of the world and the briefing is given without any clarification or without asking any questions to ascertain what kind of information is really wanted or needed.

The briefing is almost certain to miss the mark, either by being much too detailed or by leaving out important pieces of information. Community relations at the outset of a study can be very helpful. The information gathered from community interviews in developing the community relations plan can be invaluable for determining future community concerns. Small group meetings with state and local elected officials and with citizens can help those charged with providing information deliver a message that is relevant and effective.

Communication Trap #7

"The public must know all the facts, that is the only way to deal with the bottom line."

There is nothing more deadly for an engineer than to assume that those listening to a presentation on hazardous waste cleanup want to hear how one got from point A to point B to point C to point D to the

bottom line. Too often the assumption is made that the public wants to hear the various options for groundwater treatment and recharge, when the central issue is—"Can I drink the water?"

This is another instance of the public wanting to know answers to certain basic questions and the engineer taking that interest as a request for highly detailed information. The problem again is that the engineer is projecting his information needs and assuming that they are the information needs of the public without validation. Again, unless it is checked out, the engineer is taking an unnecessary gamble, with the cards stacked against him. The engineer will probably lose not only the audience, but also any chances of reaching a consensus on the remedy.

Communication Trap #8

"Talking to the media about hazardous waste is just like talking to anyone else."

We cannot avoid the media during hazardous waste cleanup. Nor should we. We can, however, commit ourselves to making the media equal partners, and we can scrutinize very carefully how we communicate with them so that we make the most of media opportunities. They have a need to report information, and we have a need to reach the public. It is a symbiotic relationship; we are interdependent on each other.

With camcorders, as inexpensive as they are, we can practice press conferences by asking our colleagues to pose very difficult questions and hone your answers into short, sound bytes.

We can call on our community relations staff to make us go through "dress rehearsals" so that we as well as our Public Affairs staff are able to explain complex technical procedures. We also can be proactive with the media, contacting them weeks before the first drill rig or sampling crew arrives on the site. We also can contact them when we do not have "hard news" but set aside time to explain the basics of the Superfund process. Even the most hard-bitten New York Times reporter is willing to listen when the word "Superfund" is mentioned. Surprisingly, an informed media community will report more accurately on proposed cleanup actions. Good news or bad news, reporters need news. If you can give them a story, you have fulfilled their need.

Communications Trap #9

"Communicating risk is just like communicating anything else."

As stated earlier, one of the ironies of being a better engineer in hazardous waste cleanup involves a lot of non-engineer skills. One of these skills is the ability to communicate risk. But, before you communicate risk, you must communicate.

Where many engineers confront their first stumbling block is at the large public meeting. For the first time, they are meeting with the community and not only releasing the results of a multi-million dollar study, but also asking for the public's confidence in the results of that study. In 30 min., an audience of 50 or a 100 people is asked to make a "leap of faith" and wholly accept what they are being told as gospel truth. It is unfair, not only to the public, but also to the engineer. All the time and money spent on research and remedy selection go down the drain if engineers ask for public confidence when they have no relationship with the community.

Again, being proactive makes sense. Imagine how much easier it would be to make a presentation to a community whose concerns are known, with whom we have met often, whose profile we understand, and where we have had the opportunity to practice making our presentation both relevant and appropriate.

Communications Trap #10

"Everyone involved in this process—engineers, lawyers, the public,—has shared goals."

Strange as it may seem, hazardous waste cleanup sites present a different set of opportunities to everyone. While an engineer views cleanup as an opportunity for study and problem-solving, others may see it as: an issue around which to organize a community, an anti-growth initiative, a serious threat to children's health, a reason to close a military base, or perhaps even an opportunity for posturing various political

positions. The engineer needs to know that all these groups with different interests are going to have different expectations about the process, and they are going to try to use the cleanup process for different ends.

Many of these players can be identified in developing the community relations plan, and the earlier they can be singled out the better. If an engineer has to communicate information to the public and is not aware of the different actors, the presentation probably will not be successful.

CONCLUSION

Engineers, by virtue of their training as engineers, have to recognize

that very human factors come into play on hazardous waste cleanup projects that have nothing to do with their engineering expertise. As project managers, they have to recognize that technical expertise is not enough and that their stature as engineers does not buy them any extra credibility or acceptance.

Engineers also need to remember that all communities are different, and knowing the community will be an important part of communicating information effectively. Finally, becoming aware of false assumptions that are often made is the first step in developing communication strategies for coping with site remediation.

Study, Design and Construction of an On-Site Recoverable Storage Facility

Edward Patrick Hagarty, P.E.

Robert M. Gruninger, P.E.

C.C. Johnson Malhotra, P.C.

Silver Spring, Maryland

Manu A. Patel, P.E.

City of Baltimore

Baltimore, Maryland

ABSTRACT

The City of Baltimore acquired a site for construction of a wastewater treatment facility along the Patapsco River, a tributary of the Chesapeake Bay, in 1924. Since then, the Patapsco Wastewater Treatment Plant has become a regional, publicly-owned treatment works (POTW) serving the City and parts of three adjacent counties. Prior to the City's acquisition of the property, land along the shoreline of Baltimore's Inner Harbor, including part of the Patapsco site, had been filled with chromium ore tailings from a nearby refinery.

Health effects from exposure to chromium were not known at the time the original plant was constructed. However, new information is available regarding the health effects of exposure to chromium. When the regional facility required expansion, the City was faced with a severe problem. Special handling would be needed to excavate in areas of chromium-contaminated soil to protect the environment and the health and safety of construction workers, plant employees and nearby residents.

Expansion of the POTW included the replacement of obsolete primary settling tanks, the installation of additional biological treatment reactors and clarifiers, additional chlorination capacity and new dechlorination facilities. This expansion could not be postponed since the City was required to add these facilities before any more users could be added to the regional system.

The City and its consultant, C.C. Johnson and Malhotra P.C. (CCJM), prepared a plan through which the contaminated soil could be safely removed from the areas of proposed construction and stored in an on-site, recoverable storage facility. State regulatory authorities were consulted to determine the acceptability of placing the excavated soil in recoverable storage on-site. Such a plan permitted construction of the POTW improvements to begin without requiring an immediate decision on the treatment or permanent disposal of the contaminated soil.

After obtaining approval from the State, the remedial investigation, including the preparation of the report, was completed in less than 6 mo. Additional data were collected by drilling boreholes, installing wells and collecting and analyzing soil and groundwater samples. The results of the study were used to prepare the plans and specifications for construction of an on-site recoverable storage facility area, excavation and handling of contaminated soil and a pretreatment plant to reduce the chromium concentration of groundwater and water from decontamination.

The project, including project planning, the remedial investigation and design were completed for bidding in only 15 mo. Construction of the on-site recoverable storage facility and storage of the contaminated soil from construction of the primary settling tanks was completed in August, 1989.

INTRODUCTION

Site History

In the late 1800s and early 1900s, residue from chromium ore refining operations was used as fill along some of the shoreline of Baltimore's Inner Harbor. In 1924, the City of Baltimore acquired a 65-ac site for construction of a wastewater treatment facility along Baltimore's Inner Harbor bordering the Patapsco River, a tributary to the Chesapeake Bay. The site was located in an area that had fill material consisting of chromium ore tailings. Nevertheless, the wastewater treatment facility was constructed and began serving the residents of the City.

Since its initial operation, the treatment facility has been expanded to become a 70 mgd publicly-owned treatment works (POTW) serving the City and parts of three adjacent counties. Throughout the initial construction and subsequent expansions, no concern was expressed about the POTW being constructed within an area containing chromium. This oversight was primarily due to a lack of scientific knowledge regarding potential hazardous characteristics of chromium and a lack of regulation of such material.

In 1984, it was determined that the POTW would require expansion from 70 mgd to 87.5 mgd to meet the anticipated population projections and to provide a higher level of treatment. To meet these needs, the City prepared plans and specifications to replace obsolete primary settling tanks, add new biological treatment reactors, provide additional chlorination capacity and add new dechlorination facilities. After the design for most of these facilities was complete, the prospect of excavating within an area contaminated with chromium ore tailings forced the City to determine a course of action which would allow the necessary construction to proceed without subjecting construction personnel, plant employees and the nearby public to high levels of chromium. After discussion with the State of Maryland Department of the Environment (MDE), the City determined that the best solution was to construct an on-site, recoverable storage facility. This option was selected over other alternatives considered, such as on-site treatment of soils and off-site disposal, on the basis of cost and the potential that the fill material might be exempt from hazardous waste handling requirements because it is a waste from the processing of chromium ore. An on-site, recoverable storage facility allowed the City to construct the necessary POTW expansion while retaining the flexibility to properly handle the chromium-contaminated soil. The on-site storage facility could accept chromium-contaminated fill incrementally during different phases of the plant expansion and avoid the costlier on-site treatment until a long-term management plan for the material could be determined.

Previous Investigations

Prior to 1986, no investigations had been conducted to determine the

nature and extent of contamination at the site. As part of the geotechnical investigation for the POTW expansion, the City had samples collected for analysis. The geotechnical consultant collected numerous surface and subsurface soil samples and groundwater samples¹. Analyses included total chromium, hexavalent chromium and EP Toxicity (for chromium only).

Results

Samples were collected throughout the entire 65-ac plant site and showed a general pattern of chromium-contaminated soil within the old bulkhead line and cleaner material located outside of this line. The old bulkhead line was the limit of the site until 1976 when clean fill material was used to extend the shoreline to its current configuration (Fig. 1). Data review focused on the two areas of proposed construction: the new primary settling tanks and the chlorination/dechlorination area shown on Figure 1. Chromium levels in the majority of the soil from ground surface to a depth of 16 ft exceeded EP Toxicity Standards in the area of the proposed primary settling tanks. Unfiltered groundwater samples from this area had a maximum total chromium concentration of 180 mg/L and a maximum hexavalent chromium concentration of 6.2 mg/L.

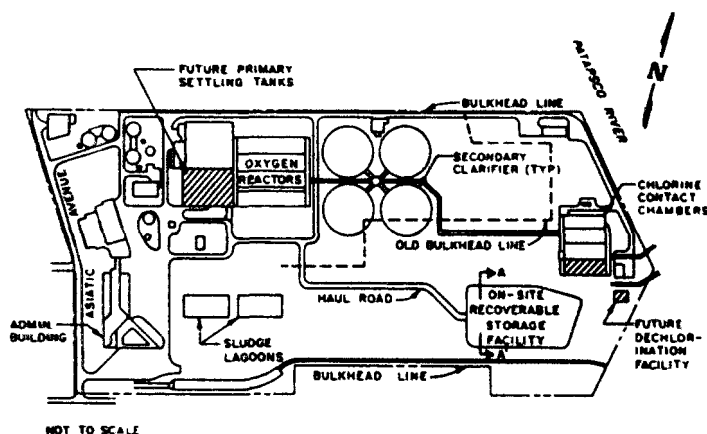


Figure 1
Patapsco POTW Site

The area of proposed additional chlorination and dechlorination facilities is located outside of the old bulkhead line and showed a different pattern of contamination. High concentrations of chromium in this area are generally limited to the surficial soils. The only groundwater sample collected from this area had a total chromium concentration of 130 mg/L and hexavalent chromium concentration of less than 0.1 mg/L. The results of this investigation provided a good basis for gathering the additional information needed to design the excavation of the contaminated soil and the on-site recoverable storage facility. The additional site investigation, described in the following section, included surficial and split spoon soil sampling and well construction for groundwater sampling in the specific areas of proposed construction.

SITE INVESTIGATION

Investigation Objectives

This project was completed utilizing a standard engineering approach to accomplish the project objectives. The overall objective of the project was to allow the construction of the POTW expansion to proceed as quickly as possible in an environmentally safe manner. The standard engineering approach, consisting of plan, design and construct, is similar to that followed in the Superfund program.

The major phases of the project comparing the standard engineering approach to the corresponding Superfund project phases are as follows:

Project Phase	Engineering Approach	Standard Superfund Phase	Objective
Site Investigation	Plan	Remedial Investigation	Gather Information
Preliminary Design	Plan	Feasibility Study	Select Approach
Design	Design	Remedial Design	Prepare plans and specifications
Construction	Construction	Remedial Action	Implement plans and specifications

One major difference between the Patapsco POTW expansion project and a Superfund project is the difference in objectives of the site investigation. The usual objective of the Superfund remedial investigation is to fully characterize the nature and extent of contamination at the entire site. The site investigation for the Patapsco POTW expansion had the following objectives:

- Confirmation that chromium was the only contaminant of concern
- Determination of the extent of chromium contamination in the areas of proposed construction
- Determination of groundwater contamination

Cleanup Criteria

A major problem of remedial actions at soil contamination sites is the determination of cleanup criteria. Federal cleanup criteria exist for drinking water sources; however, no such criteria exist for soils. Some State regulatory agencies have developed site-specific cleanup standards that are applied during real estate transactions of industrial properties². No such criteria were established for the Patapsco POTW site. In lieu of such regulations, the State Hazardous and Solid Waste Management Administration agreed with the City of Baltimore to use the EP Toxicity Criterion for chromium as the guideline for determining what soil had to be placed in the on-site, recoverable storage facility.

The EP Toxicity test is one of the tests used to determine if a waste material is considered hazardous under RCRA. Soil samples are subjected to an Extraction Procedure using acetic acid intended to simulate natural leaching in a landfill over a number of years. The extract obtained is tested for total chromium. The maximum allowable value for non-hazardous material is 5.0 mg/L of total chromium in the extract.

In addition to testing for EP Toxicity, a few selected soil samples were analyzed for U.S. EPA's priority pollutants. This sampling and analysis was performed to confirm that chromium was the only contaminant of concern and to establish minimum health and safety requirements for the construction contractors. Groundwater samples were collected in both areas of proposed construction and analyzed for priority pollutants.

The City of Baltimore has an industrial pretreatment program which has established maximum allowable contaminant concentrations for industrial discharges to the POTW. These criteria were compared to the results of the groundwater sampling to determine the need for treatment prior to discharge to the plant influent.

Results

The results of the previous investigation were combined with the results of the additional site investigation. The evaluation indicated that chromium was the only contaminant of concern in either area of proposed construction. In the area of the proposed primary settling tanks, the majority of the soil to be removed during construction contained chromium at levels exceeding the EP Toxicity Standard of 5.0 mg/L. Therefore, all soil excavated from this area was recommended for storage in the on-site, recoverable storage facility. Unfiltered groundwater samples from this area contained maximum concentrations of total and hexavalent chromium of 180 mg/L and 6.2 mg/L, respectively.

The results of the investigation in the area of proposed construction of the chlorination and dechlorination facilities differed from those in the area of the new primary settling tanks. Chromium contamination in this area is primarily limited to soil at depths of less than two ft. The only groundwater sample that showed any chromium contamination had a total chromium concentration of 130 mg/L. This sample was taken from an open boring and was probably high in sediment content.

DESIGN PHASE

Following the site investigation, an on-site, recoverable storage facility for contaminated soil was designed. During an earlier phase of development of the site, a lagoon was constructed of native clay soils having a permeability of 10^{-6} cm/sec. Various materials including some chromium contaminated soil and some sludge were already in the lagoon. The remaining capacity in the lagoon was estimated to be sufficient to accept all of the contaminated soil associated with the current expansion of the plant from 70 mgd to 87.5 mgd. It was agreed that the existing lagoon should be lined, and when the soil placement was complete, it would be covered with a high density polyethylene (HDPE) material (Fig. 2). The bottom liner was designed to be 80 mil thick and the top cover to be 40 mil thick.

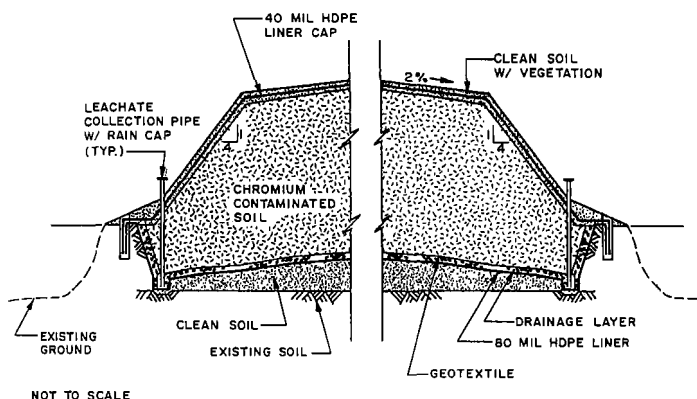


Figure 2
Section A-A'
Recoverable Storage Facility

The presence of contaminated material within the existing 4-ac lagoon required that the design include construction staging so that half of the lagoon was to be cleared of contaminated soil, the bottom surface was to be shaped to provide sumps in which leachate could be collected and the bottom liner was to be installed. When the first half of the 80-mil liner was installed and tested, a synthetic drainage mat and layer of soil was to be placed over the liner. This would be covered with geotextile; then the contaminated soil in the lagoon would be moved to the newly lined area. The liner construction process was to be repeated for the second half of the lagoon.

Following the placement and testing of the liner and placement of the drainage mat and soil, the contaminated soil from the new primary settling tank construction could be safely moved to the on-site facility. The new primary settling tank construction was to be done on a site containing six old, low level tanks. These were a part of the original plant construction and had been incorporated into the 1971 design when the present plant was constructed. An Archimedes screw pumping station was constructed in 1971 to lift the primary effluent from the low level tanks to the biological treatment reactors. Because the old tanks were no longer functional, they and the screw pumps were to be removed under the current contract. Samples of the concrete from the walls and floor of the old tanks indicated no chromium contamination in the concrete, so the plan was developed to brush or scrape soil from the demolition debris and remove the concrete debris from the Patapsco POTW site to a nearby rubble landfill. The plan for demolition required removal of interior walls first, then exterior walls and finally the bottom slab. In this way, exposure to the contaminated soil was minimized.

Following the removal of the concrete rubble, soil excavation would occur. A dedicated haul road between the excavation site and the recoverable storage facility was constructed. The sites and the roadway were fenced to deny access to the contaminated zone during the removal of approximately 25,000 yd³ of contaminated soil. Including the haul road in the contaminated zone also eliminated the need for frequent equipment decontamination.

Dewatering of the site was necessary since the construction would occur below the groundwater level. Based on pumping and sampling the observation wells installed during design, it was determined that 7,000 gpd of chromium contaminated groundwater would be pumped and treated. A treatment system was designed to meet the total chromium concentrations prescribed in the City's industrial pretreatment ordinance. Additional water from equipment and personnel decontamination and precipitation also required pretreatment. The total capacity was specified to be 30,000 gpd. Because most of the chromium contamination was associated with soil particles in the water, a dissolved air flotation system with chemical addition was designed and specified. Once treated to City standards, the effluent from the portable pretreatment plant would be discharged to the POTW influent for final treatment and discharge to the Patapsco River.

The primary path for chromium contamination of the environment and site personnel is airborne dust. The site health and safety plan recognizes airborne dust as the major problem. Skin contact with soil and contaminated water are also possible contaminant paths. Therefore, the site health and safety plan required workers at the site to keep the contaminated soil moist to minimize airborne particles. Also, the workers were required to wear washable cotton coveralls, boots, gloves and hard hats. An emergency respirator was part of each worker's standard gear. Dust monitors were specified for the perimeter of the work zone with alarms set for the 5 ppm dust action level. With the prescribed dust control procedures during the soil excavation, haul and placement operations, alarms were not expected to sound at this site.

CONSTRUCTION PHASE

Dust monitors were installed on the perimeter fence of the contaminated zone as specified. During the construction work, field inspectors enforced the requirement that all exposed soil be kept moist. Therefore, except for a single malfunction due to a spider, no dust alarms were triggered during construction.

Several field changes were implemented during construction. At the contractor's request, disposable Tyvek coveralls were used instead of washable cotton coveralls provided the contractor assumed responsibility for the disposal of the Tyveks apparel.

Unanticipated infrastructure was found during construction of the lagoon liner. This included an abandoned, 42-in. diameter storm sewer which had to be removed prior to installing the base liner. Also, it was discovered early in the earth moving phase, that the existing contaminated stock pile extended several feet beyond the old lagoon boundaries on the northern side of the area.

Construction of the 80-mil base liner occurred as planned without other significant problems. However, placement of the top HDPE cover presented some interesting problems. The second construction contract for chlorination and dechlorination facilities that was planned to dovetail with construction of the primary settling tanks was delayed. The City decided to reject bids and readvertise with the result that less material was placed into the recoverable storage facility than planned. Therefore, the top cover was placed on the slope of the contaminated soil facing the empty northeast quadrant. A problem of inadequate anchorage of the toe of the HDPE cover was encountered. Wind got under the cover, lifted it and formed an air bubble. The toe of the cover moved approximately 10 ft up the slope. Before the cover could be adequately secured, the wind lifted almost the entire cover. The cover was kept within the containment area only by the anchor trench holding down two sides of the liner. The cover had to be pulled back in place, slit, spliced and welded to repair

the damage. When sufficient sand bags for temporary anchorage were placed on the toe of the cover, the problem was resolved.

Due to the high permeability of the soil and the proximity of the Patapsco River, the flow rate required for the dewatering operations was much higher than planned. However, analysis of groundwater samples revealed that the water being pumped from the site was not as contaminated as anticipated. Therefore, groundwater could be discharged to the Patapsco POTW influent without treatment while meeting the prescribed pretreatment standard for total chromium. The groundwater quality was monitored daily for the initial two weeks and on a weekly basis thereafter. Any adverse changes in quality would have resulted in increased frequency of testing followed by pretreatment to reduce the chromium to concentrations within the pretreatment discharge standard.

COMMUNITY RELATIONS

Two meetings were held with the concerned public regarding the Patapsco contaminated soil containment project. One meeting was held with the staff of the POTW to explain the nature of the problem and the project, the precautions taken in preparing the design and the requirements imposed on the construction contractor and the plant staff. The plant staff was denied access to the contaminated area for the duration of the project. The practical aspects of contaminant transfer and the mitigation measures were explained to the staff. Following the meeting, questions were answered by the consultants and City engineering staff. It was agreed that results of monitoring would be made known to the POTW staff.

A meeting for the general public, including residents living adjacent to the POTW, was held several days following the meeting with the POTW staff. The consultant presented the information in a similar manner. A fact sheet was distributed by the City to local residents to acquaint them with the project. The meeting for the general public received local media coverage. As expected, the initial public reaction

was adverse, but after careful explanation, the neighbors were satisfied that adequate mitigation measures were planned to protect them and the environment from contamination.

CONCLUSIONS

The City of Baltimore was in the difficult position of being required to expand the Patapsco POTW while controlling potential exposures to chromium-contaminated soil. The City reached an agreement with the State Hazardous and Solid Waste Management Administration that an on-site, recoverable storage facility would be used for long-term storage of the contaminated soil.

A streamlined site investigation was conducted so that plans and specifications to construct the facility could be completed. The process from the start of the site investigation phase through the end of the design phase was completed within 15 mo. Construction of the recoverable storage facility has allowed the City to continue with its required POTW expansion while handling the chromium-contaminated soil on-site in an environmentally sound and cost-effective manner. This approach has not precluded future decisions regarding treatment, disposal or reuse of the stored material.

ACKNOWLEDGEMENTS

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REFERENCES

1. Earth Engineering & Sciences, Inc., *Subsurface Investigation Patapsco Waste Water Treatment Plant*, Baltimore, MD, Nov., 1986.
2. New Jersey State Legislature, *Environmental Cleanup Responsibility Act*, Trenton, N.J.

The Observational Approach for Site Remediation at Federal Facilities

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ABSTRACT

The current approach to hazardous waste site remediation is based on the assumption that all important information about the site will be known before remediation begins. This approach, based on the conventional engineering paradigm of study, design and construct, leads to the selection of a single remedial alternative with no contingencies for variations encountered during construction. The design and construction of remedial alternatives is approached much as the design and construction of a bridge or a treatment facility.

This approach works well for traditional engineering activities, where uncertainty can largely be eliminated by study and investigation and by the existence of a large body of empirical evidence. However, hazardous waste site characterization and remediation is dominated by uncertainty. Variations in soil conditions, geo-hydrology, transport mechanisms, waste source and chemical and physical characteristics make it impossible to completely characterize and understand actual site conditions. In an attempt to overcome this uncertainty, site characterization all too often consists of excessive rounds of sampling. At best, excessive sampling requires too many resources. At worst, excessive sampling can lead to a false sense of confidence and a disregard for reasonable variations that could disrupt the effectiveness of the selected remedial action.

There is, however, another way to approach hazardous waste site remediation. The observational approach, developed by geotechnical engineers to cope with the uncertainty associated with subsurface construction such as tunnels and dams, can be applied to hazardous waste site remediation. During the last year, the observational approach has gained increasing attention as a means of addressing the uncertainties involved in site remediation.

In order to evaluate the potential advantages and constraints of applying the observational approach to site restoration at federal facilities, a panel of scientists and engineers from Pacific Northwest Laboratory and CH₂M Hill was convened. Their review evaluated potential technical and institutional advantages and constraints that may affect the use of the observational approach for site remediation. This paper summarizes the panel's comments and conclusions about the application of the observational approach to site remediation at federal facilities. Key issues identified by the panel include management of uncertainty, cost and schedule, regulations and guidance, public involvement and implementation.

INTRODUCTION

The remedial process, as it typically is approached, has become "bottlenecked" by the uncertainties associated with fully understanding the nature of hazardous waste problems. As it typically is implemented, the current approach to site remediation is based on principles from

conventional engineering. The assumption is that uncertainties in site conditions can be effectively reduced to manageable levels during the RI/FS phase of the process, thereby allowing the design and implementation phases to proceed routinely and predictably. This has not been proven to be the case for many sites; new information discovered during design and implementation has often forced significant alterations in planned remedies¹.

The current process leading to site remediation follows a traditional engineering paradigm of study, design and build. Following a series of discussions about the scope of the project, U.S. EPA's objectives, budget, operating assumptions and initial data, an RI is initiated, followed by a FS that compares alternatives. A ROD declares the preferred alternative, and a design is then prepared for remedial construction. This process of site investigation, alternative evaluation and remedy selection is described in U.S. EPA guidance² and followed by remedial managers and planners in all U.S. EPA regions. There is, however, often a significant difference between the process as described in U.S. EPA's guidance and regulations and the process as it typically is implemented. For example, the current guidance and regulations provide considerable support for many of the fundamental elements of the observational approach. Nonetheless, many of these elements, such as the early screening of general response actions or including engineering considerations in early characterization efforts, are not generally included in remedial investigations.

This evaluation of the observational approach used the process of site remediation as it generally is conducted as a baseline for comparison with the observational approach.

Problems with the Current Approach to Site Remediation

The process of site remediation, or at least the RI/FS phase of that process, has been going on long enough to establish a track-record. Recent reports conclude that the site remediation process, as it generally is conducted, often fails to provide effective, efficient cleanups³. One of the fundamental problems with the current process or approach is the failure to explicitly recognize the role that uncertainty plays in virtually every aspect of site remediation. It generally is assumed, for example, that more study will reduce uncertainty. But to date, it has not been fully recognized that the marginal value of further studies at Superfund sites declines rapidly. At some point, more study does not lead to better information.

Another problem with the current approach to site remediation is the emphasis on a "paper" product: contractors and managers tend to focus their efforts on producing an RI/FS and a ROD. As a result, they often obscure the important goal of protecting human health and the environment in their rush to meet the milestones of the RI, the FS or the ROD. The extensive uncertainty of site conditions, as well as the

complex nature of the process remediation process, tends to keep both technical contributors and management focused on a series of short-term objectives (paper studies) and tends to prevent "big picture" perspective of the ultimate goal (cleanup). This emphasis on producing a paper product has contributed to excessive costs and prolonged schedules. At complex sites, for example, millions of dollars may be spent over many years to simply issue the ROD.

The problems with the site remediation process derive largely from the ever-present element of uncertainty and the apparent inability of the process to respond appropriately to that uncertainty. Many factors contribute to uncertainty in site remediation. The subsurface environment is complex, heterogeneous and almost impossible to fully characterize. Moreover, small subsurface features or changes in geologic conditions can have substantial impact on contaminant movement. Major uncertainty also plagues source characterization; assessment of chemical fate and transport in the environment; assessment of exposure risks and health effects and; remedial action performance. Taken together, these factors make uncertainty an inherent feature of hazardous waste sites.

This state of uncertainty should not lead to inaction. Uncertainty is not unique to hazardous waste problems; geotechnical engineering has had to respond frequently to similar situations. The engineering community now has the opportunity to bring a different and a generally more appropriate, paradigm to Superfund site remediation.

The Observational Approach to Site Remediation

The observational approach is based on principles developed by geotechnical engineers in response to the uncertainty of conditions encountered when constructing tunnels and other sub-surface structures. Instead of trying to completely characterize sub-surface conditions before beginning construction, the observational method, as it is referred to in geotechnical literature, requires only that the probable conditions of a site be known. Once the expected conditions are defined, potential, but reasonable, deviations to those conditions can be identified and contingencies can be prepared to respond to those deviations. If the contingencies for all reasonable deviations can be accommodated by the projected construction techniques, construction is begun. If, however, the projected construction techniques cannot accommodate all reasonable deviations, then further characterization is required to more precisely define the expected conditions and thereby reduce the number of reasonable deviations.

A complete explanation of the observational approach is beyond the scope of this paper. Such an explanation is included, however, in Peck⁴. The fundamental elements of the observational method have been refined by CH₂M HILL for use on hazardous waste sites as follows:

- Define scope of work: establish goals and objectives, review existing data, develop a conceptual model and identify data gaps
- Conduct an initial screening of general response actions
- Collect information on site conditions, including the nature and extent of contamination
- Use the information collected to construct a conceptual model of the site to establish probable conditions and reasonable deviations
- Prepare a feasibility study: evaluate the remediation alternatives and prepare conceptual contingency plans as a response to identified deviations; recommend the most effective alternative, given probable conditions at the site
- Design the chosen remedial action, select parameters to observe and prepare contingency plans
- Implement remedial action and measure responses
- Respond to deviations

These eight steps represent an outline of the observational approach to site remediation. It is probably more useful, however, to think of the observational approach as a conceptual framework for site remediation. The three basic tenets of this conceptual framework are: (1) characterization should be undertaken for a specific purpose, not just to find out about the contamination at or the general characteristics of the site; (2) more data do not automatically lead to better infor-

mation; and (3) the process should converge on a general response action as early as practical. Keeping these basic tenets in mind throughout the RI/FS process should provide a better focus to the technical work, thereby offering the opportunity for lower costs, shorter schedules and a superior technical product.

The observational approach also may lend itself to maintaining a "big picture" perspective throughout the remediation process. This perspective could help change the focus from producing a RI/FS to determining the problem and the best solution and could result in a higher quality of work, lower costs and a shorter schedule.

Other advantages to the observational approach include:

- Providing an opportunity for decision-makers to prepare for events, rather than merely respond to them.
- Establishing a more formal mechanism for evaluating the work done during a previous phase before proceeding to the next phase this crucial step in strategic planning generally is missing from most current site remediation activities.
- Providing for specific contingencies to respond to potential deviations from expected conditions.

Implementing the observational approach for site remediation at federal facilities will involve a number of issues. The key issues, as identified by a panel of scientists and engineers from PNL and CH₂M Hill, are discussed below.

BETTER MANAGEMENT OF UNCERTAINTY

Uncertainties in site remediation exist regardless of how the remediation process is conducted. Most current site remediation strategies, however, either ignore those uncertainties or assume that sufficient study and assessment will essentially eliminate them. But one of the harsh realities of site remediation remains constant: uncertainty can be neither ignored nor studied away. The observational approach, by explicitly recognizing uncertainty, offers a credible mechanism for dealing with that uncertainty. The practical advantages of such a mechanism include an improved technical understanding as well as a more honest presentation of the situation to the public.

Unexpected conditions always will be a possibility in any site remediation effort. Since no amount of study will eliminate the possibility of surprise, planning for reasonable deviations is simply good risk management. The observational approach provides a mechanism for planning for the unexpected. One of the fundamental elements of the observational approach, the inclusion of contingencies to deviations from expected conditions, can help with planning for the unexpected. By identifying reasonable deviations to expected conditions, planners can consider general responses to, or contingencies for, those deviations. The deviations to expected conditions could be identified in the FS together with their implications for each of the alternatives under consideration. Specific contingencies to respond to those deviations would be developed in the remedial design (RD) phase, after the ROD has been issued.

By establishing contingencies as a formal part of the process, the observational approach offers an opportunity to identify potential problems and responses to those problems, before they occur. Instead of facing a crisis when something goes wrong, decision-makers have the advantage of being prepared with pre-planned contingencies for possible problems. Consequently, when a problem occurs, the response can be implemented more quickly, potentially saving time, money and embarrassment. The more conservative alternative is to over-design the remedial action so that any possible contingency can be readily handled. The excessive cost of such a conservative approach, however, essentially precludes it as a meaningful response to uncertainty.

In summary, uncertainty will exist regardless of the method or approach used for characterization and remediation. The observational approach simply offers a better way of managing that uncertainty.

REGULATIONS AND GUIDANCE

U. S. EPA regulations and guidance offer substantial support, both

direct and indirect, for the use of the observational approach for site remediation. Direct support comes from an OSWER Directive issued early in 1989 recommending several measures to reduce the time and the cost of the RI/FS process¹. This guidance included a direct recommendation for each U.S. EPA region to use the observational approach in at least one Superfund-lead site or operable unit in 1989. Other recommended streamlining measures that support the concept of the observational approach include:

- Identifying the use of data before obtaining those data
- Identifying probable remedial action(s) as early in the process as possible
- Tailoring the level of detail of the alternative evaluation to the scope and complexity of the action

Portions of the proposed NCP also reflect, or offer further support for, elements of the observational approach. According to the proposed NCP, a primary program management principle to be followed by the U.S. EPA is a "bias for action." The observational approach offers a structure for applying this principle by integrating action and study as the RI and the FS proceed. This integration could include:

- Narrowing down the field of potential remediation technologies earlier in the process
- Tailoring the level or detail of the analysis of evaluation criteria to the scope and complexity of the action
- Tailoring the selection and documentation of the remedy based on the limited scope or complexity of the site problem and remedy.

The NCP clearly advocated that action be taken to move forward with the actual work of remediation as early as site data and information make it possible to do so. The observational approach provides a credible mechanism for doing so.

Although there is specific support for the observational approach in the U.S. EPA regulations and guidance, it is nonetheless possible that implementing the observational approach could be perceived as an "end run" around the regulations. It will, therefore, be very important to get early agreement from the appropriate agencies (and individuals) about establishing a mechanism for dealing with uncertainty (i.e., the observational approach).

NEPA Constraints: One cannot pre-judge the process

In addition to compliance with all federal, state and local regulations applicable to all Superfund sites, federal facilities often must conform to the requirements of the National Environmental Policy Act (NEPA). One of the primary constraints of NEPA, which many federal facilities are obliged to work with in site remediation, is not pre-judging the outcome of the process. The potential issue here is that one of the goals of the observational approach is to converge on a probable remedy early in the process. To work within the requirements of NEPA, however, it is imperative that any such convergence not be made to the exclusion of considering a wider range of alternatives. In other words, even if early in the process there is little question about what the final remedy will be, the investigation cannot be narrowed down to looking for only information that will support decisions about that remedy. On the other hand, there will be different levels of detail associated with the consideration of various alternatives. There is no requirement under NEPA to apply the same level of detailed information to all potential alternatives, so it is possible to pursue "less likely" alternatives to a lesser depth than the more (or most) likely alternative. In all cases, however, there must be enough information on each alternative to justify the eventual decision to either eliminate or select it.

COST AND SCHEDULE

One of the potential advantages of the observational approach is the opportunity to start sooner on the actual work of site remediation. Given the bias for action of the NCP and the consequent U.S. EPA guidance, a remedial project manager does not need to "use the observational approach" to get started sooner on actual site remediation. However, the observational approach does provide a conceptual framework that allows remediation to begin as soon as the regulating agency(ies) allow.

There are two primary ways that actual cleanup work can begin on

an expedited basis. The first is to move through the RI/FS process more quickly, primarily because of a more focused and therefore reduced, sampling program. An appropriately focused sampling program will provide much of the information necessary for engineering design during the RI phase. Such an integrated sampling program also may reduce the length of time it takes to produce the FS report. Although interim response actions are possible under the current process, they are not typically integrated with the conventional aspects of investigation and alternative evaluation. The observational approach offers the opportunity for integrating interim response activities with the longer-range objectives of site remediation.

A second way that cleanup action can begin sooner is to incorporate cleanup activity into the RI process. Examples of integrating cleanup activities with remedial investigations include removing underground drums and tanks and initiating soil vapor extraction to recover volatile organics that would otherwise continue to disperse into the environment.

Although it is possible that the observational approach may lead to faster action, it would be unwise to claim that the observational approach will lead to faster cleanups. A conservative claim is that the observational approach provides the opportunity for faster action, but it is not clear it will do so in all, or even most, situations.

Just as the observational approach provides the opportunity for faster action, it also may provide the opportunity for lower cost. The potential for lower costs comes from the possibility that an observational approach RI/FS will be "leaner and meaner" than the conventional approach, as it is typically implemented, would allow. With specific targets for information, sampling costs could be lower. And narrowing down the set of alternative remedies early in the process could reduce the time and therefore the cost, of producing the RI/FS report.

There is support from the regulations for this sort of "streamlining" that could lead to lower costs. According to the proposed NCP, "The RI should be focussed so that only data needed to develop and evaluate alternatives and to support design are collected."⁵ The observational approach, could provide a coherent framework for decisions about what data to obtain. Under the observational approach the specific goals of sampling and analysis would be more strictly defined and the quantity of samples required to reach a given decision could therefore be reduced.

It is very important to realize, however, that there is no guarantee that using the observational method will result in lower costs.

CONCLUSIONS

Hazardous waste site remediation has, to date, been conducted following the conventional engineering paradigm of study, design and build. The reality of hazardous waste sites, however, is dominated by uncertainty, a condition for which the conventional engineering paradigm is poorly suited. The observational approach offers a way of acknowledging and dealing with the inherent uncertainty of hazardous waste site conditions. Specific conclusions include:

- Uncertainty in site remediation activities cannot be eliminated by further study at some point in the remediation process, uncertainty must be confronted.
- The observational approach can provide a central philosophy for the entire process of site remediation, from project planning through post-closure monitoring; the potential advantages of incorporating such a philosophy throughout the process include providing a framework for various streamlining measures which can lead to a more efficient use of resources to achieve a high level of remediation.
- The observational approach provides a better mechanism for managing risk; uncertainties will always be present in site remediation work, but acknowledging those uncertainties and preparing for deviations can minimize the consequences of the unexpected.
- There is nothing in the current regulations and guidance that precludes the use of the observational approach for site remediation; in fact, an aggressive remedial project manager can implement the observational approach based on support from various elements of the regulations and guidance.

ACKNOWLEDGEMENT

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REFERENCES

1. U.S. EPA Office of Solid Waste and Emergency Response (OSWER) Directive 9355.3-06, *RI/FS Improvements Phase II, Streamlining Recommendations*, Feb., 1989.
2. U.S. EPA, OSWER Directive 9355.3-01, *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA*, Oct., 1988.
3. U.S. Senators Lautenberg and Durenberger, *Report on Superfund Implementation: Cleaning Up the Nation's Cleanup Program*.
4. Peck, R.B., Advantages and Limitations of the Observational Method in Applied Soil Mechanics, *Geotechnique*, 19, pp. 171-187, 1969.
5. U.S. EPA, Proposed Rule: Proposed National Contingency Plan, 300.430, *Fed. Reg.* 53, (245), Dec. 21, 1988.

New Capability For Remote Controlled Excavation

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ABSTRACT

Remote controlled operation of construction equipment has been state-of-the-art for some years. The availability of remote controls which have been designed and developed for general use on commercial machines is a recent development and is the subject of this paper. The John Deere teleoperated excavator represents a new capability that is now available to the construction industry for use on construction sites that preclude the on-site presence of human operators. This paper will describe the basic machine, the controls, vision system and integration of the remote control adjunct to the operational system. Much of the development of the initial capability was done with the cooperation of Vectran Corporation of Pittsburgh, Pennsylvania.

THE BASE MACHINE

The John Deere 690 Excavator is a commercially available production machine. The first teleoperated unit was fielded on this variant (Fig. 1). The base machine is a 41,000-lb excavator, modified for the Air Force to include a wheeled undercarriage, a dozer blade, stabilizers, a hardening package and variable boom geometry. The 690CR and now



Figure 1
John Deere 690OCR Excavator

the 690DR are the mainstays of the Air Force rapid runway repair fleet. The machine has 125 net hp, 31-ft reach and 20-ft dig depth. It is supplied to the Air Force with a bucket, hydraulic breaker and tamper that enable it to perform the functions needed to repair craters on damaged runways. The repair of runways is currently a manned operation. However, the Air Force needed an additional unmanned capability to deal with unexploded bombs at an Air Force test range. This capability was provided by the Teleoperated Remote Controlled Excavator (TORCE).

The TORCE excavator will transport and perform all work functions from a distance of 5,000 ft on radio command and 1,000 ft on coaxial cable. The Air Force has used this machine with success since its delivery in March, 1987. The conversion of the base machine to remote controlled operation involved the integration of servo hydraulic controls, vision and audio feedback, remote operator's station and data links.

ELECTRONICS

The remote adjunct has three basic subsystems. The simplified block diagram shows the operator's console, the on-board package and the data link (Fig. 2). The console includes the video monitor and audio/video receivers and the decoding electronics needed to process incoming signals. It also includes the control devices and encoding electronics to generate and broadcast commands. The on-board package

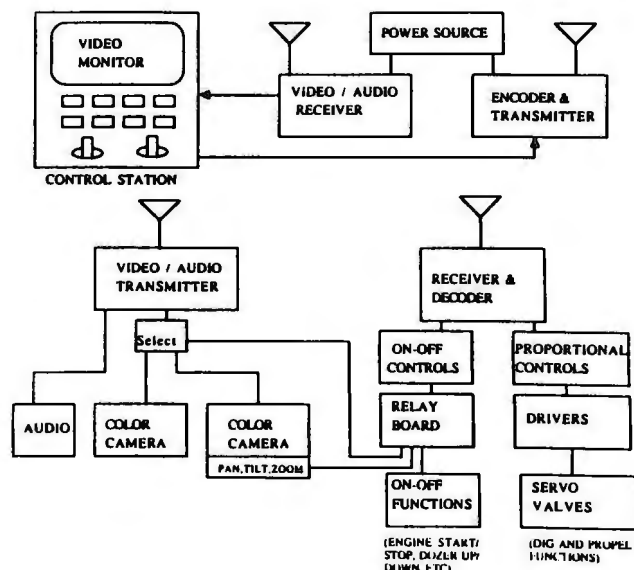


Figure 2
690 Remote Control Block Program

receives incoming commands and converts them to electrical signals for valve and camera control. It also processes video and audio data and sends these out to the operator.

The remaining element is the link that joins the on-board electronics to the operator's console. This data link can be a coaxial cable, radio waves or optic fiber.

The 690C on-board package consists of two separate subsystems for the present version (Fig. 3 and 4). The digital receiver package provides the functional interface with the machine while the video transmitter provides the sensory feedback data.



Figure 3
Digital Receiver



Figure 4
Video Transmitter

This environmentally sealed container (Fig. 3) is mounted on the rotating house of the excavator. The system includes two receivers capable of 9600 baud. Its function is to receive a data string of digitally encoded commands on RS232, decode and interpret the command signals and then relay them to hydraulic servos and actuators. The relayed commands are analog signals that provide proportional control capability to the boom, arm, bucket, swing and transport hydraulics. This unit also generates signals that command discrete functions for engine stop/start, high/low speed select, blade up/down, engine speed, road speed, auxiliary tool, stabilizers and bucket clamp. Fail-safe sensors in this unit will shut down the engine in the event that clear commands are not received.

This second container is similar in size and shape to the first (Fig. 4). Its function is to code and transmit video and audio data from the machine to the operator and to control the power pan/tilt/zoom functions of the roof mounted camera. This unit is also environmentally sealed and mounted on the rotating house.

The operator's console is designed for adverse weather and handling (Fig. 5). It weighs under 50 lbs and can be accompanied by a battery pack (Fig. 6) for 8 hr of isolated continuous operation. The 8-in. monitor provides viewing from either the fender mount or roof mount camera. A camera select switch, pan/tilt/zoom and manual iris override controls are mounted on the panel. The four joysticks are operated in the same manner as the cab mounted controls.



Figure 5
Operator's Console

This feature maintains the continuity of similarity with the cab and aids the operator in quick and errorless operation of all machine functions. The console can be operated from a 60Hz, 110 v source or the batteries can be charged from that source.

The RF data link has a 5,000 ft range operating at 5 w on the command link and 10 w on the video. The Air Force system operates in the UHF frequency band with 12 KHz bandwidth on the command link and 6 Mhz on the video link. RF communications continue to be a problem in the United States and abroad due to the heavy demand for military and commercial use of the air waves. Video transmission, which is essential to remote operation, requires wide bandwidths which are increasingly difficult to obtain from the Federal Communications Commission (FCC). The ideal frequency range for teleoperation lies in the low end of the spectrum to achieve omni directional flexibility and maximum penetration of interposed ground features. The frequencies,



Figure 6
Battery Pack

however, tend to be preallocated or available only in narrow bands. One solution to the dilemma is to operate at higher frequencies and adapt to the limitations. Deere has addressed this issue as noted in the following paragraphs.

The heavy duty coaxial cable is provided for teleoperation with stand-off distances up to 1,000 ft. This secondary data link enables fast response to areas where the RF link is not approved or appropriate. It may also be used on occasions where the suspect hazardous materials may be affected by RF energy or in locations where the RF transmission is blocked by geological features or metal structures. The cable was provided in coil form on the first unit for manual payout.



Figure 7
Electrohydraulic Valves

VALVES

John Deere 690 excavators are equipped with pilot operated hydraulic valves. The remote control system is superimposed on the pilot pressure system with this valve manifold assembly (Fig. 7). Proportional functions are controlled through commercially available servo valves while the discrete functions apply solenoid valves. The remote control valve assembly is designed and integrated to be transparent to an operator seated in the cab who has the machine under manual control. Electromechanical actuators are mounted on engine fuel control and speed selector controls in a way that does not interfere with manned operation.

VISION

Vision is provided to the remote operator with two cameras on the 690C model. The first camera is fixed focus auto iris, fixed but manually variable mount, located on the front right side. The camera has a wide angle lens directed to the area swept by the excavator linkage (Fig. 8). Experience has shown this to be an essential view for remote operator inspection of details in the work area. The camera is color as is the roof mounted camera. This camera has power pan/tilt/zoom with auto iris. Additional manual iris override permits adjustment for improved vision in dark excavations. The roof mount with remote controlled aiming and zoom results in a narrower field of view with full operator discretion of the viewing target. The camera also provides visual operating feedback when manipulated to look through the cab roof at the instrument panel. This is a patented feature of the John Deere TORCE 690C. The sensory feedback includes an in-cab microphone which transmits operating system audible warnings and engine and hydraulic system operating sound levels. This audio feedback is a valuable link of operator to machine as he seeks to optimize performance by loading the engine and hydraulics to capacity without creating stall or relief valve opening. The antennae that are needed to receive command signals and transmit sensory data are mounted on the cab roof.

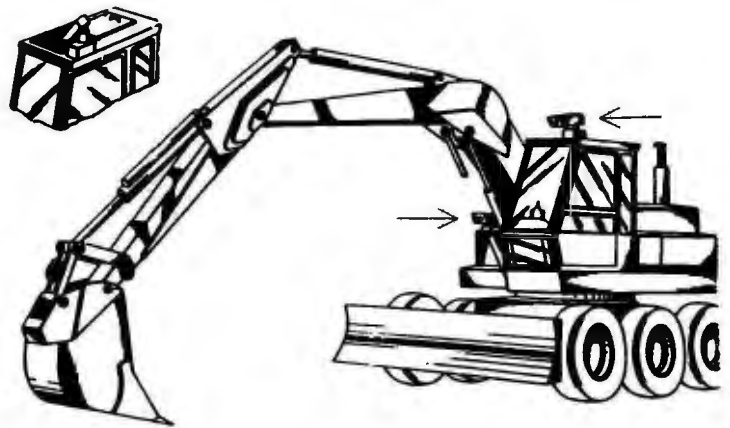


Figure 8
Cameras

MOUNTING

Modifications to the production excavator are needed to provide mounting points for the on-board hardware and electromechanical actuators. These brackets and components are designed to be mounted in less than 8 manhours using only simple tools. They also provide for on-board storage of the operator's console. The design for superposition of the teleoperation subsystems over the existing manual systems gives the user the option of removing the remote control components for storage during long-term manual operation or moving the remote control capability to any similar excavator equipped with an adaptor kit. This feature is expected to be particularly valuable to commercial users who may have multiple machines at widely separated sites.

THE PRODUCT IMPROVEMENT UPGRADE

John Deere has introduced the next evolution of the 690 excavator called the 690D (Fig. 9). It incorporates a number of performance and reliability upgrades including a new closed center hydraulic system. The new model has the same operating features as the previous model. A major difference is the addition of a third camera inside the cab. This offers the operator an instant view of his machine instrument panel at the flip of a selector switch rather than repositioning and refocusing the roof mounted camera. The third camera is a color, fixed focus, fixed mount unit.



Figure 9
John Deere 690D

Finally, the RF data link is being modified to operate partially in the microwave frequency regime. This change has the advantage that FCC approval is more easily obtained. The wide bandwidth is more readily available at microwave frequencies and therefore more appropriate for commercial uses. The disadvantage of operating at these high frequencies is the requirement for line-of-sight communication between the sending and receiving antennae. Present experience has not shown this to be a problem for the ordnance disposal and cleanup tasks that have been accomplished to the present time. Commercial uses, presently envisioned, should be equally insensitive to broadcast frequencies. The RF link that is now in development has the added feature of selected bands within the available frequency range. This enables control of up to five systems simultaneously at the same site. Control of multiple units from the same console is an option if only one machine is being worked at any given time. If multiple machines are in operation, then multiple consoles would be required.

The hardware data link also is being upgraded with the addition of a cable reel that will simplify the payout/retrieve task for the coaxial cable. Fiber optic links have not been ordered up to this time, but they also are readily adapted to the system. The advantages of fiber optic links lies in their resistance to electromagnetic interference which particularly concerns the military.

FIELD EXPERIENCE

The production excavator evolved over a number of years to employ manual valve actuation of functions using both hand and foot controls. Each succeeding generation was an improvement over its predecessor in the man/machine interface. The design of the remote operator's station leveraged the previous design evolution by duplication of the hand control motions and relative locations. The propel controls could not be incorporated as foot controls but did conform to the control response patterns that are common to hydrostatic transmissions. The removal of the operator from the cab, nevertheless, results in loss of sensory inputs from tactile and vibration sources, and it considerably reduces visual inputs. The result of this is reduced productivity when engaged in benign or conventional earthmoving but with substantial increases in productivity compared to the alternatives when operating in hazardous

environments. Learning to operate a remote controlled excavator from a remote station appears to be readily accomplished by totally unfamiliar operators and slightly more time-consuming for operators accustomed to a full range of sensory information. In either case, very high levels of productivity can be achieved with practice.

The TORCE I, adaptation of the JD690CR wheeled excavator to the Air Force rapid runway machine, has been in operation at an Air Force base since March, 1987. The Explosive Ordnance Disposal (EOD) team stationed at the site has used the system on a routine basis to excavate unexploded munitions and recover them for inspection. Their objective is to retrieve live pretriggered explosive devices intact for failure analysis while remaining safe from harm. The EOD team has changed personnel through the period, but has found that new people are readily trained. The excavator has functioned reliably and effectively in its assigned role.

The EOD team with its remote excavation capability was enlisted in the summer of 1987 to evaluate its use in cleanup activities at the Milan, Tennessee, Army Ammunition Plant. Since its opening in 1941, the plant has buried a variety of explosives and obsolete munitions in trenches around the area. The exact locations and contents of the burial sites were unknown, but the Corps of Engineers is concerned about ground-water contamination and identification of the buried materials. The Corps of Engineers engaged the EOD team to remotely excavate 55 sites. At the conclusion of the operation, the team had excavated 64 sites to an average depth of 18 ft in 84 machine hours or about half of the time originally scheduled to complete the project. It had recovered over 300 items of ordnance and provided soil samples for analysis. The engineer in charge of the project estimated that 30 to 40% cost savings could be realized using remote controlled excavation as compared to using manned excavators. Onboard operators at hazardous sites could be required to wear fully encapsulated life support systems and then for only short working intervals. The reduced capacity, downtime and multiple crews needed to support a single excavation are all unnecessary with remote control. It also was noted that the Milan task was only a survey, that real cleanup work was yet to be done and that there are 12 other similar plants in the United States. Clearly, remote controlled excavation is here to stay.

Another major change is the upgraded on-board electronics package which includes miniaturized relays and compact circuitry. This eliminates one of the sealed on-board containers. The reduction in package size and weight simplifies the mounting design and results in location which is more immune to the rigors of construction machine environment. The new operator's console will incorporate an 8-in. monitor and sufficient electrical power to complete 8 hr of operation.



Figure 10
Air Force Automatic Excavator

THE FUTURE

The Air Force Engineering and Services Laboratory (AFESC) is concerned with rapid runway repair and with the availability of trained

personnel to operate repair machines as the time to repair becomes more critical. The Engineering and Services Laboratory initiated a program that was headed toward full automation of the runway repair process. The first task in the program was to provide automatic tool change. Deere, University of Florida and Westinghouse worked with the Air Force to produce the machine shown here (Fig. 10). With the added expertise of an on-site contractor, the system can now change tools, dig trenches, dig pie-shaped or circular holes, level blade, tamp and break concrete all automatically by calling up the desired task on a computer menu. The operator need not be on board while the machine is working. This particular machine is a proof-of-concept system and normally prone to the reliability problems that engineers and laboratory technicians often find in prototypes. The manager of R&D systems

at the AFESC has reported that the machine has logged 780 hr of operation with the sensors and computers on board.

Where do we go from here? It is possible to remove operators from construction machinery cabs. It is certainly a necessary thing in operations like the Milan ammunition plant and any job where hazardous materials or dangerous conditions are likely to exist. Whether or not it becomes commonplace in day-to-day construction work depends on its cost-effectiveness. Can a contractor achieve a return on his investment by replacing manpower with computer power? Today, the answer is yes only when conditions exclude human beings. Tomorrow's answer will depend on the cost of labor and on the availability of low cost electronics.

Capture of a Groundwater Contamination Plume in Fractured Bedrock by an Artificially Produced Fracture Zone Created Through Controlled Blasting

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ABSTRACT

Recovery of contaminated groundwater in a fractured bedrock system presents some unique problems. Typically, the most common problem occurs from the hydrogeologist's inability to adequately characterize the discrete fractures through which contaminants may be migrating. Without adequate characterization, difficulties arise in properly positioning recovery wells and verifying the performance of the system. To overcome these difficulties at a site in Upstate New York, an innovative approach was developed involving the creation of an artificial fracture zone through controlled blasting to intercept contaminated groundwater flow.

Site investigations delineated the extent of a groundwater contamination plume migrating within a fractured bedrock aquifer (Medina sandstone) which underlies approximately 15 ft of glacial till. A 72-hr aquifer test involving one recovery well resulted in a low yield (3.5 gpm with 20 ft of drawdown). Data collected from adjacent observation wells indicated poor interconnection among the naturally occurring fractures. Although the response of some observation wells mirrored that of the recovery well, others showed little or no response to pumping. Therefore, achieving the corrective action objectives (i.e., preventing further contaminant migration and removing and treating contaminated groundwater) would be difficult using a traditional, multiple recovery well system. It was decided that controlled linear blasting could provide the enhanced fracture interconnection necessary to successfully intercept the contaminated groundwater plume, which would then be captured and removed by judicious placement of recovery well(s) installed within the fracture zone.

Using a carefully controlled single line pattern blasting technique, a 6-ft wide, 300-ft long fracture zone was created in the upper 25-ft of the bedrock aquifer perpendicular to the centerline of the plume. Following fracturing, a second 72-hr aquifer test was conducted at the same location and under conditions similar to the first test. The second test indicated that the single recovery well located in the newly created fracture zone should be fully capable of recovering contaminated groundwater and preventing further migration of the plume. The recovery well produced a substantially higher yield of 18.5 gpm with only 11.2 ft of drawdown. Furthermore, all of the nearby observation wells showed significant response to pumping. Success at this site is promising and the approach may prove useful at other sites involving contaminated bedrock aquifers.

INTRODUCTION

A manufacturing facility in Upstate New York operated a series of surface impoundments used to treat wastewater from plating operations and various other metal finishing processes (Fig. 1). A comprehensive groundwater quality assessment program conducted at the facility identified contamination of the groundwater by volatile organic compounds (VOCs) within both the overburden and bedrock aquifers. A corrective action program was implemented upon completion of the groundwater assessment program.

This paper focuses on the corrective action measure that was developed at this site to prevent further migration of the contaminated groundwater. Background information is included on the nature and extent of the contamination, site hydrogeology and conceptual development of the fracturing technique. Also presented are a description of the fracturing process, results of pre- and post-fracturing aquifer tests and a discussion of the effectiveness of the technique.

SITE HYDROGEOLOGY

Unconsolidated deposits at the site consist of 5 to 20 ft of Late Woodfordian sandy glacial till overlying approximately 50 ft of Medina sandstone (Grimsby member) of early Silurian age. Underlying the Medina are several hundred feet of Upper Ordovician Queenstone shale. Regional bedrock dip is to the south at approximately 50 ft/mi.

Groundwater at the site is presently under unconfined conditions. The water table is typically 4 to 8 ft below ground surface. Although the overburden and bedrock units are discussed below as two separate aquifers, they are hydraulically interconnected. The basis for discussing the two aquifers separately arises from the inherent differences between the two units with regards to the geologic material and nature of groundwater flow.

Groundwater flow within both the overburden and bedrock aquifers is predominantly to the northwest across the site with an increasing gradient to the north in response to the topography. There is generally a downward gradient between the two aquifers and within the bedrock. Based on slug and bail tests performed at the site, the average hydraulic conductivity (K) of each of the aquifers is roughly the same, 10 cm/sec (0.28 ft/day).

Groundwater flow within the till is assumed to be predominantly through intergranular pores. Based on hydraulic conductivity

values, water level data and an estimated effective porosity of 10 to 20%, the average linear rate of groundwater flow within the overburden aquifer ranges from 0.04 to 0.26 ft/day. Groundwater flow within the Medina sandstone occurs predominantly through secondary porosity openings such as fractures, joints and bedding planes. Intergranular flow is judged to be minimal. Due to the nature of fracture flow, the true groundwater flow rate varies considerably between individual fractures, making accurate calculations of flow velocities and travel times almost impossible. However, based on hydraulic conductivity values, water level data and an estimated effective porosity of 5 to 15%, the average linear rate of groundwater flow within the bedrock aquifer is expected to range from 0.04 to 0.31 ft/day.

In an attempt to better understand the nature of groundwater flow within the bedrock, several studies were performed. These studies included a fracture trace analysis utilizing historic aerial photographs, a joint analysis based on a nearby outcrop, correlation of rock core data and the evaluation of geologic tunnel data collected approximately 20 mi from the site. The information indicated that two major sets of nearly vertical fractures existed within the bedrock: a northwest trending set and a northeast trending set. Although a great deal of generalized information had been gathered, insufficient site-specific data were available to determine the spacing of the fractures or to identify the existence of major fractures into which recovery wells could be installed.

CONTAMINANT PLUME DELINEATION

A groundwater quality assessment program was implemented to delineate the nature and three-dimensional extent of the contamination. Many of the monitoring wells on-site were installed as pairs, with one well monitoring the overburden and the other well monitoring approximately the upper 10 ft of bedrock. Several bedrock monitoring well clusters, located along the northern boundary of the site, were installed to monitor the upper 25 ft of bedrock. These wells were screened to monitor discrete 8-ft zones within the bedrock (Fig. 2).

Utilizing this approach, the vertical and lateral extent of contamination was evaluated at the property boundary.

Contamination by VOCs associated with the degreasing activities at the site was determined to be greatest within the bedrock aquifer. VOCs identified included trichloroethylene (TCE) and associated daughter products: trans- and cis-dichloroethylene (DCE) and vinyl chloride. 1,1,1-trichloroethane (TCA), which replaced TCE around 1975, also was found in the groundwater.

The TCE contamination plume within the bedrock aquifer is shown in Figure 1. TCE concentrations were much higher than concentrations of the other compounds. The bedrock contamination is the result of a non-active source located southeast of the manufacturing building. The resulting plume is migrating in a northwesterly direction in response to groundwater flow.

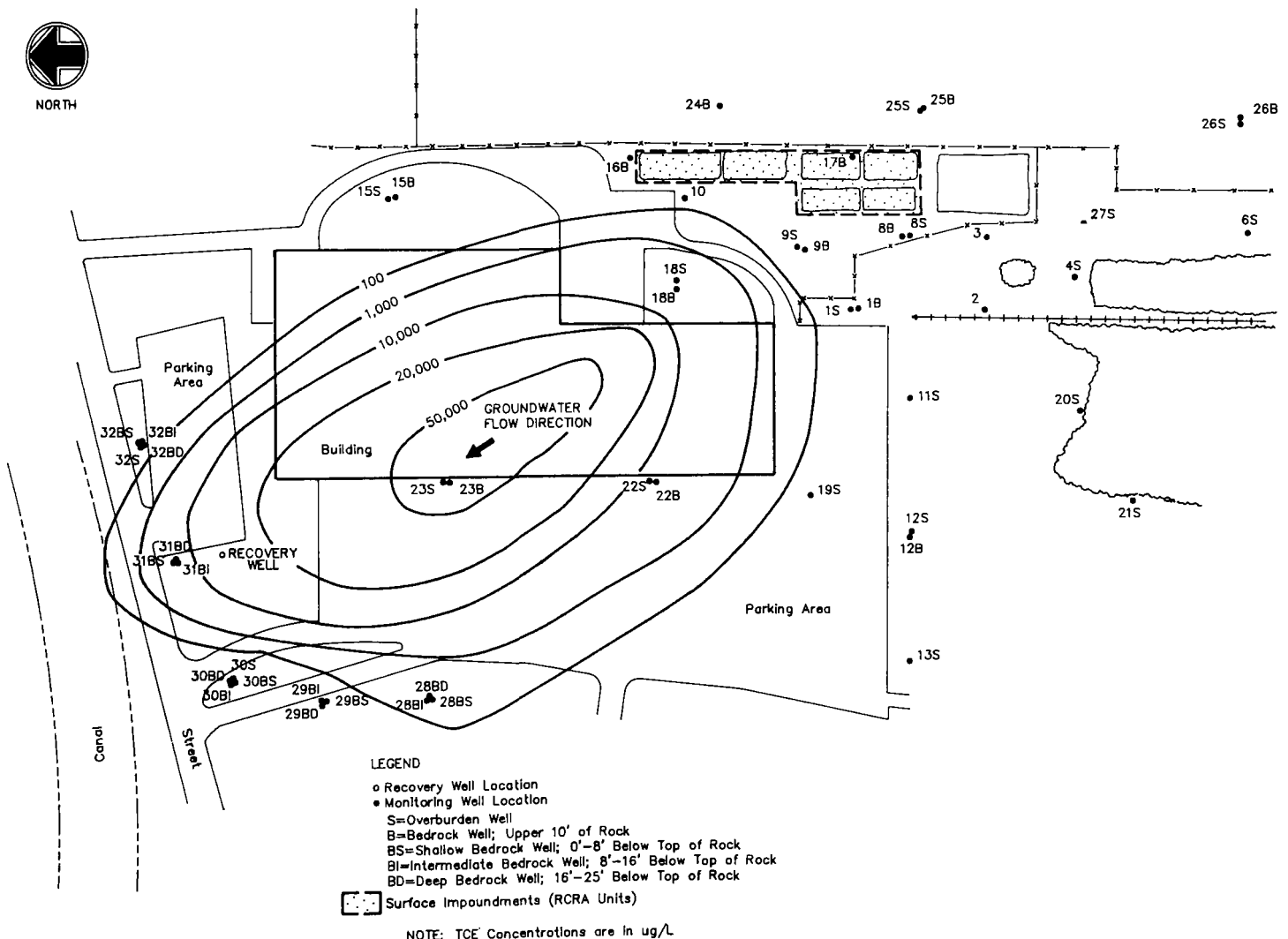


Figure 1
Location of Monitoring Wells; Trichloroethylene Concentrations
(in ug/l) in the Bedrock Aquifer

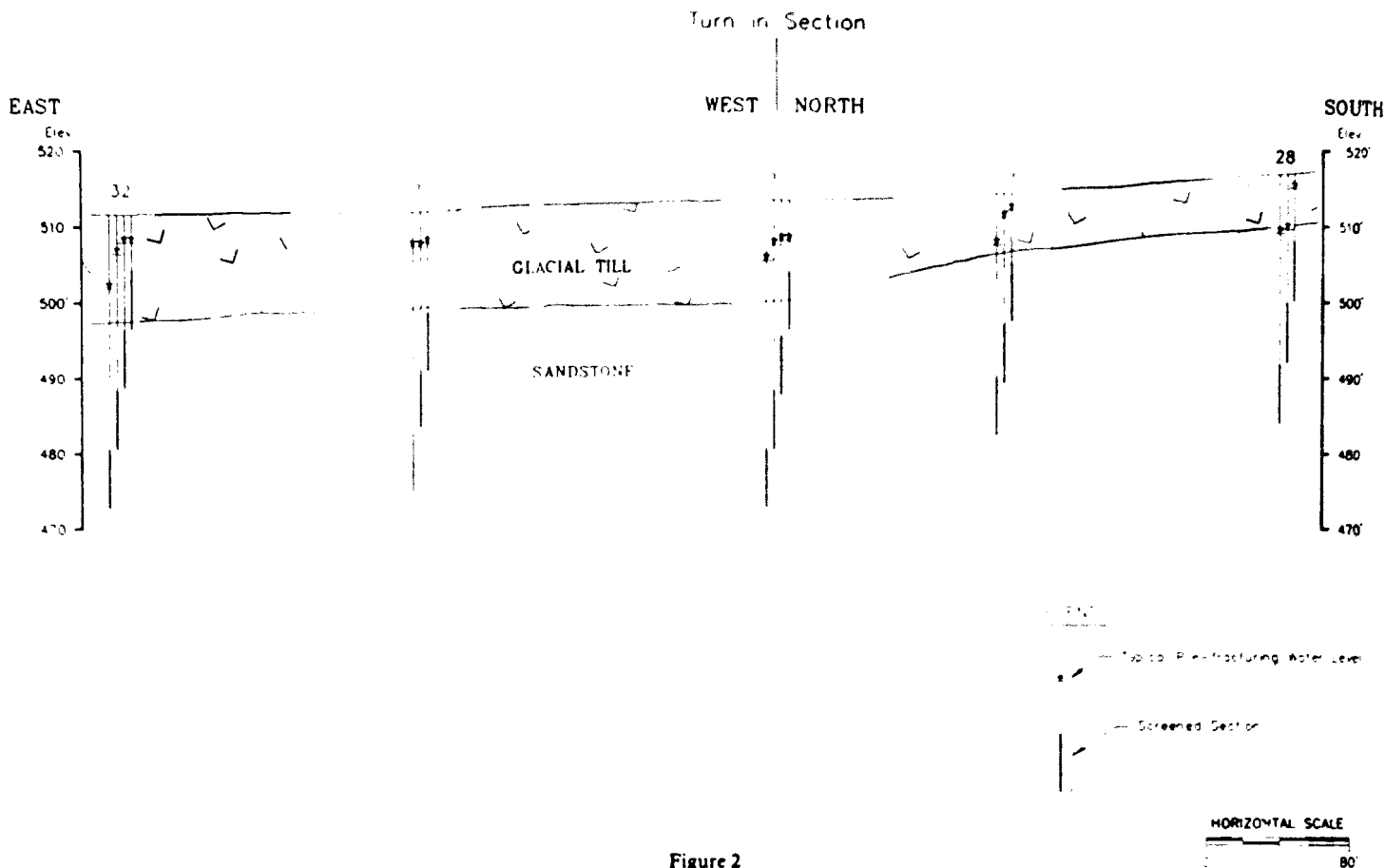


Figure 2
Geologic Cross-Section

PRE-FRACTURING AQUIFER TEST

Remedial measures were deemed appropriate after assessing the magnitude and extent of groundwater contamination. Current remedial alternatives were evaluated and it was determined that a recovery well system would be an effective approach to mitigate further groundwater degradation. In order to design an effective recovery well system, it was necessary to further investigate the hydrogeologic characteristics of the bedrock aquifer. Therefore, a 72-hr aquifer test was performed.

A recovery well was installed downgradient of the facility in the centerline of the plume. The optimal location for the recovery well was determined from in situ permeability test results on six preliminary test borings. The recovery well was installed 25 ft into bedrock at a total depth of 40 ft. The overburden material was cased off and the bedrock section was left as an 8-in. diameter open hole. The well was installed to a depth of 40 ft as no significant contamination was detected in any of the bedrock monitoring wells below this depth.

Static water levels were measured at all monitoring wells on site during the 3 days preceding the test to identify background water levels and trends. During the aquifer test, water level readings were obtained for 54 wells installed within the bedrock and overburden. Sixteen wells were continuously monitored using pressure transducers and associated data loggers. These included the pumping well, bedrock monitoring well 23B and well clusters 28, 29, 30, 31 and 32. The remaining well water levels were measured using electronic water level indicators. Water levels also were obtained in selected wells during a 4-hr recovery period after pumping ceased.

The pumping rate for the aquifer test was set at 3.4 gpm and this rate was maintained throughout the test by monitoring the rate at 30-min intervals. The water generated during the test was

treated using an air stripper and carbon adsorption unit in the series to remove VOCs. In accordance with a temporary SPDES (State Pollution Discharge Elimination System) permit, the effluent, with total VOC concentrations at the non-detectable level, was released to a nearby canal.

The water level in the pumping well dropped approximately 20 ft during the test. Rapid response to pumping was noted in monitoring wells 32BI and 31BD, with the water level in these wells essentially mirroring the water level in the pumping well. Other wells within these two clusters showed little response to pumping. With the possible exception of wells 29BD and 30BI, water levels in clusters 28, 29 and 30 did not appear to have been influenced by the pumping. Semi-log drawdown curves for the recovery well and clusters 29, 31 and 32 have been included as Figure 3. Wells within clusters 28 and 30 responded similarly to wells in cluster 29 (i.e., little or no response).

The irregular responses of individual wells within clusters 31 and 32 reflect the complicated three-dimensional capture zone created by pumping within the fractured bedrock aquifer. This effect is particularly troublesome when realizing that verification of the recovery well's capture zone would be essential in determining the effectiveness of the corrective action. Based on existing data, a meaningful mathematical prediction of the capture zone associated with the recovery well would be both exceedingly difficult and costly.

The system had not reached steady-state by the end of the 72-hr test. The possibility exists that additional drawdown would have occurred at some wells under continued pumping. Although budgetary, regulatory and logistical restraints precluded extending the pumping period, the length of the pumping was sufficient to develop an adequate understanding of the bedrock hydrology.

Based on the results of the pre-fracturing 72-hr aquifer test, the following observations and conclusions were made:

- Variable response to pumping (i.e., drawdown) in monitoring wells, even within clusters, indicates that monitoring wells are, in general, hydraulically poorly interconnected
- No response to pumping was observed in any monitoring well located upgradient of the recovery well
- Delineation of the capture zone is extremely difficult due to the irregular responses observed in the monitoring wells
- The single recovery well installed and tested would not adequately prevent further migration of the contaminant plume
- The installation of additional recovery wells would not be a particularly cost-effective approach to creating a well-designed capture zone

CONCEPTUAL DEVELOPMENT

In order to create an effective capture zone, the influence of the pumping must extend to all of the fractures that were transporting the contaminated groundwater. Initial ideas aimed at meeting this objective revolved around methods of increasing the number of fractures intersected by individual recovery wells. Options explored included angle drilling or "frac-ing" wells. Angle drilling is particularly effective if the fractures are relatively vertical and closely spaced. The existence of such a fracture geometry was not evident at the site. Frac-ing of wells is performed by using either explosives or high pressure water in an effort to artificially enhance existing fractures or create new fractures around individual wells. Both the shallow depth of the recovery well(s) and the variable effectiveness of the frac-ing procedure warranted exploring other alternatives.

An ideal solution to the problem would consist of a method that would interconnect and drain all of the fractures transporting the contaminants. The creation of a single, artificial fracture oriented perpendicular to the direction of groundwater flow was considered as an option. Such a fracture could be produced using explosives positioned in a shot line similar to the pre-splitting technique used to produce the neat face in road cuts. After creating the fracture, one or more recovery wells could be installed in the fracture to remove the contaminated groundwater for treatment. Two major concerns arose from this option. First, the possibility existed that complete interconnection along the fracture might not occur. Second, the resulting fracture might not have sufficient cross-sectional area to allow the drawdown necessary to capture the plume.

To overcome the concerns of insufficient flow area and hydraulic interconnection, a method was designed to create a thoroughly fractured zone, several feet in width, within the upper 25 ft of rock. The rock within this zone would essentially be transformed into rubble, thereby creating a highly interconnected "drain" capable of transmitting substantial amounts of groundwater. The fracture zone would be positioned perpendicular to the direction of groundwater flow near the leading edge of the contaminant plume. One or more recovery wells would be installed into the fracture zone to produce the desired draw-down. The plume would be prevented from migrating further and contaminated groundwater downgradient of the zone would be drawn back into the fracture zone for removal and treatment.

The concept of creating a fracture zone offered some major advantages over a conventional recovery well network approach. Foremost, verifying contaminant capture, often a difficult task in fractured bedrock, would become much easier as the recovery

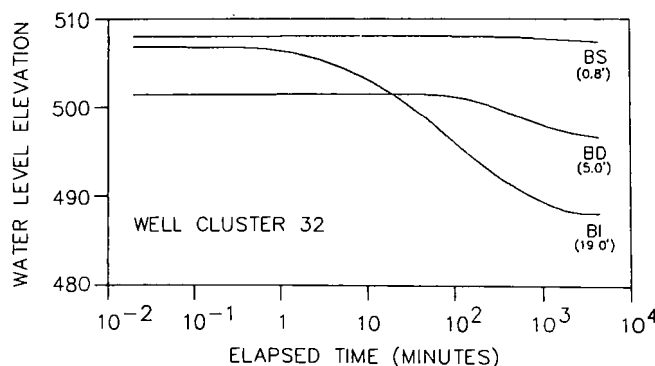
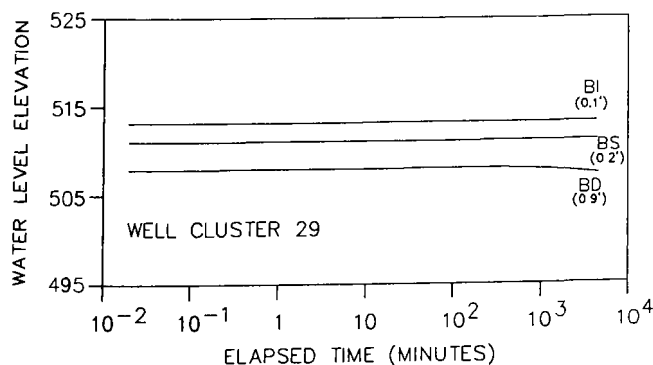
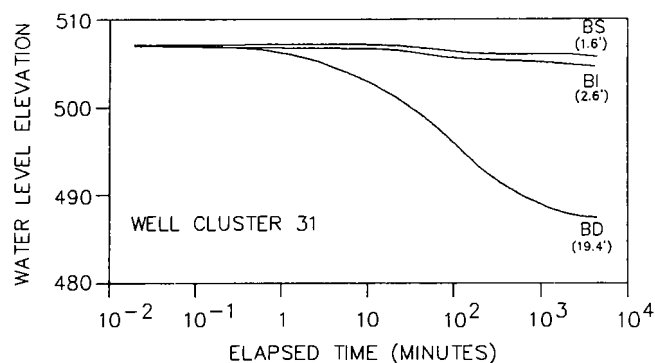
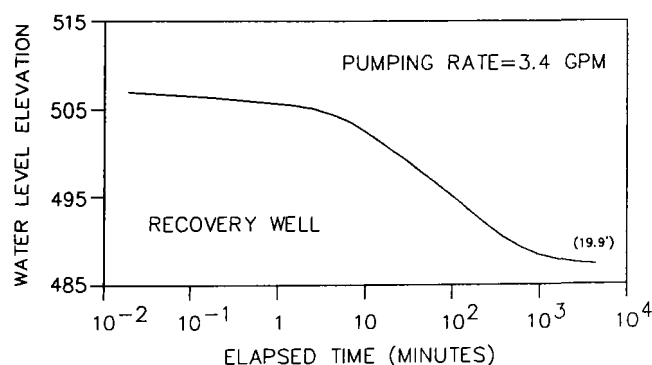


Figure 3
Pre-Fracturing Aquifer Test Drawdown Curves for Selected Wells

well(s) would be directly connected to fractures along the entire cross-section of the fracture zone. Assuming that the fracture zone extends to the lowest depth of contamination, verification would be reduced to assessing the extent of the capture zone downgradient and on either end of the fracture zone. Because fewer recovery wells are required, another advantage would arise from the savings in operation and maintenance costs (e.g., well redevelopment and pump replacement) that would be expected with a recovery well network. Finally, higher pumping rates would be possible and could result in faster remediation.

FRACTURE ZONE CREATION

Using a carefully controlled single line pattern blasting technique, a 6-ft wide, 300-ft long fracture zone was created in the upper 25 ft of the bedrock aquifer perpendicular to the centerline of the plume.

Prior to any blasting, utility companies were contacted and plant diagrams were reviewed to determine any potential blasting restrictions due to buried underground water mains, sewers, cables, etc. The existence of a water main and a sewer line did restrict the length of the fracture zone to 300 ft, which included a safety margin of 25 ft from each of the buried lines. The fracture zone, as depicted in Figure 4, was positioned perpendicular to the direction of groundwater flow and centered near the leading edge of the contaminant plume.

It was necessary to restrict fracturing to the upper 25 ft of the rock as significant contamination was not observed belows that depth. It was estimated initially that approximately 30 lb of explosives placed in 3-in. diameter shot holes would produce the desired degree of fracturing. However, during the actual field activities, the amount of explosives loaded into each hole varied according to the vibrational impact of the previous blast. To reduce the potential for damage, shock waves resulting from each blast were recorded by a seismograph that was positioned next to the manufacturing building's foundation at the closest point to the blast site. The maximum readings at the building did not exceed 1.4 in./sec peak particle velocity which was well below the normally accepted 2 in./sec. Maximum pounds/delay ranged from 22 to 44 lb.

Due to the high water table and relative instability of the unconsolidated material, it was necessary to case each hole. In order to accomplish this, two air track rigs were employed. A smaller air track initially drilled a 5-in. hole into the top of rock and set a 4-in. OD, 3.5-in. ID steel casing. A larger air track then set up over the hole and drilled a 3-in. hole 25 ft into rock. Austin Powder Co., 2-in. by 16-in., 40% Gel Extra was lowered to the bottom of the hole using premeasured cord with an electric cap inserted into the bottom stick. The cord was used for purposes of safety and to insure a full column shot. Each hole was drilled and blasted before the next adjacent hole was drilled. A spacing

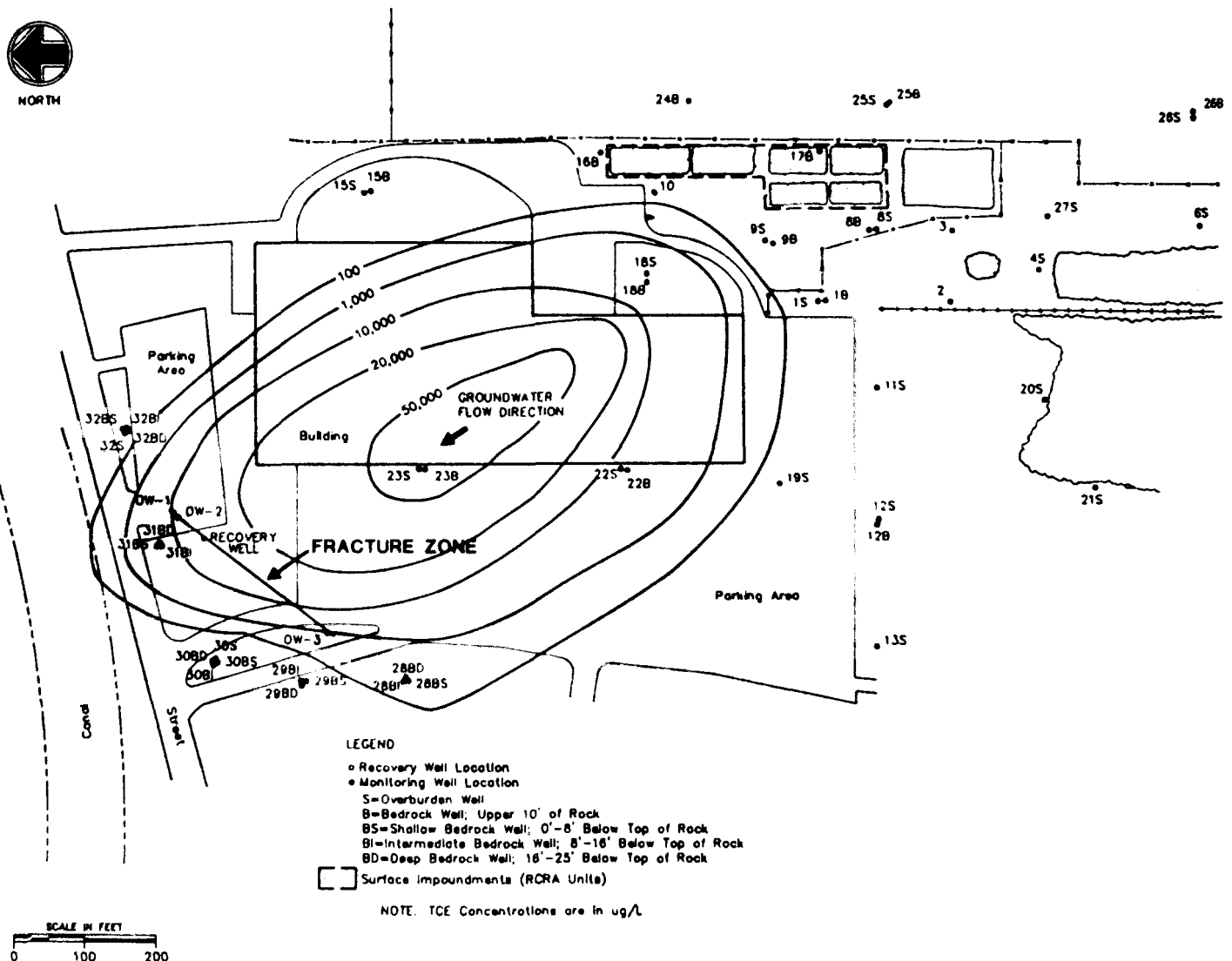


Figure 4
Location of the Fracture Zone; Trichloroethylene Concentrations
(in ug/l) in the Bedrock Aquifer

of 4 to 5 ft between holes was determined to be appropriate. If fractured rock was not encountered at the next drilling location, a new hole was drilled closer to the previously blasted hole until fractured rock was encountered. The flexibility in spacing the holes associated with this "drill and blast" method allowed immediate verification of the effectiveness of the blasting.

Once the explosives were in position and the hole was back-filled with stemming stone, the lead lines were connected to a 450 VME condenser discharge blasting machine. The charge was detonated from the bottom of the hole upwards using an electric millisecond delay blasting cap. Little, if any, permanent surface displacement occurred due to the blasting. Groundwater spouted from the previously blasted holes for several seconds after each blast. This spouting demonstrated the high degree of hydraulic interconnection that had been created between blast holes.

The blasting program took 2 wk to complete and required 60 shot holes and approximately 2000 lb of explosives. Extensive fracturing is expected to extend several feet radially from each shot hole with hairline cracks possibly extending as much as 10 to 15 ft. Fractures are not expected to extend below the bottom of the shot holes due to the positioning of the explosives and the detonating sequence. A cross-section of the fracture zone is shown in Figure 5. The reduced depth of fracturing near each end of the fracture zone is due to reductions in the amount of explosives used near the underground utilities.

POST-FRACTURING AQUIFER TEST

A second 72-hr aquifer test was performed approximately one month after the completion of the blasting program. An effort was made to simulate, as closely as possible, the conditions of the pre-fracturing aquifer test.

Prior to the blasting, the steel casing of the recovery well used in the first aquifer test was removed and the boring filled with coarse sand. Following the blasting of the fracture zone, which passed through the recovery well, the coarse sand in the boring

was reamed out to its original depth (40 ft). A 12-ft long, 6-in. diameter, 0.060-in. slot stainless steel well screen was installed at the bottom of the boring with the remainder of the well constructed of steel riser pipe.

Three 2-in. observation wells were installed at the ends of the fracture zones to monitor water levels. Two of these wells (OW-1 and OW-2) were installed at the east end of the fracture; OW-1 was screened in the upper half of the fracture zone and OW-2 was screened in the lower half of the fracture zone. This pair of wells was necessary to verify that the entire vertical section of the rock was thoroughly fractured.

If the anticipated degree of hydraulic interconnection was attained, the response to pumping should be essentially identical in these two wells (OW-1 and OW-2). OW-3, located at the western edge of the fracture zone, was installed to monitor the draw-down at the opposite end of the fracture. Only one observation well was positioned at this location due to the reduced depth of fracturing at the west end of the zone.

Based on the response during development of the replacement recovery well, an anticipated well yield of 20 gpm was determined. This represents more than a five-fold increase in yield over the first aquifer test (3.4 gpm).

As in the first aquifer test, a portable treatment system consisting of an air stripper and carbon adsorption tank in series was utilized. Pressure transducers were again installed in the same wells monitored during the pre-fracturing aquifer test as well as in wells 30S, 30BD, 32S, OW-1, OW-2 and OW-3. Water levels were again recorded throughout the test at all other wells on-site using electronic water level meters.

A conservative pumping rate of 18.5 gpm was selected for the second aquifer test. The water level in the recovery well dropped a total of 11.2 ft during the 72-hr pumping period. Nearly identical drawdowns were observed in wells OW-1, OW-2 and OW-3. This "bathtub effect" emphasizes the high degree of interconnection created by the fracturing.

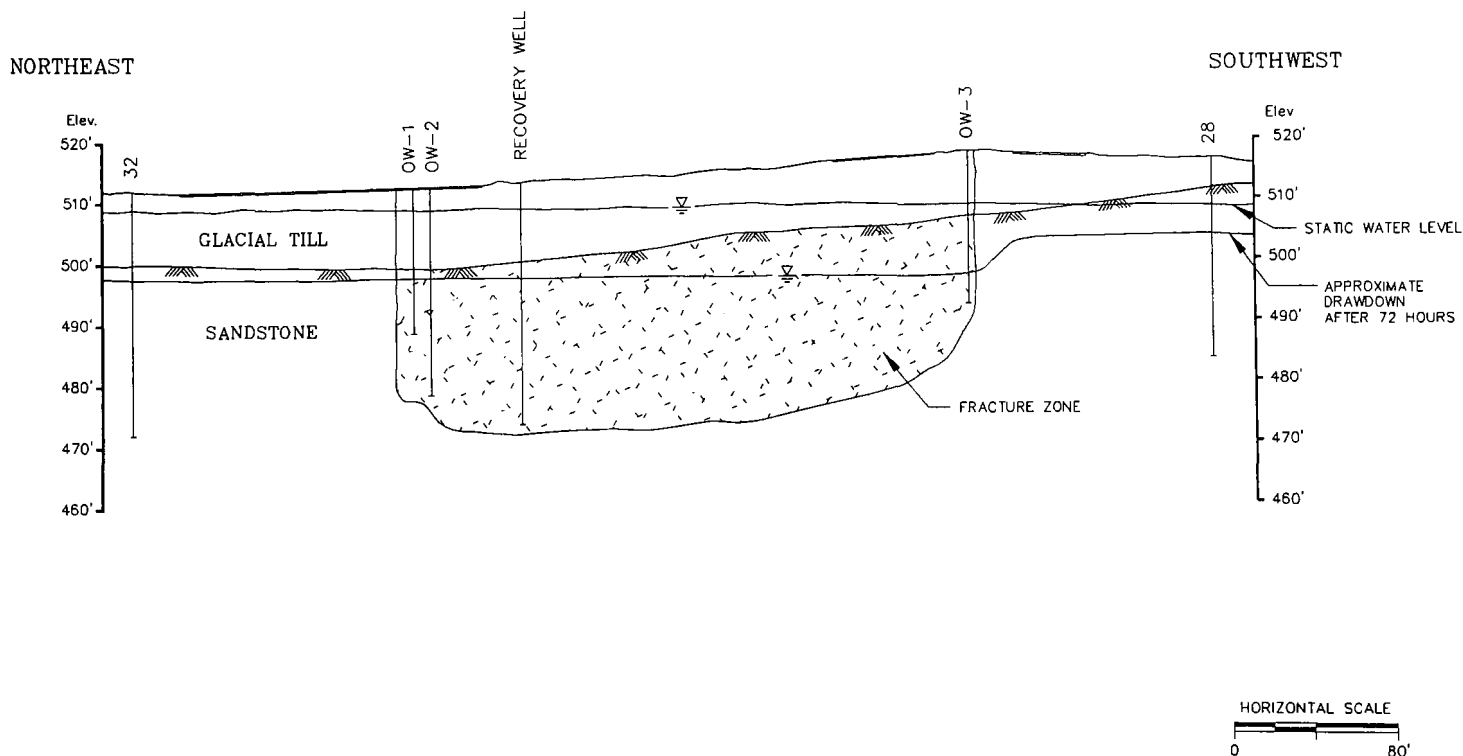


Figure 5
Fracture Zone Cross-Section

Semi-log drawdown curves for the recovery well; observation wells OW-1, 2 and 3; and well clusters 29, 31 and 32 are shown in Figure 6. A comparison of results from the pre- and post-fracturing aquifer tests is presented in Table 1. Significant drawdown was noted in all bedrock wells in clusters 28, 29, 30, 31 and 32 with more than 3 ft of drawdown occurring in 12 of the 15 wells. Drawdowns ranged from a minimum of 1.6 ft in 28BS to a maximum of 11.2 ft in 31BD. In contrast, during the pre-fracturing aquifer test only three of those same 15 wells exhibited drawdowns greater than 3 ft.

Table 1
Comparison of Pre- and Post-Aquifer Test Results.

Well No.	Pre-Fracturing Aquifer Test 2.4 gpm Maximum Drawdown (in feet)	Post-Fracturing Aquifer Test 18.5 gpm Maximum Drawdown (in feet)
Recovery Well	19.9	11.2
OW-1	----	11.1
OW-2	----	11.3
OW-3	----	10.9
28BS	0.0	1.6
28BI	0.3	4.6
28BD	0.4	4.6
29BS	0.2	6.0
29BI	0.1	3.8
29BD	0.9	9.4
30S	0.3	1.3
30BS	0.6	2.4
30BI	1.8	6.3
30BD	2.3	5.1
31BS	1.6	7.8
31BI	2.6	9.9
31BD	19.4	11.2
32S	0.7	1.8
32BS	0.8	1.8
32BI	19.0	11.0
32BD	5.0	5.9

An excellent response to pumping was again observed at 32BI with a drawdown of 11.0 ft. Increased responses over the pre-blasting aquifer test occurred in wells 32BD and 32BS. The water levels in 32BI and 32BD dropped to within 1 ft of the water level elevation in the fracture zone. Additionally, over a two-fold increase in drawdown occurred in 32BS when compared with the pre-fracturing aquifer test results.

Dramatic increases in drawdown occurred at wells 31BI and 31BS as well as continued excellent response in 31BD. The sudden drop in the water level in 31BS at approximately 600 min into the test is believed to be due to a fracture "cleaning out" in response to the pumping.

Drawdowns at cluster 29 ranged from 3.8 ft in 29BI to 9.4 ft in 29BD as compared to 0.1 to 0.9 ft during the pre-fracturing aquifer test. Similar drawdowns were experienced in clusters 28 and 30. As observed in the pre-fracturing aquifer test, no other wells on-site were influenced by the pumping.

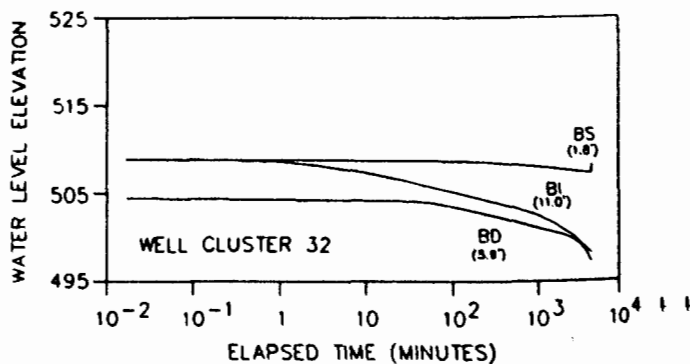
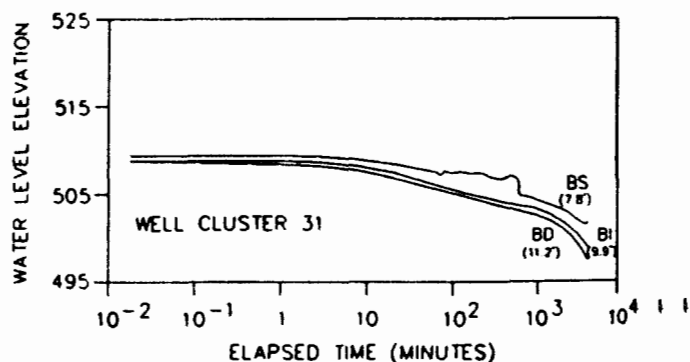
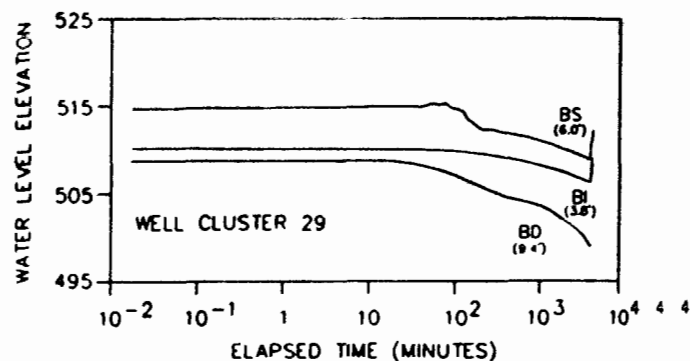
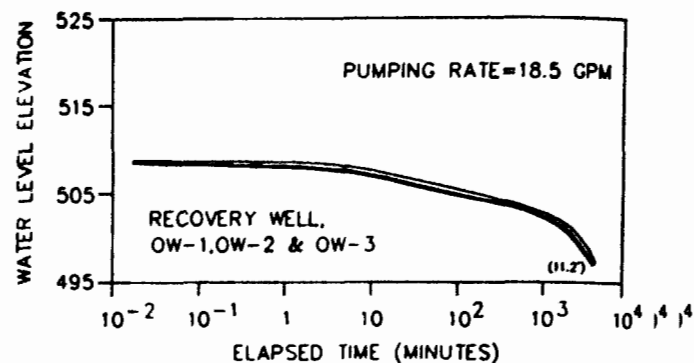


Figure 6
Post-Fracturing Aquifer Test Drawdown Curves for Selected Wells

CONCLUSIONS

A thorough understanding of the hydrogeology and nature and extent of the contamination is necessary before creating an artificial fracture zone. Limitations of the technique are expected to revolve around the thickness of the overburden, proper positioning of the explosives and the ability of the nearby buildings and other structures to withstand the vibrational impacts caused by the amount of explosives required to sufficiently fracture the rock. With appropriate guidance, these limitations can become manageable and the technique a viable alternative to other existing technologies.

The groundwater system had not reached equilibrium by the end of the 72-hr pumping period. Additional drawdown is expected to occur when the permanent pumping and treatment system is placed on-line and allowed to run for an extended period of time. Some degree of dewatering of the overburden aquifer is expected to occur over time. Continued monitoring of water levels in the surrounding monitoring wells as well as groundwater

quality analyses will be necessary to evaluate the long-term effectiveness of the remediation system.

The coupling of existing blasting technology with site-specific groundwater remediation needs has produced an innovative remedial alternative. Through blasting, a selected zone of bedrock has been essentially transformed into a conduit which directly drains the individual fractures. A single recovery well should prove to be fully capable of preventing further migration of the groundwater contamination plume as well as capturing contamination that has traveled downgradient of the fracture zone. As only one recovery well was required by this technique, substantial savings are expected in operational and maintenance costs. Furthermore, the very nature of the fracture zone alleviates the concerns associated with determining if individual recovery wells are successfully intercepting all of the fractures transporting contaminated groundwater. This method should prove to be applicable to many sites with contaminated fractured bedrock aquifers.

Successful PRP Remediation of the Pepper's Steel and Alloys Site

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ABSTRACT

This study established the feasibility and the performance characteristics of the on-site, in situ immobilization technology used for the remediation of the 120,000 yd³ of heavy metal and PCB-contaminated, trans-former-oil soaked soils at the Pepper's Steel and Alloys (PSA) Superfund site in Medley, Florida (N.W. Miami). Until its June, 1988 remediation, the PSA site was on the NPL. This 30-ac site, used for a junk yard and scrap recovery operation, had used transformers purchased from the Florida Power and Light Company (FPL). Subsequently, FPL became the major "deep-pocket" principal responsible party.

The PCB-oil and heavy metal contamination on the site extended from 2 to 8 ft into the soils and into the Biscayne aquifer that is the sole source of drinking water for the Miami metropolitan area. This site is up-gradient within 6 mi of Miami's well fields.

With full disclosure to U.S. EPA Region IV, FPL planned and conducted a formulation, testing and modeling program that demonstrated the safety of the monolithic grout formula poured directly into this critical regional aquifer.

INTRODUCTION

This study established the feasibility and performance characteristics of the proposed on-site stabilization/solidification treatment technology¹ using cement-based, pozzolanic monoliths for the oily fill and peat at Pepper's Steel and Alloys (PSA) Superfund site in Medley, Florida, which was contaminated with both heavy metals and PCBs.

This preliminary grout development and leach-testing program was conducted on behalf of the Florida Power and Light (FPL) Company. The treatment of these contaminated soils by on-site solidification with cementitious grouts was identified by FPL as a potential remedial action alternative in its Final Report of its RI/FS in September, 1983 (Alternative Four). In FPL's Feb. 20, 1985, letter to the U.S. EPA, this remedial action was outlined in detail in a Draft Scope of Work Design Program to accomplish the on-site stabilization or fixation of the PSA soils. In the report, Energex R85-003, the interim status of this program was reported to Region IV of the U.S. EPA on July 29, 1985 in a letter from F. Mullins, FPL, to J. Orban, U.S. EPA Region IV.

BACKGROUND

FPL evaluated several options before selecting the in situ solidification as the remedy at the PSA site¹. The cost of hauling the contaminated material 850 mi to a hazardous waste landfill was over \$43 million, and several thousand trucks would have had to traverse one of the most heavily traveled interstate corridors in the eastern United States. Incineration was opposed vehemently by the local citizens, and there are no incinerators which could meet air quality standards with

the high lead concentrations (to 100,000 ppm) in the site soils. Incineration would have cost close to \$25 million.

Solvent washing of the soil cost approximately \$16 million, but did nothing for the vast quantities of heavy metals at the site. Dole then proposed a plan to develop an in situ disposal option using cement-based pozzolans to treat the site soils and to form large impermeable monoliths, an option that cost \$7 million.

Cement-based and pozzolanic materials are the most widely used materials for the stabilization of chemically hazardous and radioactive wastes because they result in: (1) low-cost waste forms that are processed with standard "off-the-shelf" equipment, (2) waste forms that resist leaching and degradation in many geochemical settings and (3) high-waste loadings with minimum waste volume increase when the grout formulas are tailored to the specific waste streams¹.

REMEDIAL INVESTIGATION

The soil collection plan, developed and conducted under the direction of Dr. Mason, is summarized in Reference 1. The results of the analyses of these soils by RMT are also included in Reference 1. This phase of the work plan was completed, and the collected PSA samples were forwarded to Canonie Engineers to be used to develop stabilization/solidification formulas.

The locations for the soil samples were selected on the basis of the results of previous soil analyses for the presence of oil and the PCB concentrations in the oil. The classes of soils to be collected were: (1) dry fill, (2) oily fill and (3) oily peat. Some of the oil collected from the PSA site contained up to 2,000 ppm of PCBs (Aroclor 1260). These results are summarized in Table 1.

Table 1
Summary Analytical Results for PSA Soils

% Solid	Dry Fill	Oily Fill	Oily Peat
Water	17.0	45.0	107.0
Oil & Grease	1.2	2.6	3.8
PCB*, ppm	42.0	116.0	44.0
Lead, ppm	6980.0	1030.0	836.0

* PCBs were Aroclor 1260

TREATABILITY

The success of the proposed in situ monolith at PSA was based on the establishment of performance objectives which included: (1) mixing and emplacement characteristics, (2) curing rates and the timely development of adequate physical properties and (3) leaching of contaminants at rates that protected the public.

A detailed formulation and testing program to screen materials and verify that the performance objectives were achieved. The formula screening and treatability study tasks⁵ included:

- Task 1 Screening available materials from South Florida, based on their availability, cost, workability and physical properties
- Task 2 Testing compressive strength penetration resistance and permeability
- Task 3 Leaching and Durability Testing:
 - (1) EP-TOX (U.S. EPA SW-846)
 - (2) Modified MCC-1 Static Leach Test
 - (3) Modified ANS 16.1 Multi Extraction

The completion of Task 1 was reported in the interim Status Report², and the results of the remaining tasks are reported in the Final Report¹. These studies selected the dry-solids blend that is summarized in Table 2.

Table 2
PSA Soil-Grout Formulation

Component	wgt	(wt %)
1. Soil Solids	1,680	55
2. Soil Water	340	11
3. Cement, Portland-I	300	10
4. ASTM Class F Ash	450	15
5. Mix Water	260	9
Solids Blend:Soil Ratio	0.45	
Volume Ratio of Fixed Soil	<1.1	

The soil-grout's overnight penetration resistance and 28-day unconfined compressive strength were <500 and <21 psi, respectively, and were sufficient to allow unrestricted traffic and construction over the buried monoliths.

The constant-head permeabilities, using a modified triaxial apparatus, on 28-day cured specimens of spiked dry-fill and oily-peat grouts are summarized in Table 3.

Table 3.
Soil-Grout Permeabilities

Soil-Grout	Darcy Permeability (cm/s)	Hydraulic Conductivity (cm/s)
Dry Fill	1.6E-8	1.5E-11
Oily Peat	6.5E-8	6.2E-11

Since the permeabilities of the soil components at the PSA site ranged between 10^{-2} to 10^{-4} cm/sec, the monoliths range of permeability was at least 10,000 to 1,000,000 times lower than PSA soil. Therefore, these

grouts will be relatively impermeable; groundwater or precipitation cannot percolate through these stabilized masses⁶.

LEACHING

Then, two series of leach-test specimens were prepared with spiked PSA soils. A composite PSA soil sample was prepared from the known heavy metal "hot-spots." The soils were spiked with oil collected at the PSA site in the summer of 1983. To this oil sample, FPL's laboratory had added more Aroclor 1260 in order to increase its PCB concentration to 3000 ppm. Based on the soils' oil and grease analyses and using this spiked oil sample, the total oil concentrations of the soil for the leach-test specimens were adjusted to 10% (PCBs to 490 ppm) based on the soil solids (see Table 4.). This spiking was done in order to ensure that the treatability tests were done with samples that exceeded any expected oil and PCB contaminations at this site.

Table 4
Content of Oil-Spiked PSA Soil

Water	15.6 %
Oil & Grease	10.0* %
PCB**	490.* ppm (216 original)
Lead	31,490. ppm

Two series of right-circular leach specimens prepared with spiked soil, having surface areas of 100 cm² and 30 cm² respectively, were analyzed for the organic and heavy metal in separate leaching tests. These specimens then were leached by the MCC-1 and ANS 16.1 methods in PSA groundwater. Also, the 40 CFR 261 structural-integrity and EP-TOX tests were performed.

Both the Modified MCC-1 and ANS 16.1 methods can measure an effective-diffusion coefficient (D_e , cm²/sec) that conservatively estimates the maximum credible release rates of contaminants from the monolith⁷.

The effective diffusion coefficients (D_e) for the soil-grout, used in the in situ monolith at the PSA site, are summarized in Table 5.

Table 5
ANS 16.1 Leachability Indices

Element	-LOG [D_e]
Arsenic	15.9
Barium	>13.0 **
Cadmium	>11.9 **
Chromium	>12.8 **
Lead	13.5
Mercury	> 9.2 **
Selenium	> 9.8 **
Silver	> 8.4 **
PCBs*	>14.0 **

* PCB Aroclor 1260

** leachate concentrations below detection limits

The leach tests showed that only arsenic and lead were above the detection limits in the leachates. In the fixed, spiked-fill soil-grout, cadmium, chromium, mercury, selenium and silver were below the detectable limits after 28 days of leaching the cured solid. More important, these low effective-diffusion coefficients predict infinitesimal source-term of potential contaminants diffusing from large in situ monoliths.

Figure 1 describes the general case of diffusion from a semi-infinite solid and will conservatively predict the maximum credible release rates from a submerged monolith⁴⁰.

Model

$$F_i = \frac{S}{V} \sqrt{\frac{t}{De}}$$

F = Cumulative Fraction Released of i
S = Specimen Surface Area
V = Specimen Volume
De = Diffusion Coefficient of i
t = Leaching Interval

Figure 1
Semi-infinite Slab Diffusion Model that
Conservatively Over-estimates the Cumulative Fractions Released

RESULTS

The PSA soil fixation blend development and testing program has achieved the goals of the fixation/stabilization work plan by successfully identifying a formula to fix the U.S. EPA priority metals and PCBs in place at Medley, Florida. Using materials from South Florida, this study selected an initial 60/40 fly-ash/cement blend, shown in Table 2, based on its engineering properties of cost, mixability, set time, compressive strength and permeability.

Then, two series of leach tests verified that the monolith's in situ performance was adequate to protect the public's health. For example, based on Equation 1 and the effective-diffusion coefficients, Figure 1 shows the leach fraction released over 1,000 yr.

When the small fractional releases from Figure 1 are integrated into the PSA site hydrology and annual tropical rainfall for the first 1,000 y⁴⁰, the resulting maximum credible groundwater concentrations for lead (Pb), PCBs and Arsenic (As) are very low. (Table 6)

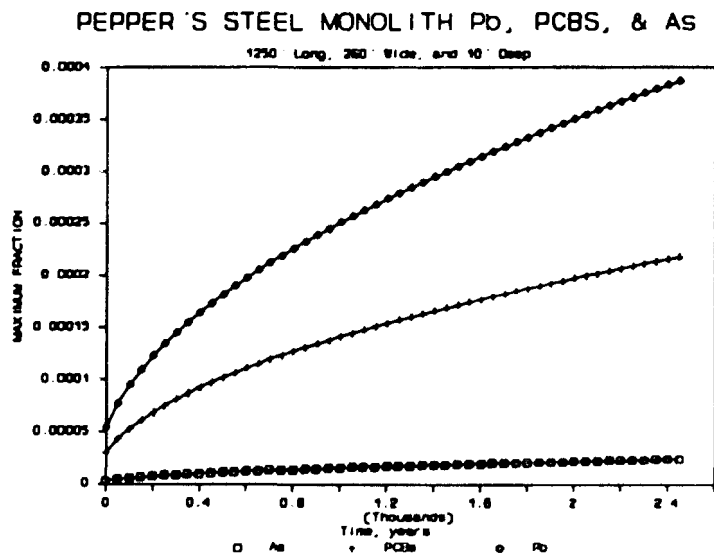


Figure 2
Maximum cumulative fractional losses of Lead,
PCBs and Arsenic from the PSA monolith over 2.4 millenia.

Table 6
Resulting Groundwater Concentrations After 1,000 yr
at Stabilized Site.

ELEMENT	Concentration, ppm
Lead (Pb)	0.001
PCBs	0.0004
Arsenic (As)	0.00005

These worst-case concentrations are below current standard analytical methods and below any known thresholds for health effects. Therefore, based on these conservative overprojections of the maximum credible concentrations, FPL was permitted to treat and solidify the PSA metals and PCBs into a monolith that was poured directly into the Biscayne aquifer without requiring a liner or a cap for the trench. This monolith was located within 5 and 7 mi upgradient from the well fields for the cities of Medley and Miami, respectively.

The Pepper's Steel and Alloys Site is the largest superfund site yet to be closed. It was the first ROD to be signed after SARA was passed in 1986, and it contained an innovative alternative technology for the permanent disposal of non-volatile organics.

REFERENCES

1. Florida Power and Light, Fixation/Stabilization Final Report: Pepper's Steel and Alloys Site, Medley, Florida, Volumes 1 and 2, Florida Power & Light Company, Juno Beach, FL, Nov., 1985.
2. Dole, L. R., "Interim Status Report: Soils Fixation and Stabilization and Remedial Action Alternative for The Pepper's Steel and Alloys Site located at Medley, Florida," Energex R85-003, Energex Associates, Oak Ridge, TN, July, 1985.
3. Florida Power and Light, Final Report: Remedial Investigation/Feasibility Study, Florida Power & Light Company, Juno Beach, FL, Sep., 1983.
4. Dole, L. R., "Overview of the Application of Cement-Based Immobilization Technologies at US-DOE Facilities," Volume 2 of the *Proc. of Waste Management 85*, Ed. Roy Post, Tucson, AZ, pp. 455-463, March, 1985.
5. Florida Power and Light, Remedial Alternative Fixation/Stabilization Workplan, Florida Power & Light Company, Juno Beach, FL, July, 1985.
6. Atkinson, A., "The Influence of Wasteform Permeability on the Release of Radionuclides from a Repository," *Nuclear and Chem. Waste Management* 5, pp. 203-214, 1985.
7. Gilliam, T. M., Dole, L. R. and McDaniel, E. W., "Waste Immobilization in Cement-Based Grouts," *Hazardous Solid Waste Testing and Disposal: Sixth Volume, ASTM STP 933*, D. Lorenzen, R. A. Conway, L. P. Jackson, A. Hamza, C. L. Perket, and W. J. Stacy, Eds., American Society for Testing Materials, Philadelphia, PA, pp. 295-307.
8. Godbee, H. W. and Joy, D. S., "Assessment of the Loss of Radioactive Isotopes from Wastes Solids to the Environment," ORNL/TM-4333, Oak Ridge National Laboratory, Oak Ridge, TN, 1974.
9. Landreth, R. E., "Guide to the Disposal of Chemically Stabilized and Solidified Waste," EPA/SW-872, EPA Municipal Environmental Research Laboratory, Cincinnati, OH, September, 1982, Revised Edition.
10. Dole, L. R., "Leach Testing of In Situ Immobilized Soils Contaminated with PCBs and Lead," Papers Presented at the 194th National Meeting of the American Chemical Society, Symposium on Leach Testing for Radioactive and Chemically Hazardous Wastes: Mass Transport and Chemical Reactions, New Orleans, LA, pp. 283, August, 1987.

Remediation at the Verona Well Field Superfund Site

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ABSTRACT

The Verona Well Field (VWF) supplies potable water to most of the City of Battle Creek, Michigan, three townships, and another small city. The combined service area equates to a population of approximately 50,000 people. In 1981, the well field and surrounding area were found to be contaminated with volatile organic compounds (VOCs), and principally with chlorinated solvents. The contaminant plume extended throughout an area of approximately 0.5 to 1 mi. Two facilities run by a local solvent wholesaler were identified as major sources of contamination. VOC concentrations as high as 1,000 mg/L were found in groundwater and soil on the facilities' properties. The U.S. EPA chose groundwater extraction with treatment in combination with enhanced volatilization using soil vapor extraction (SVE) to clean up contaminated groundwater and soil at the site.

The groundwater extraction system included nine extraction wells with associated instrumentation and controls, extraction force main piping from extraction wells to an existing air stripper and a GAC pretreatment system. From March, 1987 to August, 1989, approximately 11,000 lb of VOCs were removed. Groundwater concentrations initially were as high as 19,000 ug/L total VOCs; by August, the concentration had decreased to approximately 2,000 ug/L. An extensive monitoring program provided analytical data to evaluate compound-specific performance in the air stripper and carbon adsorption pretreatment system.

The SVE system consists of 23 vapor extraction wells, two blowers (30 hp and 40 hp) and a vapor-phase carbon emission control system. The full-scale SVE system has been operating since March, 1988, resulting in the removal of about 40,000 lb of VOCs thus far.

INTRODUCTION

The Verona well field supplies potable water to residents and commercial establishments in Battle Creek, Michigan. In August, 1981, it was discovered that a number of private and city wells in the well field were contaminated with volatile organic compounds. Subsequent testing revealed that nearly half of the city's potable water wells were contaminated.

In the fall of 1983, a remedial investigation was initiated to determine the extent and potential sources of the well field contamination. The investigation revealed a contaminant plume with VOC concentrations varying from 1 ug/L to 356 mg/L in the area of the well field. Monitoring revealed the plume was steadily moving towards less contaminated wells. The investigation also revealed three major potential sources of contamination; two of them are sites operated by a solvent distribution center, and the third is a railroad car repair shop (Fig. 1).

The lithology at the site consists of fine- to coarse-grained sand with trace clay, silt and pebbles. The water table is approximately 25 ft below grade level and the hydraulic gradient is to the northwest.

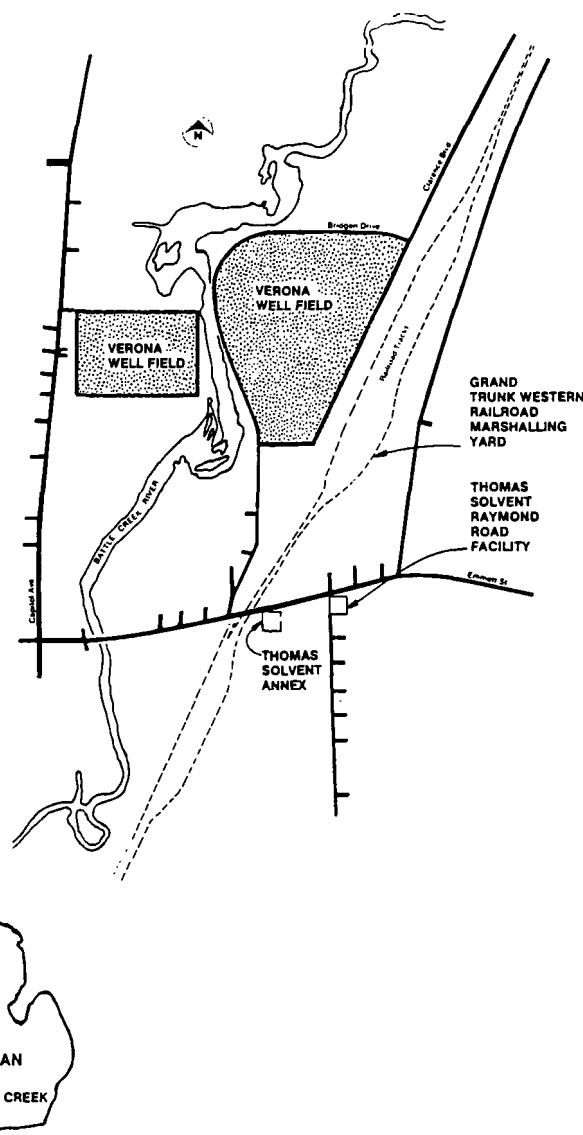


Figure 1
Vicinity Map: Verona Well Field, Battle Creek, Michigan

Remedial Measures

In May, 1984, the U.S. EPA signed a ROD to implement an Initial Remedial Measure (IRM). As part of the IRM, a series of potable wells was converted to blocking wells to prevent further migration of the contaminant plume.

An air stripping system to remove VOCs from the contaminated groundwater also was designed and built. In addition, three new potable water wells were installed to supplement the city's water supply system.

In 1985, the U.S. EPA signed another ROD that addressed the major source of contamination. The ROD specified a corrective action that included a network of groundwater extraction wells to remove contaminated groundwater, the treatment of groundwater via air stripping, and a soil vapor extraction (SVE) system to remove VOCs from the unsaturated zone.

Site Characteristics

The facility addressed in the ROD was an industrial site that had been used for the storage, transfer and packaging of chlorinated and non-chlorinated solvents from 1970 to 1984. As shown on Figure 2, there are 21 underground storage tanks at the facility, 19 of which were confirmed to be leaking in a 1984 investigation. These tanks are surrounded by heavily contaminated soil. Direct excavation and removal of the tanks was not an option since that process would seriously violate state air quality criteria. This problem is being avoided by using the SVE system to remove the majority of VOCs before removing the underground tanks.

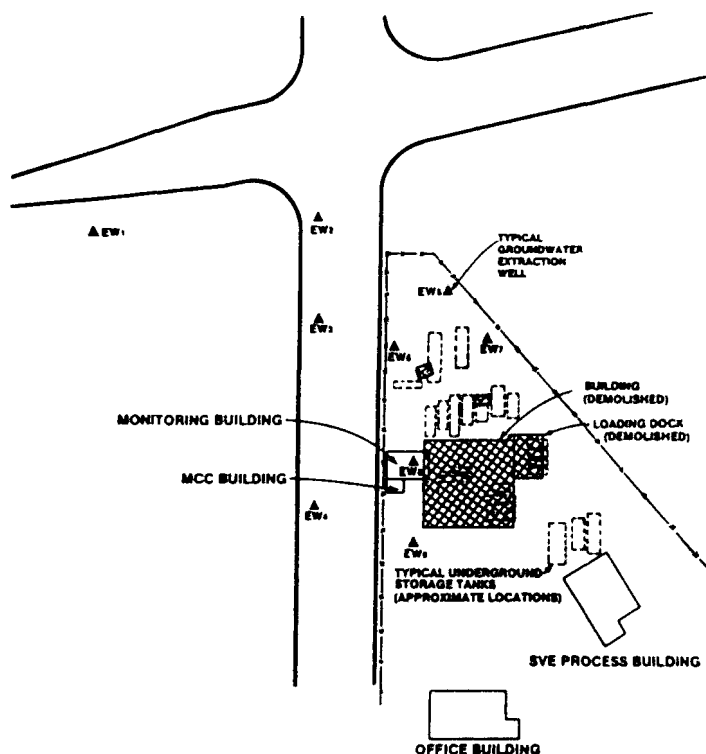


Figure 2
Location of Underground Tanks:
Verona Well Field, Battle Creek, Michigan

At the time of the 1984 investigation, vadose zone contamination extended over approximately 40,000 ft², including the area around the leaking underground storage tanks, in the tank truck loading/unloading area and near the warehouse (now demolished).

In addition to the vadose zone contamination, there was a floating product layer in the vicinity of Extraction Well 8 (EW8). This well is a product recovery well, combining groundwater extraction with intermittent removal of floating product as it accumulates.

GROUNDWATER EXTRACTION SYSTEM DESCRIPTION

The groundwater extraction system specified in the ROD removes VOC-contaminated water from the aquifer in the vicinity of the most contaminated source area. The system consists of nine groundwater extraction wells, associated instrumentation and controls, approximately

5,200 ft of extraction force main (EFM) and a carbon adsorption system that served temporarily as pretreatment for the existing air stripper. Sampling ports are located at various points all along the system.

A flow schematic of the groundwater extraction system is shown in Figure 3. Eight of the nine extraction wells discharge between 30 and 70 gpm of contaminated groundwater; at one time, the ninth well (EW1) discharged 5 to 7 gpm, but it currently is not operating.

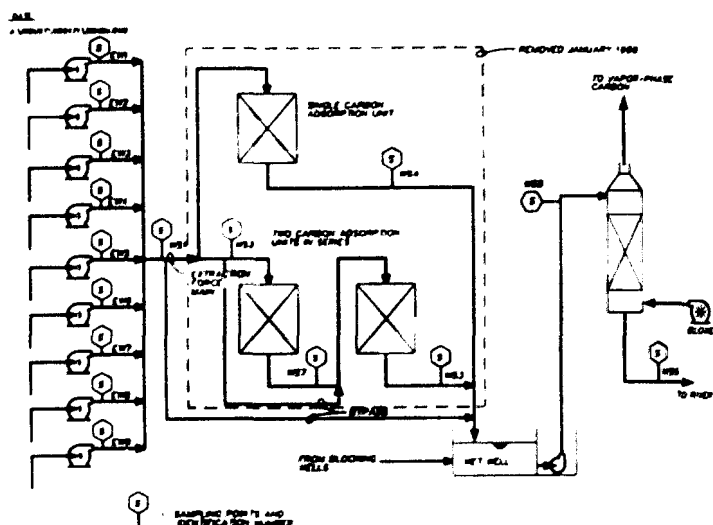


Figure 3
Groundwater Extraction System Flow Schematic:
Verona Well Field, Battle Creek, Michigan

Contaminated groundwater is piped by the extraction force main from the source area to the air stripping system (installed by the U.S. EPA in 1984). Flow from the extraction force main discharges directly to the air stripper pump station (wet well).

The carbon pretreatment system was installed in March, 1987 and removed in January, 1988, when the total VOC concentration was low enough for the air stripper alone to meet NPDES permit requirements for discharge. When it was operational, the carbon adsorption system consisted of three pressure carbon units (one in parallel with two in series) located adjacent to the air stripper. Following treatment from the carbon adsorption units, the water was discharged to the air stripper pump station (wet well).

VOC-contaminated groundwater from the well field blocking wells (approximately 1,700 to 2,000 gpm) also discharges into the wet well along with the extraction well flow (approximately 300 gpm). From the wet well, the water is pumped to an air stripper, which removes more than 95% of the VOCs from the water. VOCs removed from the water by the air stripper are adsorbed from the stripper off-gas by a vapor-phase activated-carbon system.

To date, the treatment system samples generally have been analyzed for U.S. EPA Methods 601 and 602 purgeable organic target compounds, either by the NUS Mobile Laboratory or the NUS Laboratory Services Group facility in Pittsburgh, Pennsylvania. Periodic analyses were performed for naphthalene (U.S. EPA Method 610), acetone (U.S. EPA Method 656), and methyl ethyl ketone and methyl isobutyl ketone (Methods 8015/8030). Samples were analyzed semi-annually for NPDES Priority Pollutants. Treatment system sampling was done on a schedule determined by the Michigan Department of Natural Resources (MDNR).

The sampling and analytical techniques used to monitor the operation lacked some of the sophisticated quality control measures normally used in U.S. EPA CLP protocols. However, this potential limitation on the analytical quality should not have a significant impact on the overall data analysis or the evaluation of system performance.

Description of the Extraction Well System

The locations of the nine wells making up the groundwater extraction system are shown on Figure 2. The extraction wells are screened

from approximately 20 to 37 ft below grade in the unconsolidated glacial overburden unit. All extraction wells are 8 in. in diameter with the exception of EW8, which is a 24-in.-diameter dual extraction well (removes nonaqueous phase liquids and groundwater separately).

Performance of the Extraction Wells

By August, 1989, more than 375,000,000 gal of groundwater containing approximately 11,000 lb of TVOCs had been extracted through the groundwater extraction system. This estimate of TVOCs removed is probably low, since analyses were run only for priority pollutant VOCs (see the "Glossary of Compound Abbreviations" at the end of this report for a list of compounds included in TVOCs). No analyses for total organic carbon (TOC) or total petroleum hydrocarbons were made on any samples.

The predominant contaminants by total mass are PCE, CIS/TRANS, TCE, 1,1,1-TCA and TOL (for full names, see "Glossary of Compound Abbreviations" at the end of this report).

Figure 4 shows the change in concentration of TVOCs for the combined flow from the extraction wells (sampling point WS1, from Figure 2). Note that the figure uses both dates and days from startup (0 to 900) to identify points in time for the extraction system. Figure 5 shows the cumulative amount of TVOCs removed by the extraction well system.

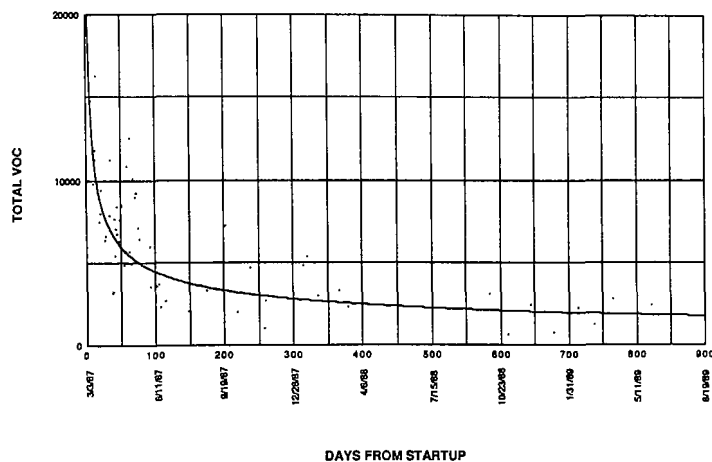


Figure 4
Concentration of Total VOCs from Combined EW Flow

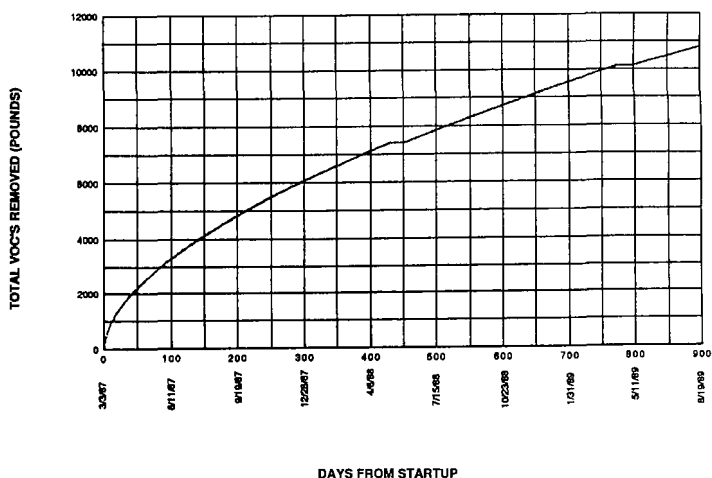


Figure 5
Total VOCs Removed by GW Extraction

Description of the Carbon System

The temporary carbon adsorption system consisted of two parallel trains, one made up of two units in series, and the other a single column adsorption unit. This arrangement provided more flexibility than housing three units in parallel and resulted in less pressure drop than three units in series.

Each unit was 10 ft in diameter, and 12 ft high and contained 20,000 lb of granular activated carbon. This amount of carbon was estimated to be sufficient for the entire period that the carbon system would be needed. Thus, no on-site carbon storage was needed and none of the units had to be taken out of service for carbon replacement. Flow was distributed to provide approximately one-third of the total flow to the single-unit train and the remaining flow to the train with two units in series.

Performance of the Carbon System

An estimated 1,830 lb of TVOCs were adsorbed in the single-unit train and 4,340 lb in the two units in series train, for a combined total of 6,170 lb of TVOCs adsorbed.

Several compounds began to desorb as the carbon beds began to load with VOCs. Desorption occurs primarily as a result of competition between compounds. Every compound has a different capacity for adsorption. When the carbon is new, the differences in adsorption capacity among the different compounds are barely detectable because competition for adsorption sites is minimal. However, as the carbon begins to reach capacity, various compounds begin to compete for the available adsorption sites. As a result, weakly adsorbed compounds are desorbed by competition from the more strongly adsorbed species. Several of the compounds desorbed at some point in the operation of the system; methylene chloride, vinyl chloride and 1,2-dichloroethane were the only compound that did so at a substantial rate.

In January, 1988, the VOC concentrations in the groundwater appeared to be low enough to bypass the activated carbon system and go directly to the air stripper without violating effluent standards.

Description of the Air Stripper

The air stripper is composed of a single 10-ft-diameter tower containing 40 ft of 3.5-in. pall ring packing in two 20-ft sections. The tower is made of fiberglass-reinforced plastic with stainless steel internals and polypropylene packing.

Water enters the top of the tower through a 12-in. header to a Norton wiew-trough distributor. Atmospheric air is pulled upward through the tower counter-current to the direction of water flow. A demister removes entrained droplets from the air at the top of the tower prior to discharge to the vapor phase carbon adsorption units.

The stripper was designed for a nominal water flow rate of 2,000 gpm with a maximum flow of 2,500 gpm. The air flow system is sized to deliver 5,000 to 6,000 acfm.

The air stripper is equipped with a recirculation system to permit periodic addition of acid or disinfectant used to control accumulation of inorganic scale or biological growth on the packing material and internals.

Performance of the Air Stripper

Air stripper performance was monitored as part of the data-taking program. Most of the data were taken while the carbon adsorption pretreatment system was operating. However, data also were taken when the pretreatment system was being bypassed and after its removal in January 1988. This set of data is presented under "Performance Without Pretreatment," after the discussion of the larger data set.

Performance With Pretreatment

Air stripper performance generally is reported as percent contaminant removal efficiency. The efficiency is determined by taking the difference between the influent and effluent concentrations and dividing it by the influent concentration.

This definition of performance poses some computational problems, particularly when the influent and effluent concentrations are below the detection limit. For data where the influent and/or effluent was be-

low detection limits, removal efficiency is reported as "NA" (not available).

Table 1 summarizes those data points where both influent and effluent concentrations were above detection limits. Results are reported as the average of such data points for each compound and are compared against results predicted by an air stripper model created by CH2M HILL. The number of data points used in each average is also reported.

Table 1
Air Stripper Performance

Compounds	Predicted Removal (%)	With Pretreatment		Without Pretreatment	
		Actual Removal (%)	Number of Data Points	Actual Removal (%)	Influent Concentration (ppb)
CCL4	99.4	66.7	1	NA	NA
CCL3	80.2	NA	NA	NA	NA
1,1-DCA	91.8	NA	NA	NA	NA
1,2-DCA	37.4	31.7	33	46.0	16
1,1-DCE	99.6	NA	NA	NA	NA
CIS	62.9	85.9*	27*	86.3	18
TRANS	98.4				
MECL	72.1	72.6	37	88.1	8
PCE	99.3	83.4	2	97.9	7
1,1,1-TCA	99.7	73.9	13	94.8	3
TCE	97.7	97.6	1	96.0	12
VINYL	99.9	57.5	1	NA	NA
BEN	90.9	NA	NA	61.2*	3
EBEN	94.6	NA	NA	77.7	2
TOL	93.1	95.0	1	95.6	13
O-XYL	85.4	NA	NA	91.8	4

*Results for CIS and TRANS combined.

*One was 3.61.

NOTES: Air stripper water flow = 2,400 gpm.

NA = Not available.

Compound	Abbreviation
Carbon Tetrachloride	CCL4
Chloroform	CCL3
1,1-Dichloroethane	1,1-DCA
1,2-Dichloroethane	1,2-DCA
1,1-Dichloroethylene	1,1-DCE
Cis-1,2-Dichloroethylene	CIS/TRANS
Trans-1,2-Dichloroethylene	
Methylene Chloride	MECL
Tetrachloroethylene	PCE
1,1,1-Trichloroethane	1,1,1-TCA
Trichloroethylene	TCE
Vinyl Chloride	VINYL
Benzene	BEN
Ethylbenzene	EBEN
Toluene	TOL
o-Xylene	O-XYL

Note: Above compounds are priority pollutants tested at the site.

Three compounds (1,2-DCA, CIS/TRANS and MECL) had more than 25 data points that could be used to compute an average removal efficiency. All of these averages showed reasonable agreement with predicted results. Thirteen data points were available for 1,1,1-TCA, which showed performance much lower than predicted (74% versus 99.7%). Other results were based on only one or two data points and showed mixed results.

Performance Without Pretreatment

Computed average removal efficiencies for CIS/TRANS, PCE and TOL agreed reasonably well with predicted values for these compound, which all had seven or more data points (see Table 1). 1,2-DCA (16 data points) and MECL (8 data points) both had computed removal efficiencies greater than predicted values. All other compounds had less than five data points.

SOIL VAPOR EXTRACTION (SVE) SYSTEM

Description of the SVE System

The SVE system was installed to remove VOCs from the vadose zone in the vicinity of the most contaminated source area. Figure 6 shows a simplified schematic of the SVE system. The system consists of a network of 4-in. diameter PVC wells with slotted screen from approximately 5 ft below grade to 3 ft below the water table. The wells are packed with silica sand, sealed at the screen/casing interface with bentonite, and then grouted to existing grade to prevent short circuiting. The extraction wells are connected by a surface collection manifold. The extraction wells are connected by a surface collection manifold. Each wellhead has a throttling valve, sample port and vacuum pressure gauge. The surface manifold is connected to a centrifugal air/water separator followed by a carbon adsorption system. The outlet of the carbon adsorption system is piped to a vacuum extraction unit (VEU), which induces a flow of air from the subsurface into the extraction wells. The vacuum not only pulls vapors from the unsaturated zone, but also decreases the pressure in soil voids, thereby causing the release of additional VOCs. After passing through the carbon adsorption system and vacuum extraction unit, air is discharged through a 30-ft stack.

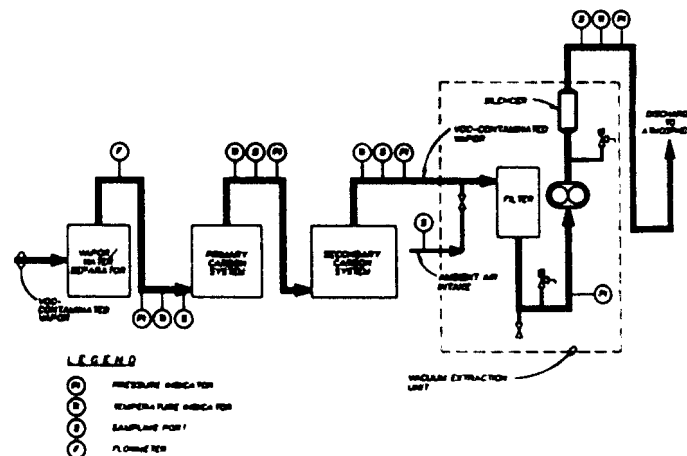


Figure 6
Schematic of Soil Vapor Extraction System:
Verona Well Field, Battle Creek, Michigan

The carbon adsorption system is operating with four parallel primary carbon units (PCU) connected to four secondary carbon units (SCU), also in parallel. The PCU are used for the majority of VOC adsorption, while the SCU act as a backup in the event of breakthrough in the PCU. The canisters each hold 1,000 lb of vapor-phase granulated activated carbon and are connected to header piping with flexible hoses and quick-disconnect couplings. A sample port, vacuum pressure gauge and temperature probe are installed upstream, downstream and between the carbon units, respectively. A carbon monoxide meter also is installed between carbon units to provide early detection in the event of combustion in the primary carbon unit. If the CO meter reaches its set-point, the VEU will automatically shut down until it is reset.

The carbon system was installed under negative pressure to make sure that VOCs would not leak. Preliminary testing determined that carbon adsorption efficiency was equivalent under negative and positive pressure.

During operation, the PCU is monitored for breakthrough by an in-line HNu (organic vapor detector). The setpoint of the HNu was established after determining the relationship between total VOCs as measured by the HNu and compound-specific concentrations as measured by an on-site gas chromatograph. The monitored compound, their detection limits, and their breakthrough criteria are listed in Table 2.

Table 2
Discharge and Test Result
Primary Carbon Unit Discharge

Compound	mg/l	ppb
PCE	0.0024	355
TCE	0.0073	1,360
MECL	0.0406	11,654
BEN	0.0057	1,783

When the breakthrough concentration is exceeded, the PCU is changed out. The carbon change consists of placing the backup carbon system into primary service and installing an unused standby carbon canister into the backup position. By installing fresh carbon in backup service at each PCU changeout, the chances of breakthrough on the backup system are minimized.

In addition to monitoring primary and secondary carbon outlet concentrations, concentrations also are monitored at the wellhead and the combined inlet. Results are used to quantify the VOC loading and help predict the rate of carbon breakthrough. Each time a sample is collected, the following process variables are logged:

- Wellhead vacuum
- Wellhead flow (as measured with a rotameter)
- Vapor/water separator water level
- Pressures and temperatures throughout the system

Performance of the SVE System

A pilot-phase SVE system was started up in November, 1987. Figure 7 shows the location of the SVE wells and the piping layout. Individual extraction wells were operated first to determine their radius of influence, flow rate and initial extraction rate. All gas stream analyses were generated by the on-site gas chromatograph. Figure 8 plots SVE performance at the Thomas Solvents Raymond Road facility.

The radius of influence was measured by recording the vacuum in nearby SVE wells and in vacuum piezometers. A 1.25-in. water vacuum was recorded 60 ft from an extraction well. Since the vadose zone consisted of homogeneous fine- to coarse-graded sand with trace silt and clay, the extensive radius of influence was not unexpected. In addition, vacuum piezometers located between tanks to analyze the effect of tank shielding showed at least a 2-in. water vacuum. In spite of the vacuum between tanks, fullscale SVE wells were installed at the end of tank clusters to further enhance axial flow between tanks.

The total mass of VOCs removed in the pilot test was measured by gas stream analyses and verified by analyzing the carbon. After operating the system intermittently over 15 days (total run time of 69 hr), gas stream analyses predicted 2,866 lb VOCs removed, and the carbon analyses showed an average loading of approximately 16.7%, or 3,006 lb removed. The 5% difference between the two methods of analysis can be attributed to the uncertainties inherent in the analytical procedures.

The average of VOC concentrations measured in the stack was 0.0666 mg/L. At an average stack flow rate of 500 cfm over the 69-hour pilot phase program, approximately 4.6 lb of VOCs would have been released through the stack (indicating a 99.8% removal efficiency).

The SVE system began full-scale operation in March 1988. The average SVE extraction well flow rate is 70 scfm at 2 to 3-in. Hg vacuum

at the wellhead. From March, 1988 through August, 1989, approximately 37,000 lb of VOCs were removed from the soil, bringing the total amount of VOCs recovered to approximately 40,000 lb.

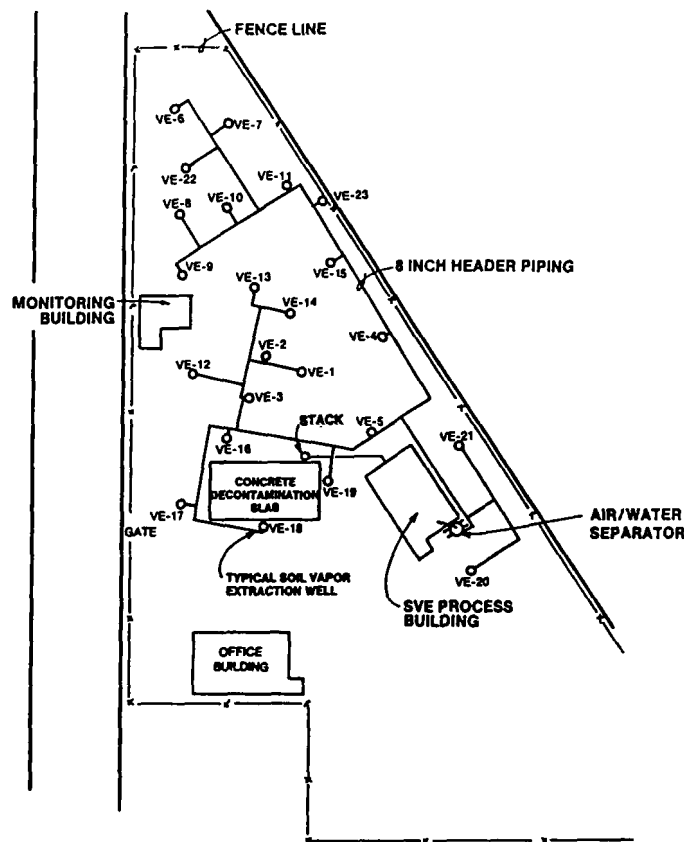


Figure 7
SVE Wells and Piping Layout

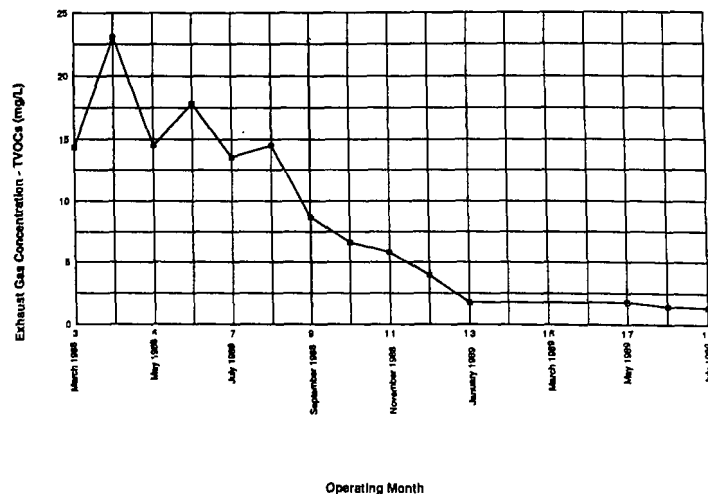


Figure 8
Thomas Solvents Raymond Road SVE Performance:
Verona Well Field, Battle Creek, Michigan

Conclusion

The loading rate of total VOCs has decreased from an initial high of approximately 45 lb/hr to less than 5 lb/hr. As shown in Figure 8, the concentration of total VOCs has dropped from a high of 23 mg/L to about 1.5 mg/L after a total run time of 117 days. The apparent NAPL layer has not been present since October, 1988. Operation is expected to continue into 1990, with the potential for removal of the 21 underground storage tanks.

ACKNOWLEDGEMENTS

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Using Bar Code Inventory Control at a Drum Site

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ABSTRACT

Ample technical guidance documentation is available to help plan and implement safe and cost-effective drum removal from hazardous waste sites, and techniques and equipment for handling drums are becoming well established and readily available.

An additional necessity at most drum sites where inordinate numbers of drums are encountered is a system of record-keeping that includes all information about the physical characteristics and handling/disposition of each drum. This system should be computerized, if possible, and allow for easy data retrieval and search programs. Information collected would include a description of each drum, its contents, a listing of any labels, locations where found and ultimate disposition (for both drum and contents when disposed of separately).

For a removal action in Pennsylvania, a system of bar coding was developed for a site containing approximately 45,000 drums. Using this system, each drum was assigned a unique bar code number that was used to track its characterization, movement, on-site and final disposition (treatment and/or disposal). This bar coding system was developed to reduce the amount of information needing manual transcription, thereby saving time and reducing errors. The data were entered into hand-held computers in the field and automatically transferred into a PC data base at the end of each day or shift. This system represents the innovative use of a well-established technology (bar coding) that greatly reduces the effort needed for information control and also eliminates errors inherent in manually transcribing data at each step.

INTRODUCTION

This paper discusses a PC-compatible system of bar coding and automated data acquisition that was developed by MK-Environmental Services to inventory and track characterization information on approximately 45,000 drums to be removed from a site in Pennsylvania. An accurate characterization of each drum on-site was important for two reasons. First, the cost of the removal action would be apportioned based on the number of drums identified belonging to individual Potentially Responsible Parties (PRPs). Secondly, it allowed for cradle-to-grave documentation verifying disposal of each drum.

In order to eliminate the time-consuming and error-prone task of manual transcription of data, a unique bar code number was assigned to each drum and menus of bar code choices were generated that contained drum characterization information of a repeating nature. This system allowed most data to be entered by wand using bar codes. Information collected in the field was then automatically downloaded into a PC data base at the end of each day.

EQUIPMENT

Data were collected in the field using D.A.P. Technologies' Microflex PC 1000, environmentally-sound (sealed to keep out dust, water and common industrial solvents), hand-held microcomputers with an attached Ricoh ProScan bar code reader wand. This microcomputer has 640 K of memory, 896 K of data storage memory, an 80C88 microprocessor running at 4.9152 MHz and operates on rechargeable

NiCad battery packs. Its operating system is MS-DOS, version 2.25. The keyboard has 47 programmable keys with audible feedback: 4 preliminary keys and 43 multi-function keys. The LCD (Liquid Crystal Display) emulates a one-quarter section of a Color Graphic Adapter (CGA) Monitor, showing 16 lines of 16 or 21 characters and acts as a window that can move over the entire CGA screen.

Sequential pairs of self-adhesive bar code labels were purchased for application on each drum. Menus of bar codes for characterization were developed using Tharo Systems Inc.'s EasyLabel Plus bar-code/label-generating software. The data base was maintained using Paradox 3 (Borland International) software on an IBM PS/2, Model 70, microcomputer connected to a Hewlett Packard LaserJet Series II printer.

DISCUSSION

Initially, drums were removed from their original locations (mostly in stacks of several thousand drums) and staged in a manner that allowed for easy access and efficient characterization. This process was accomplished by aligning the drums in rows approximately 18 in. apart (minimum distance to allow people to move between rows). At this site there was enough open space to permit staging and characterization of all drums before beginning disposal operations. Where space is limited, groups of drums could be staged, characterized and restacked or disposed of immediately.

Secondly, unique bar code identification numbers were affixed to each drum. This proved to be a problem, however, due to the variability in the condition of the drums. Rust and oil or grease on the drum surface made it difficult for a bar code label to adhere. Several methods of surface preparation were tried, but the most efficient was to mechanically wire brush an area of the drum large enough for the labels. Two labels were applied to each drum (usually one on the side and one on the end) to assure that handling activities which might render a single label unreadable would not make identification impossible. In addition, identification numbers were printed numerically on each label (in addition to being printed as a bar code), so that they could be entered manually when they were not readable by the wand. Using this system, no drums became unidentifiable due to both labels becoming unreadable. It should be noted that open-top drums with unsecured lids should have both labels applied to the side of the drum, rather than one on the top, to avoid any problems associated with tops and drums becoming separated. It may be cheaper and equally time-efficient to physically write numbers on the drums rather than apply bar code labels. However, this necessitates manually entering drum identification numbers into the data base and would certainly increase the occurrence of entering incorrect numbers.

Several methods for wire brushing drum surfaces were tried. Using hand-held brushes was slow and ineffective at removing rust. Rechargeable drills with brushes attached were fast and effective for surface preparation, but only lasted 0.5 hr before becoming discharged. The best method was using air-driven grinders equipped with brass brushes. This unit was fast, did an excellent job of surface preparation, could be operated indefinitely and eliminated any spark hazard.

SITE LOCATION:



ZONE 1



ZONE 2



ZONE 3



ZONE 4

OWNER:



AXIS CHEMICAL



XYZ OIL CO



ACME SUPPLY



NONE

DRUM COLOR:



BLUE



BLACK



RED



YELLOW



GRAY

MARKINGS:



ALCOHOL



CAUSTIC



FLAMMABLE



NONE



SURFACTANT



TOLUENE



WASTE

RCRA EMPTY?



YES



NO

Figure 1
Sample Barcode Menu Choices

Next, each drum was characterized and the information was entered into the data base. Information to be recorded included: location where the drum was found; size, color and type of drum; condition of drum; any markings that related to the original contents of the drum; all information on any hazardous waste labels found on the drum; identification numbers of any samples pulled from the drum; and the amount and type of any contents found in the drum. Most of this information was entered into the data base using menus of bar code choices of the type shown in Figure 1. If the appropriate information was not avail-

ble on the menus, it was entered manually using the keyboard of the Microflex unit.

Characterization of empty drums consisted of recording a physical description of the drum, all information written on the drum and that it was RCRA-empty. For drums that were not empty, characterization included the above plus a description of the contents and the volume of liquid contained by the drum. At the time of disposal, manifest numbers were recorded so that each drum and its contents could be traced from the site to the disposal facility.

Three problems were encountered and resolved using this system in the field. First, the internal batteries of the Microflex microcomputer were not designed to power bar code wands. Normally, the microcomputer uses minimal power other than to illuminate the screen and can operate for several days. However, during sustained use with the wand attached, the batteries were completely discharged in approximately 3 hr. Therefore, it was necessary to add to the system an additional 5-amp camcorder battery, worn on a belt, to power the wand. With the added battery, the system operated for as long as 24 hr.

The second problem was associated with operating in direct sunlight. Bright sun made it difficult, and sometimes impossible, to operate the wands. When the bar codes were in direct, bright sunlight, the wand did not receive enough contrasting light to function. There was also a problem with sunlight "burning" the LCD screens of the Microflex micro computers to the point where they were no longer readable. Other units are available with screens that are less sensitive to light. To eliminate both of these problems, beach umbrellas were used to protect the bar coding operation from direct sunlight. Two-person bar coding teams had little difficulty maneuvering the umbrella to keep the units in the shade. It also had the added advantage of keeping personnel cooler and increased the time between breaks in hot weather.

The third problem was that the wands were not environmentally sealed. When working in rainy or wet conditions, water accumulated

inside the wands. The umbrellas helped to alleviate this problem, but at times it was too wet to use the wands. At these times, all data were entered by keyboard, and the operating program was altered to produce choice menus similar to the bar code menus. However, this method is more time-consuming due to the limited amount of the screen visible at one time, which necessitates extensive scrolling to view all of the choices.

CONCLUSIONS

This method of drum characterization and information control is efficient, cost-effective and less prone to errors than manual transcription. For sites at which a large number of drums (or any other objects) need to be individually characterized and tracked, this method is ideal; there is no paper to get wet, soiled or blown about, and there are fewer opportunities for manual inaccuracies. When conditions make wand bar codes difficult or impossible, the system can be easily modified so that prompt menus are displayed on the Microflex screen.

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A Discussion of the Use of a Computer Data Base Management Program to Categorize Hazardous Waste Data

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ABSTRACT

The hazard categorization system currently employed by the Technical Assistance Team (TAT) at Ecology & Environment (E & E) has been upgraded by the development of a computer data base management program that categorizes waste streams quickly and accurately and according to RCRA regulations.

The use of this program allows both chemists and other hazardous waste management personnel to facilitate the categorization of hazardous materials. In an emergency removal, with a portable computer at the site, compatible materials can be grouped quickly with this program. Large removals involving hundreds of drums can therefore be carried out much more efficiently with this program.

The hazard categorization computer program is menu-driven and requires very little training to use. It alerts the user when an invalid or inconsistent entry has been made. Data entered previously or on the current sample are easily corrected. The program has a number of reporting capabilities including error reporting it, can be used at multiple sites and it has menus for selecting different printers and disk storage options.

This program has been distributed to and used by all U.S. EPA regions across the country. The software program, STREAMLINE, has been uploaded to the U.S. EPA Office of Solid Waste and Emergency Response (OSWER) bulletin board for use by U.S. EPA staff and U.S. EPA contractors. The types of waste sites on which the program has been used include plating facilities and drum recycling companies.

INTRODUCTION

The hazard categorization system was developed to help field investigation teams characterize chemical wastes at the time of sampling. The hazard categorization system is based on chemical testing procedures which permit a qualitative determination of waste characteristics according to RCRA (40 CFR, Part 261) and Department of Transportation (DOT) (49 CFR, Parts 171 and 172) specifications. The characteristics include ignitability or flammability, corrosivity, reactivity and EP toxicity.

Following the initial determination of the physical and chemical characteristics, waste streams can be determined. In an emergency removal, this determination allows manifests to be completed and the wastes to be legally transported to a disposal facility. At larger removals, involving several hundreds of containers of different materials, the hazard categorization information facilitates bulking of the compatible materials. Small, bench-scale testing ensures that the bulking is conducted safely. The bench-scale testing also minimizes laboratory costs involved when accurately quantifying the waste streams for disposal, recycling or treatment.

Previously, the consolidation of the waste materials could only be performed by a chemist. The process was initiated following comple-

tion of the field testing for hazard categorization. Data sheets used for the collection of data were manually segregated based on the field testing results. Not only was this procedure very laborious but also it required the full-time on-site presence of a trained chemist. It was at this time that the E & E TAT upgraded the hazard categorization system by developing a computer data base management program that categorizes waste streams quickly and accurately and according to RCRA and DOT regulations. The name of the computer data base management program is STREAMLINE.

COMPUTER SYSTEM

Description

The software, STREAMLINE, was developed using physical and chemical principles which categorize the material as a hazardous waste according to RCRA and/or DOT. Information retrieved from field testing is input into an on-screen computer data sheet (Fig. 1) which contains attributes of the container, results of the field testing for hazard categorization and the processed hazard designation of the hazardous waste.

STREAMLINE DATA ENTRY

SAMPLE ID [0004A] (A)ll/(T)op/(B)ottom		SAMPLE TAKEN? [Y]	
Container Attributes:			
TYPE (V/D/C)	[D]	MATERIAL	[S]
SIZE (Gallons)	[15.00]	((S)teel/(G)lass/(P)oly/(F)iber)	
TOP (O)pen/(B)ung	[O]	CONDITION	[P]
AMOUNT (1-Full/0-Empty)	[.75]	((P)oor/(F)air/(G)ood)	
MATRIX	[S]	SOLUBLE (Y/G/L)	[Y]
((S)olid/(L)iquid/(G)as)		((Y)es/(G)reater/(L)ess)	
PH	[2]	SULFIDE (Y/N)	[N]
OXIDIZER (Y/N)	[N]	BIC (Y/N)	[N]
CYANIDE (Y/N)	[N]	CHLORINE (Y/N)	[Y]
LABEL [Ferric chloride. Sample taken off floor of mobile]			
COMMENTS [none near drum described above. Tan sandy solid.]			
LOCATION [Mobile Home] ACT. TAKEN []			
HAZARD CLASS [AS]			

Figure 1
Data Entry Screen for Hazardous Waste Samples

The processed hazard designation is either a two or three letter code which corresponds to a specific hazard class, e.g., "AOL" references an acid oxidizing liquid. Once this step is completed for all the samples, the data can be sorted by hazard class and groups of samples with similar physical and chemical properties can be determined.

Software Design

The STREAMLINE program is written in the dBASEIII+ data base

management programming language and compiled by Clipper. The compiled version stands on its own and does not require dBASEIII+ to run. However, all the data are stored in standard dBASEIII+ files to make them easily accessible and transferable if desired. The software system includes one executable file, 14 report form files (.FRM), six system data base files (.DBF) and a data base file and two index files for each site for which a categorization is run.

The main system file, HAZSYS.DBF, contains the disk drive and code of the site categorization that is currently in progress. HAZPRNT.DBF contains printer numbers and names and the printer codes for compressed and regular printing. The data glossary and classification code definitions are stored in the HAZCLAS.DBF file. Table 1 contains a list of the contents of this file which is printed with every sample data report.

Table 1
Report of Hazard Class Codes and Data Glossary

Class Code	Hazard Class Description	Data Glossary
AL	Acid Liquid	SAMPLE ID NO. : A = All material
AOL	Acid Oxidizing Liquid	T = Top portion
AOS	Acid Oxidizing Solid	B = Bottom portion
AS	Acid Solid	CONTAINER TYPE : V = Vat
BL	Base Liquid	D = Drum
BOL	Base Oxidizing Liquid	C = Container < 55
BOS	Base Oxidizing Solid	SIZE : Size of container in gallons
BS	Base Solid	AMOUNT : 1.00 = Full
CLG	Chlorinated Gas	0.75 = 3/4 Full
CLL	Chlorinated Liquid	0.00 = Empty
CNG	Cyanide Gas	(material that G = Glass
CNL	Cyanide Liquid	the container F = Poly
CNS	Cyanide Solid	is made of) F = Fiber
FG	Flammable Gas	CONTAINER COND. : P = Poor
FL	Flammable Liquid	F Fair
FS	Flammable Solid	G Good
NCG	Non-Characteristic Gas	CONTAINER TOP : O Open
NCL	Non-Characteristic Liquid	B = Bung
NCS	Non-Characteristic Solid	MATRIX : S Solid
NFL	Non-Flammable Liquid/Oil	CONTAINER MAT. : S = Steel
NS	No Sample Taken	L Liquid
OG	Oxidizing Gas	G = Gas
OL	Oxidizing Liquid	SOLUBLE : Y Soluble in H2O
OS	Oxidizing Solid	L = Floats in H2O
SG	Sulfide Gas	G = Heavier than
SL	Sulfide Liquid	PH - 15 if material is insoluble in
SS	Sulfide Solid	water such that soluble = L or G

The system can handle and store categorization data for an unlimited number of sites. Each time a new site is begun, a new data file is created specifically to store data for that site. Each data file has a unique name created from the code that identifies that site. At the time the file is created, the user specifies the letter of the disk drive on which the data will be stored. This technique allows the files to reside on floppy or hard disks, or both, and to be easily transferable between computers. The site code and name and the disk drive letter are added to the site master file, HAZSITE.DBF. A list of the all sites that have been entered into the system can be displayed or printed (Table 2).

Table 2
Report Listing All Sites For Which Data Has Been Entered
List of All Sites in STREAMLINE Database

Site ID No.	Site Name	Data Drive
AZ0055	Bugfree Pesticide Co.	C:
CA1000	ABC Recycling & Salvage	C:
CA1052	Aladdin Barrel & Drum Company	A:
NV0206	Nevada Auto Parts	C:
NV0777	Phoenix Barrel & Drum	A:

HZXX0000.DBF is the boilerplate data file from which new site data files are created. The new data files names are determined by the site code that is entered by the user. The site code consists of two letters and four digits. The letters can be used to identify the state in which the site resides; for example, "CA0314" identifies a California site. The data file name would then be HZCA0314.DBF. There are two index files associated with this data file: HZCA0314.NTX which indexes by

class, and H2CA0314.NTX which indexes by sample number. See Table 3 for a list of the fields in this data file and the field attributes.

Table 3
Contents and Description of the STREAMLINE Sample Data File

Field Name	Field Type	Width	Dec	Description
SAMPLEID	Character	5		Identifies the individual sample
TAKE_SAMP	Logical T/F	1		Was sample taken? (Y or N)
CONTTYPE	Character	1		Container Type: Vat,Drum,<55 gal
CONDITION	Character	1		Condition of container G=Good, F=Fair, P=Poor
TOP	Character	1		Was top open or bung?
SIZE	Numeric	5	0	Size (in gallons) of container
AMOUNT	Numeric	4	2	Amount of material in container by dec. fraction (0 - 1.00)
MATCONT	Character	1		Container material: Steel, glass, poly, or fiber
LOCATION	Character	10		Location on site of container
CLASS	Character	3		Hazard classification code
MATRIX	Character	1		Is material solid, liquid or gas?
SOLUBLE	Character	1		Soluble yes, greater, less
PH	Numeric	2	0	pH of material in container
OXIDIZER	Logical	1		Is the material an oxidizer?
CYANIDE	Logical	1		Does material contain cyanide?
SULFIDE	Logical	1		Does material contain sulfide?
BIC	Logical	1		Does material contain bicarbonate
CHLORINE	Logical	1		Does material contain chlorine?
LABEL	Character	50		Label to be affixed to container
COMMENT	Character	50		Comments/Description
ERR_FLAG	Logical	1		Possible inconsistency in data
ACTION	Character	25		Action to be taken

Hardware Requirements

STREAMLINE can be run on any IBM-PC compatible computer on either a floppy or hard disk. Because the program is compiled, no additional software is required to run it. Currently, there are print settings in the HAZPRNT.DBF file to run the program with either a HP Laser-Jet, a Panasonic KX or an Okidata u93. If the HP option is selected, the reports will print out in the landscape mode with compressed printing. The dot matrix printers will print compressed (portrait mode) on 8.5- x 11-in. paper. The print codes in the HAZPRNT.DBF file can be modified for other printers through dBASEIII+ if required. Approximately 300K bytes of disk space are required for the program and standard system files and report forms. The additional amount of space needed for the specific site files depends on the number of samples collected and entered for that site.

Procedure for Using STREAMLINE

STREAMLINE is menu-driven and easy to use. The program is started by typing HAZ at the DOS prompt. After displaying a title screen, you are asked to select a printer from a menu. The program then displays the code and name of the last site for which data were entered or edited (Figure 2).

Pressing F1 at this point displays a list of all sites that have been set up in the system. You then have the option to continue with the site currently displayed on the screen, enter a new site code, edit the current site's name or disk drive designation, or quit the program.

If you enter a new code, the system will check to see if the site is already in the master file, or if data files exist for that site. If it is a new site, you will need to enter a site name, and a new empty data

file will be created. The program main menu is then displayed (Figure 3).

STREAMLINE

SITE I.D. (XX9999) :	NV1006
SITE NAME :	Nevada Barrel and Drum
DATA DRIVE :	A

Set Up Current/New Site/Edit/Delete/Quit (S/N/E/D/Q) :

Press <F1> for List of Current Sites.

Figure 2
Site Selection and Update Screen

1 \	Select Another Site
2 \	Update/Edit Data
3 \	Re-Classify All Samples
4 \	Generate Reports
Q \	Quit to DOS

Figure 3
Main Menu of the STREAMLINE Program

The first option on the main menu is to select another site. Use this if you are working on one site, then wish to enter or edit data for a different site. Use the second option, Update/Edit Data, to add data for new samples for the site or to edit data for samples that have already been entered in the system.

The screen format for entering the data into the computer is almost identical to the data entry sheet from which the information is taken. At the sample data entry screen, first type the sample ID number. If the sample has already been added, the current information is displayed and can be edited. Each item of information entered is checked so that only allowable values can be entered. After all data for the sample have been entered, the program determines into which hazard class the sample falls. The code for the hazard class is displayed at the bottom of the screen.

If inconsistent data are entered so that the system is unable to determine a hazard class for the sample, an error message is displayed, and the user has the option to correct the data or leave it flagged for later editing. For example, this might occur if the sample is marked true for both cyanide and oxidizer. At this point the sample would be added to an error file, and an algorithm would be used to determine both a primary and a secondary hazard class. A list of all samples flagged as errors can be printed through the report menu.

The third option on the main menu, Re-Classify All Samples, need only be used if the program has been modified to change the way the hazard classes are determined. The hazard class usually is determined when data for the individual sample are entered or edited. If the program algorithm for determining classes is changed, only those samples that have been edited or newly added would use the new algorithm. This option provides the opportunity to run the modified classification

program on each sample in a file automatically and re-classify it, if necessary.

STREAMLINE Reports

The program provides a standard set of reports that can be selected from the report menu. If different reports are desired (and the user has dBASEIII+), additional report formats can be easily created at the dBASEIII+ dot prompt or in the dBASEIII+ assist mode. The reports available through the STREAMLINE report menu include: lists of all the data for all samples on a site, listed either by sample ID number, or grouped by hazard classes (Table 5); an error report showing all the samples from a site that were flagged because of inconsistent data; and a list of all the sites that have been set up in the STREAMLINE site data master file. The hazard class code and data glossary are printed with each report of sample results, as well as a report titled "Classifications of a Material Having More Than One Hazard as Defined in Title 49" (Table 4). This report is used if the sample you entered falls under more than one class. The primary class is the one that is higher up on the list.

Table 4
Hierarchy Used For Determining Hazard Class Code

Classification of a Material Having More Than One Hazard
As Defined in Title 49

Hazard No.	Description
1	Radioactive material (except a limited quantity).
2	Poison A.
3	Flammable gas.
4	Non-flammable gas.
5	Flammable liquid.
6	Oxidizer.
7	Flammable solid.
8	Corrosive material (liquid).
9	Poison B.
10	Corrosive material (solid).
11	Irritating materials.
12	Combustible liquid (in containers having capacities > 110 g)
13	ORM-B.
14	ORM-A.
15	Combustible liquid (in containers having capacities <= 110 g)
16	ORM-E.

CASE STUDIES

Aero Quality Plating Company

The initial site where STREAMLINE was implemented by the E & E Emergency Response Section was the Aero Quality Plating Company (APC), located in Oakland, California². APC was an electroplating facility which operated from 1958 to 1985. In October, 1985, APC filed for bankruptcy under Chapter 11 and later converted the filing to Chapter 7. In April, 1987, the State of California Department of Health Services requested U.S. EPA assistance in the stabilization of the hazardous wastes at the site.

The stabilization efforts were initiated by collecting over 1,000 samples and performing field testing for hazard categorization³. The field testing results were then processed using STREAMLINE. The processed information aided stabilization efforts by assisting in the consolidation of on-site materials from both structurally unsound and sound containers. The computer-generated report, grouping the samples by hazard classes, simplified enforcement sampling. The report was used to zero in on drums that were both structurally unsound and contained very hazardous materials, i.e., those drums that were prime targets for enforcement sampling. The stabilization efforts at APC were completed in June, 1987.

Lorentz Barrel and Drum Company

Another site where the STREAMLINE program was used was the Lorentz Barrel and Drum Company (LB&D) located in San Jose, California⁴. LB&D had been reconditioning used steel drums for approximately 40 yr, since the 1940s. As a result of the operation, about 800 full drums of hazardous waste had been accumulated. In July, 1987, the State of California Department of Health Services (DOHS) investigated LB&D and discovered that several State of California laws had

been violated during the handling and disposal of hazardous waste. Operations at the facility completely ceased in July, 1987.

In September, 1987, the U.S. EPA, assisted by the E & E TAT, conducted a site assessment at the facility as a result of the threat posed to human health and the environment by leaking drums. U.S. EPA assistance was requested by DOHS due to the lack of proper resources needed by DOHS and local agencies to stabilize the site.

A total of 687 samples were taken. Field testing for hazard categorization revealed the presence of such hazardous wastes as acids, caustics, oxidizers, flammables and cyanides. The testing results were entered into STREAMLINE and the data were then processed, assigning a hazard class to each sample. The processed information later was used to bulk compatible wastes and composite samples for laboratory analysis.

categorization, a chemist familiar with STREAMLINE can perform both functions.

Reporting

The hazard categorization results are entered into a computerized data sheet, processed and then assigned a hazard class by the computer. The processed information can be sorted alpha-numerically and/or by hazard class. The printed output varies with the user and purpose, but the most common output is by hazard class. This output is most helpful when bulking and/or compositing.

An error report is another type of STREAMLINE-generated report. This report alerts the user to invalid entries or possible stratification in the sample container. The user can then re-test the sample for a hazard

Table 5a
Report of All Data for All Samples-Sorted by Hazard Class

Sample Cont				Container					Hazard				Sample							
ID No.	Type	Size	Amount	Volume	Mat.	Cond.	Top	Locale	Class	Matrix	Soluble	Ph	Ox	Cn	Sulf	Bic	Cl	Taken?		
** DATA FOR HAZARD CLASS : AOL																				
0017A	D	55	0.75	41.25	S	F	B	Semi tr.	AOL	L	Y	1	.T.	.F.	.F.	.F.	.T.	.T.		
0018A	D	30	0.50	15.00	S	F	B	Semi tr.	AOL	L	Y	1	.T.	.F.	.F.	.F.	.T.	.T.		
** DATA FOR HAZARD CLASS : AS																				
0004A	D	15	1.00	15.00	S	P	O	Mobile hom	AS	S	Y	2	.F.	.F.	.F.	.F.	.T.	.T.		
0005A	D	15	1.00	15.00	S	P	O	Mobile hom	AS	S	Y	2	.F.	.F.	.F.	.F.	.F.	.T.		
0010T	D	55	1.00	55.00	P	P	O	Lg cluster	AS	S	Y	1	.F.	.F.	.F.	.F.	.F.	.T.		
** DATA FOR HAZARD CLASS : BL																				
0001A	D	55	1.00	55.00	S	F	B	Nr lab tr	BL	L	Y	13	.F.	.F.	.F.	.F.	.F.	.T.		
** DATA FOR HAZARD CLASS : FL																				
0019A	D	55	1.00	55.00	S	F	B	Semi tr.	FL	L	Y	7	.F.	.F.	.F.	.T.	.F.	.T.		
** DATA FOR HAZARD CLASS : NCL																				
0006T	D	55	1.00	55.00	P	G	O	Lg cluster	NCL	L	Y	10	.F.	.F.	.F.	.F.	.F.	.T.		
0020A	D	55	1.00	55.00	S	F	B	Semi tr.	NCL	L	Y	5	.F.	.F.	.F.	.F.	.F.	.T.		

Hazard Data - Sample Comments - By Hazard Class

Sample ID	Sample Taken?	Hazard Class	Label/Comment	Action Taken
** Samples for Hazard Class : AOL				
0017A	.T.	AOL	Algae-green, clear liquid. EM Cu=0. HNU=3.	
0018A	.T.	AOL	AuS, Au Sol Dark green clear liquid. EM Cu=0. HNU=2.	
** Samples for Hazard Class : AS				
0004A	.T.	AS	Ferric chloride. Sample taken off floor of mobile home near drum described above. Tan sandy solid.	
0005A	.T.	AS	Ferric chloride, anhydrous 100 1 lb plastic bags in each drum. No hazcat done	

BENEFITS

Cost Minimization

As a result of using STREAMLINE, the costs at a hazardous waste site removal can be minimized. The cost savings can be attributed to the bulking of compatible materials and the compositing of samples for laboratory analysis. Cost control can also be achieved by minimizing the need for personnel. The size of the field investigation teams can be decreased by using individuals who can perform a variety of tasks including STREAMLINE. For example, rather than assigning a chemist and a data entry clerk to conduct an investigation field testing for hazard

categorization to prevent a chemical reaction during bulking or compositing.

Resource Utilization

As mentioned previously, chemists familiar with STREAMLINE can perform a variety of tasks at a hazardous waste removal site. Another aspect of resource utilization lies in the fact that other hazardous waste management personnel who are familiar with field testing for hazard categorization can be trained to use STREAMLINE. This allows other personnel to become diverse in their duties and distributes the responsibility among a number of personnel.

Table 5b
Report of All Data for All Samples-Sorted by Sample I.D. Number

Sample Cont				Container					Hazard				Sample						
ID No.	Type	Size	Amount	Volume	Mat.	Cond.	Top	Locale	Class	Matrix	Soluble	Ph	Ox	Cn	Sulf	Bic	Cl	Taken?	
0001A	D	55	1.00	55.00	S	F	B	Nr lab tr	BL	L	Y	13	.F.	.F.	.F.	.F.	.F.	.T.	
0002B	V	3500	0.01	35.00	F	P	O	Nr lab tr	NCS	S	Y	10	.F.	.F.	.F.	.F.	.F.	.T.	
0003A	C	2500	0.01	25.00	F	P	O	Nr lab tr	NCS	S	Y	5	.F.	.F.	.F.	.F.	.F.	.T.	
0004A	D	15	1.00	15.00	S	P	O	Mobile hom	AS	S	Y	2	.F.	.F.	.F.	.F.	.T.	.T.	
0005A	D	15	1.00	15.00	S	P	O	Mobile hom	AS	S	Y	2	.F.	.F.	.F.	.F.	.F.	.T.	
0006T	D	55	1.00	55.00	P	G	O	Lg cluster	NCL	L	Y	10	.F.	.F.	.F.	.F.	.F.	.T.	
0007T	D	55	1.00	55.00	S	F	O	Lg cluster	NCS	S	Y	9	.F.	.F.	.F.	.F.	.F.	.T.	
0008T	D	55	1.00	55.00	S	F	O	Lg cluster	NCS	S	Y	7	.F.	.F.	.F.	.F.	.F.	.T.	
0009T	D	55	0.75	41.25	S	P	O	Lg cluster	NCS	S	Y	6	.F.	.F.	.F.	.F.	.F.	.T.	
0010T	D	55	1.00	55.00	P	P	O	Lg cluster	AS	S	Y	1	.F.	.F.	.F.	.F.	.F.	.T.	
0011T	D	55	0.75	41.25	P	P	O	Lg cluster	AS	S	Y	1	.F.	.F.	.F.	.F.	.T.	.T.	
0012T	D	55	0.75	41.25	P	P	O	Lg cluster	AS	S	Y	1	.F.	.F.	.F.	.F.	.F.	.T.	
0013T	D	30	1.00	30.00	S	P	O	Lg cluster	NCS	S	Y	10	.F.	.F.	.F.	.F.	.F.	.T.	
0014T	D	55	0.25	13.75	F	P	O	Lg cluster	NCS	S	Y	10	.F.	.F.	.F.	.F.	.F.	.T.	
0015A	C	0	0.00	0.00	S	P		Under semi	NCS	S	Y	10	.F.	.F.	.F.	.F.	.F.	.T.	

Hazard Data Sample Comments By Sample ID No.

Sample ID	Sample Taken?	Hazard Class	Label/Comment	Action Taken
0001A	.T.	BL	"Gold Stripper C Concentrate Alkaline Liquid N.O.S Potassium Hydroxide NA 1719 4086607M" Red/org opaq	
0002B	.T.	NCS	Beige,gray,orange sludge & sandy solid. HNU=0.5	
0003A	.T.	NCS	Green sandy,chunky solid. HNU=0. EM Cu=100 ppm.	
0004A	.T.	AS	Ferric chloride. Sample taken off floor of mobile home near drum described above. Tan sandy solid.	
0005A	.T.	AS	Ferric chloride, anhydrous	
0006T	.T.	NCL	100 1 lb plastic bags in each drum. No hazcat done	
			25% liquid, 75% sludge. Brown opaque liquid. HNU=4	

FUTURE APPLICATIONS

A possible future application of STREAMLINE is to integrate it with a hazardous waste manifest generation program. The data base generated by STREAMLINE would be combined with a data base that contains transporting and safety information, to automatically print the appropriate hazardous waste information on the manifest form. This procedure would eliminate mistakes and lessen the workload of the on-site personnel.

The STREAMLINE data base could be linked to an Alternative Treatment Technologies data base to determine the appropriate treatment standards for the hazardous waste on any particular site.

Another possible application would be to use the information entered through the STREAMLINE program to search a computerized data base for disposal sites that are designated for the types of hazardous waste that need to be removed from the site.

CONCLUSIONS

When dealing with an emergency removal situation, it is important to have tools in hand that help make the removal process expedient and

efficient. Because STREAMLINE is easy to learn and easy to use, it also can make a field investigation team more productive. It is advantageous to have the data computerized, particularly in the widely used dBASEIII+ format, not only for hazard categorization by STREAMLINE, but also because the information can be easily transferred to a word processing program for inclusion in a report, to Lotus123 or to other data analysis software.

REFERENCES

1. Worobel, R.S., *The Response Kit*, U.S. EPA Rept. No. T98702-017, U.S. EPA, San Francisco, CA, Dec., 1987.
2. Worobel, R.S., *Aero Quality Plating Company, Oakland, CA*, U.S. EPA Rept. No. T98704-010, U.S. EPA, San Francisco, CA, May, 1987.
3. Floyd, G.A., *RCRA Quantification of U.S. EPA Enforcement Samples Collected at the Aero Quality Plating Facility Stabilization Effort, May 19-June 15, 1987, Oakland, CA*, U.S. EPA Rept. No. T98705-008, U.S. EPA, San Francisco, CA, Apr., 1987.
4. Worobel, R.S., *Site Assessment of the Lorentz Barrel and Drum Company, San Jose, CA*, U.S. EPA Rept. No. T98708-015, U.S. EPA, San Francisco, CA, Dec., 1987.

Remediation of Underground Explosives Contaminated Sewer Lines

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ABSTRACT

O.H. Materials Corp. (OHM), under contract to the United States Army Toxic and Hazardous Materials Agency, was tasked with the decontamination of approximately 7 mi of buried sewer line contaminated with 2,4,6-trinitrotoluene (TNT) at the former West Virginia Ordnance Works. The sewer line had removed the industrial wastewater effluent from ten TNT manufacturing lines used during World War II for production of explosives.

An innovative, safe and cost-effective approach was needed. Since thermal destruction of explosives is the only assured method of decontamination, OHM focused on this technology.

In situ methods could not be certified as effective. The age and unknown condition of the pipe and its contents precluded such an approach.

Excavation and verifiable decontamination of the pipe was necessary. Several approaches to decontamination were then available. Rotary kiln technology was judged not only too expensive, but also might require crushing the pipe with the attendant risk of detonation. Stationary furnaces could be used, but the logistics of such an operation in a remote area presented formidable obstacles.

A handheld flamer torch technique was adopted. This approach was judged the safest, most cost-effective approach. Verification of the effectiveness of the decontamination was achieved using Certipaks, which are small ceramic beads impregnated with TNT and DNT. The Certipaks, placed in the pipe during flaming, are retrieved after flaming and analyzed using a field colorimetric method to verify the effectiveness of the process in decontaminating the explosives.

To illustrate the effectiveness of this approach, the decontamination of over 7 mi of sewer line, including excavation, flaming, certification and backfilling, was accomplished, accident free, in less than 2 mo at a cost of approximately \$1.4 million.

INTRODUCTION

The former West Virginia Ordnance Works (WVOW) encompasses an 8,323-ac parcel of land in Mason County, West Virginia. It is located approximately 6 mi north of Point Pleasant, West Virginia, on the east bank of the Ohio River (Fig. 1). The property is now owned by various state, local and private concerns. The largest portion of the site is occupied by Clifton F. McClintic State Wildlife Station (MCCLINTIC) operated by the West Virginia Department of Natural Resources (WVDNR).

During World War II (1942 to 1945), the site was used to produce TNT. Contaminants from those operations were present in

the sewer lines which conveyed process wastewaters. The contamination was in the form of TNT and its associated process by-products and environmental degradation products.

In 1946, the property was declared excess by the government and portions were sold. Most buildings have been removed; however, some foundations remain. In 1949, the U.S. Army deeded the process and waste disposal property to the state of West Virginia for use as a wildlife refuge.

In 1981, evidence of contamination was found in one of the ponds of MCCLINTIC, and the WVDNR and the U.S. EPA were notified. The U.S. Army was notified of the contamination in 1983.

An RI/FS was begun in 1984 to study the contamination problem. As a result of the study, it was determined the cleanup project should be conducted in two remediation phases (operable units). The first unit (i.e., TNT Manufacturing Area, Burning Grounds and Industrial Sewer Lines) is described in this paper. This project was almost entirely contained within the McClintic Wildlife Station.

In 1987, a formal ROD was agreed to by the U.S. EPA and the U.S. Army (in concurrence with the WVDNR). The ROD provided for excavation, flaming, and backfilling to clean-up the explosives-contaminated sewer lines.

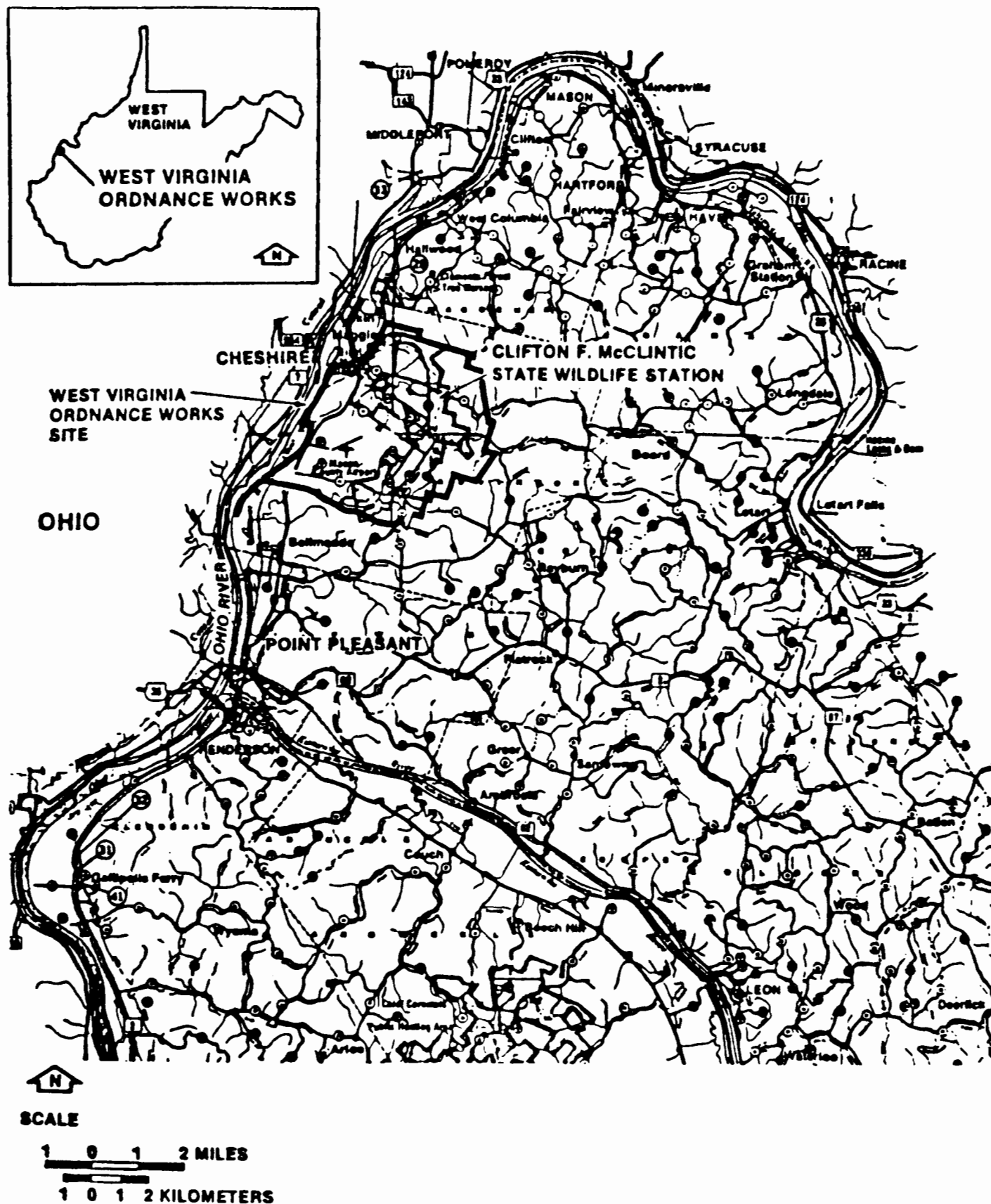
SEWER LINE EXCAVATION, FLAMING AND BACKFILLING

MCCLINTIC was overgrown with trees, brush and weeds. Prior to beginning sewer line excavation, trees and underbrush had to be cleared. Manholes were used for location reference points and a 60- to 100-ft wide path was created.

There were 10 manufacturing area sewer systems at MCCLINTIC which has to be remediated. The 10 areas all drained into a common sewer system, which also had to be remediated (Fig. 2). Initial excavation of the sewer lines began near the first manufacturing area in the common sewer system and proceeded through each manufacturing area, cross-country and eventually to three settling basins.

At the same time as the common sewer line excavation, sewer lines from each of the 10 manufacturing areas were excavated, remediated and backfilled. Two independent crews were used to accomplish the sewer line remediation in less than 2 mo.

A unique method was used to decontaminate the explosives in the sewer lines and verify the decontamination. The cleaning method is called flaming. Verification was accomplished using Certipaks.



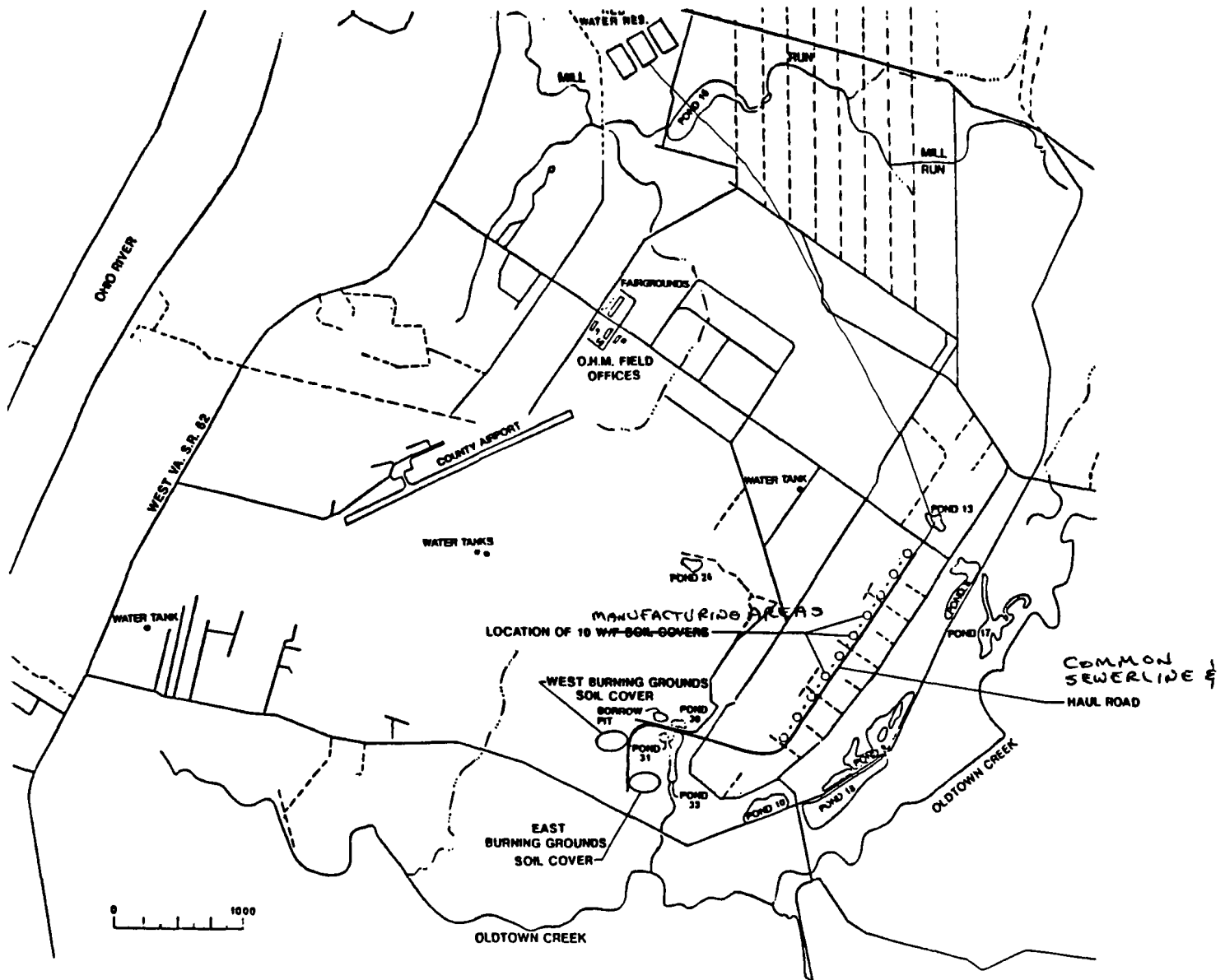


Figure 2
Manufacturing Area & Sewer-Line Locations

After the sewer lines were excavated, they were brought to ground level and stacked in a triangular pile (Fig. 3). Each clay tile piece was 3 ft long and each pile of tiles contained approximately 10 clay tile pieces. Thus, about 30 linear feet of sewer line were stacked in each pile.

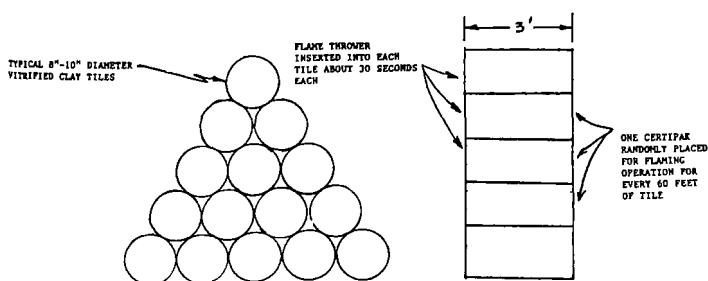


Figure 3
Piling of Sewer Tile for Flaming

All loose explosive pieces were removed from each piece of tile using sparkless shovels or plungers. These explosive pieces were collected in plastic lidded buckets and transported to a storage magazine located on MCCLINTIC.

Flaming

The tile pieces then had only a thin residue of explosive powder remaining on the inside walls. The residue was so firmly attached to the walls that it could not be removed by any conventional method without breaking the clay tile pieces. If tile pieces were broken, all loose explosives would have to be collected by hand and taken to the on-site magazine. The tile pieces would then have to be burned separately to destroy the explosives remaining and then backfilled into the trench. Aside from the explosion hazard in using this approach, it was not considered a desirable method of remediation because it was not the most cost-effective approach.

Certipak Analysis

The cleanup method chosen, as noted above, was to flame the tiles at the excavation site using handheld flammers. To verify that

the tiles were completely cleaned, a Certipak was randomly placed on the side of the tile opposite the flame throwers. After a period of "flaming", the Certipak was removed from the stack of tile pieces and the enclosed ceramic bead removed. Using a field colorimetric method, the bead was checked for remaining explosive residues. If the bead has no explosive material, the flaming operation was considered successful in destroying the explosive residue and the clay tile pieces could be backfilled in the trench. If the bead had remaining explosive residues, the flaming and Certipak placement were repeated, the field colorimetric method again was applied and the results were noted. This process was repeated as many times as necessary to obtain a "clean" Certipak. Very few times did the flaming process require a second pass and only once, a third pass.

A Certipak is a foil packet with an enclosed ceramic bead with a length of wire attached for handling. The ceramic bead has a standard amount of explosive impregnated in it. The standard amount and placement of explosives on the bead are accomplished in a laboratory under controlled conditions. In this project, the method for preparing the beads was written by an approved laboratory and submitted to, and approved by, the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) prior to the Certipaks being used in the field.

The method used to determine the presence (or absence) of residue on the ceramic bead was a colorimetric process. When the bead is removed from the Certipak, it is contacted with reagents and the color noted. Basically, a colored bead indicated that the bead still had explosives on it. Thus, the flaming had not successfully removed all the explosives and had to be repeated. On the other hand, a white bead indicated that the bead was free of explosives and the flaming process had been successful.

Use of Certipak in Flaming Process

Certipak beads are impregnated with explosive residues in the laboratory as noted above. The explosive material is then driven off by the application of heat on a few test beads and the field colorimetric method is tested to assure that it is working properly. This testing is done daily.

The beads are put in a foil packet with an attached wire. The packet assures that the bead is subjected to the temperatures of flaming without being soiled with any smoke residues which make the developed colors hard to see. The attached wire makes it easier to retrieve.

When the Certipak is placed in the stack of clay tile pieces, it is put on the opposite side of the pile from the flame thrower. This placement assures that the Certipak is being subjected to the minimum temperature achieved within the clay tile pieces. Then, if the ceramic bead has been successfully treated to remove all explosive residues (i.e., subjected to enough heat), the clay tile pieces, which had a higher contact temperature, also would be

clean.

The system of stacking and flaming tile pieces was used throughout the project. Initially the length of time it took to properly flame clay tile pieces was determined. This same time period was then used on subsequent clay tile piles.

In all, over 7 mi of sewer tiles were decontaminated this way. The work was accomplished with no accidents.

DESTRUCTION OF TNT PIECES FROM STORAGE MAGAZINE

The pieces of TNT recovered from the excavated sewer lines were taken to an on-site magazine. Subsequently, they were incinerated. The procedure used was as follows.

A burning pad was constructed. It consisted of a semi-cylindrical vessel with a cap on each end. TNT pieces were placed in the vessel in a single layer; no more than 50 lb were burned at one time. A handheld flamer was used to burn the TNT in the vessel. The flame configuration was arranged so the flame did not impinge on the TNT until all personnel were a prescribed distance away from the burning vessel. After each successful burn, a cool-down period was required before more TNT could be loaded in the burning vessel. Burning and cool-down had to be completed during daylight hours.

In total, nearly 1 ton of TNT pieces was destroyed using the burning vessel approach. Safety standards were very high and no injuries occurred.

INTERESTING SIDELIGHTS

Along the cross-country sewer line route there was a section of pipe running uphill. Because this was a pressurized system (i.e., pumps were being used at that point), the pipelines had been constructed of steel and wood staves rather than the clay tiles used elsewhere. These pipelines, although buried for nearly 50 yr, were in excellent condition, almost like new. Our expectation was to find pipe badly deteriorated in spots, possibly even corroded through. That was not the case. These lines also were clean of any explosives contaminants as one would expect of pressure pipe.

Another item of interest was the on-site magazine used to store explosive materials until destruction could be accomplished. The magazine used was found to be almost like new with little mustiness, almost no cracks in the concrete liner and a workable door—after 45 years!

CONCLUSION

The project successfully decontaminated over 7 mi of underground sewer lines. Also accomplished was the installation of nearly 14 ac of soil cover and the creation of a sizeable wetland area (pond) in the process. There was virtually no disturbance to existing wetlands as a result of remedial activities.

Characterization and Remedial Assessment of DNAPL PCB Oil in Fractured Bedrock: A Case Study of the Smithville, Ontario, Canada Site

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Golder Associates

ABSTRACT

In 1986, the Ontario Ministry of the Environment commissioned hydrogeological investigations at the site of a former PCB transfer and storage facility in Smithville, Ontario. Previous studies had identified widespread soil contamination by PCBs and the potential occurrence of PCB-bearing DNAPL oil within the fractured dolostone bedrock underlying 6 m of clay beneath the site. The subsequent investigation characterized the physical and chemical hydrogeological conditions at the site and identified the sources, pathways and occurrence of DNAPL. At the present time, DNAPL is identified as covering an area approximately 150 m in length and 70 m in width in the upper 5 m of bedrock. The estimated volume of the DNAPL plume is 30,000 L. The DNAPL contains approximately 50% PCB and lesser amounts of other chlorinated organic compounds.

Extensive rock coring, monitoring well installation and pump testing, coupled with intensive groundwater quality monitoring, has allowed the delineation of the DNAPL plume and two associated dissolved constituent plumes of trichloroethene and trichlorobenzenes within the bedrock which necessitated the closure of a municipal well serving the Town of Smithville.

A thorough understanding of the microstratigraphy at this site is critical to the technical assessment of remedial alternatives. A short-term remedial action plan has been implemented to control the migration of the dissolved plumes from the source area by means of a system of recovery wells, water treatment and discharge. Longer term remedial options are being assessed, with the objective of cleaning up the contaminated bedrock using in situ techniques. The hydrogeological investigations are continuing concurrently with ongoing site decommissioning activities, which include the proposed on-site incineration of nearly 180,000 L of PCB-bearing oil, contaminated soil and other solids which are in secure on-site storage.

INTRODUCTION

In 1978, a private waste management firm was issued a Certificate of Approval from the Ontario Ministry of the Environment (MOE) to operate a PCB transfer and storage facility at a location in the Niagara Peninsula region of south-central Ontario, Canada. The site, as shown in Figure 1, is located in an industrial park in the northern outskirts of Smithville, Ontario, and originally consisted of approximately 0.8 ha, of which 0.25 ha were used for the transfer and storage activities. Between 1978 and 1985, the site reportedly received approximately 434,000 L of liquid waste including approximately 266,000 L of PCB-contaminated wastes. The remainder of the waste inventory included organic solvents, resins, acids, alkalis, inorganic liquids and inert sludges. In early 1985, the site was effectively closed when the Certificate of Approval was revised to permit only the storage of wastes then

located on the site. Since that time, the site owner/operator has not been involved in any activities and MOE has assured ownership and responsibility for the site.

Subsequent to the closure of the site, testing by MOE disclosed the presence of PCB-contaminated soil and water in a retention lagoon located near the southeast corner of the site. During the fall of 1985, a short emergency cleanup was performed. Approximately 72,000 L of PCB-contaminated sludge, oily water and soil were removed from the lagoon by a specialist decontamination contractor retained by MOE, and these materials were placed in secure containers for on-site storage until their ultimate disposal could be addressed.

In January 1986, MOE retained Proctor & Redfern Ltd. as the overall Project Manager for the decommissioning of the site. The initial task was to secure and subsequently arrange for the disposal (destruction) of the PCB wastes then in unsecured storage at the site.

The work of cleaning up the site progressed during 1986, and all of these wastes are currently in on-site secure storage within a specially designed and constructed warehouse. An area of near surface contaminated soil (including the original retention lagoon area) was temporarily secured by covering it with a synthetic membrane.

In 1985, MOE began to investigate the potential for off-site migration of contaminants from the facility. Due to the presence of 6 to 10 m of clay overburden beneath the site, it initially had been assumed that any migration of contaminants would be via surface and/or near-surface pathways. However, in early February, 1987, Dense Non-Aqueous Phase Liquid (DNAPL) PCB oil was detected within the dolomitic limestone bedrock underlying the clay. This discovery significantly expanded the scope of the proposed decommissioning work and, as a result, MOE, through Proctor & Redfern Ltd., retained Golder Associates Ltd. to act as a specialist subconsultant to Proctor & Redfern with a mandate to investigate the extent and advise on the remediation of the subsurface contamination.

Since May, of 1987, investigations have characterized the physical and chemical hydrogeological conditions at the site and identified the sources, pathways and occurrence of the plume of DNAPL which contains up to 50% by weight PCB and lesser amounts of trichlorobenzenes (TCB), trichloroethylene (TCE), trichloroethane (TCA) and other organic constituents. In addition, two distinct but interrelated dissolved contaminant plumes exist within the bedrock which forms the water supply aquifer for the Smithville vicinity. In late 1987, one of the two municipal wells serving the Town of Smithville was ordered closed due to its location within about 600 m of where the PCB contamination had been detected in the bedrock aquifer. Primarily because of this situation, MOE in co-operation with the Regional Municipality of Niagara undertook to construct a water main to connect the Smithville distribution system to that of the Town of Grimsby, located below the

escarpment on Lake Ontario, 20 km away.

RESULTS OF INVESTIGATIONS TO DATE

The investigations completed to date at the Smithville site consist of a detailed evaluation of the regional geology, hydrostratigraphy and groundwater chemistry of the original waste management site and approximately 60 h of adjoining property. The scope of the study to date has included the drilling of 78 cored boreholes to various depths within the bedrock, the installation of 120 monitoring wells, aquifer testing to determine relevant hydraulic parameters and detailed groundwater chemical monitoring for the organic constituents associated with the site. While the studies at the site are continuing, the focus has changed to one of assessing the long-term remedial alternatives and designing, implementing and monitoring the performance of the interim control measures required to secure the site while the evaluation of the most appropriate remedial action proceeds.

DNAPL SOURCES AND OCCURRENCE

Investigations at the site have identified DNAPL containing PCB, TCB and TCE within the Overburden and Shallow Aquifer beneath the Smithville site. Complete characterization analyses of the DNAPL indicate that the oil contains between 35 and 55% PCB and 5 to 8% TCB. The laboratory analyses of the PCB congeners suggest that a mixture of Aroclor 1242, 1254 and 1260 comprises the DNAPL. Analyses for organic solvents including TCE and TCA indicate that these constituents are present in the DNAPL in concentrations ranging from the high hundreds of ppm to approximately 1.8%. It is probable that the solvents are present as contaminants in the PCB oil, arising from co-storage or disposal at the site. Other principal constituents identified in the ppm range include benzene, chloroform and mono-di- and tetra-chlorobenzenes.

It has been demonstrated through drilling and coring of the overburden on the site that DNAPL oil migrated vertically downwards through the bottom of the former retention lagoon. DNAPL oil was observed in weathered fractures in the clay 6 m below ground surface at the lagoon site.

Investigations of other potential sources and migration pathways, including the vicinity of two vertical storage tanks which formerly held up to 160,000 L of PCB oil, a Quonset hut formerly used to store wastes and the original geotechnical borings put down at the time of construction of the facility, have indicated that the former lagoon is the only probable significant source of the DNAPL, and that vertical migration under gravity via the weathered fractured clay is the only probable pathway. The implications of this finding may have significant impact on the way in which existing and proposed chemical storage and handling facilities situated on clay deposits are evaluated in the future.

Estimates of the volume of DNAPL that could be resident within the bedrock range from the low thousands of litres to as much as 30,000 L, based on drilling evidence and observation of recovered oily rock core. Borehole drilling and sampling in the vicinity of the former lagoon have delineated a kidney shaped plume of DNAPL centered around the area of the former lagoon, extending down dip to the southeast within the Shallow Aquifer for a distance of 160 m, achieving a maximum observed width of approximately 70 m and a depth of penetration into the bedrock of approximately 5 m.

Free oil has been observed to migrate rapidly within the open bedding partings over distances of several metres under imposed gradient conditions. As the lateral distance from the area of the former lagoon increases, the depth of the first occurrence of DNAPL within the Shallow Aquifer increases, strongly suggesting that the migration under gravity occurred in a step-wise vertical fashion through vertical fractures in the bedrock. However, monitoring suggests that the DNAPL plume presently is stable and no longer is expanding in the horizontal plane. The observed extent of DNAPL in the bedrock is shown in Figure 2.

CONTAMINANT PATHWAYS AND MIGRATION WITHIN THE BEDROCK

The DNAPL plume within the upper bedrock zone provides the source of an elongated dissolved contaminant plume within the Shallow

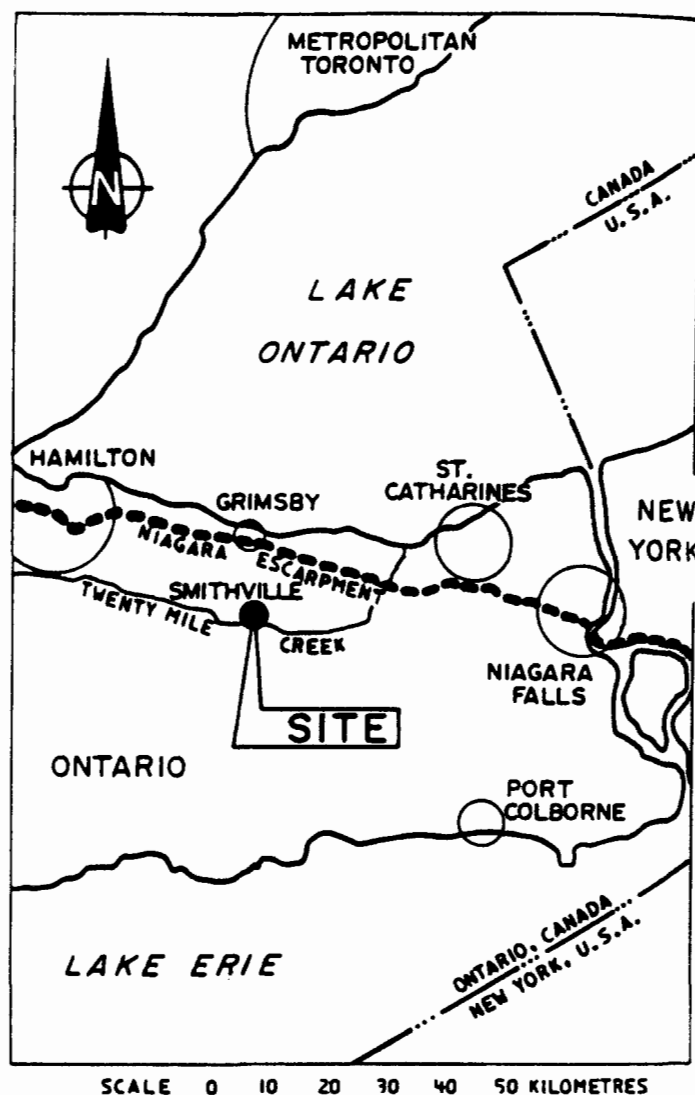


Figure 1
Location of Smithville Site
In the Niagara Peninsula Area
of Ontario, Canada

Aquifer. The movement of groundwater within this zone is governed by the open bedding partings. The porosity of the open bedding partings is expected to be quite viable. Observations of plume migration suggest a contaminant velocity of 50 to 100 m/a for TCE, one of the relatively more mobile constituents of the plume.

As shown in Figure 2, the shallow dissolved plume extends at least 600 m downgradient from the former lagoon where the TCE concentration exceeds 5 $\mu\text{g/L}$. Lesser concentrations may extend beyond 600 m, but the results of additional drilling and testing to define the leading edge are not yet available. The groundwater within the Shallow Aquifer is inferred to discharge to Twenty Mile Creek approximately 2 km south of the Smithville site.

The advance of the TCB plume within the Shallow Aquifer appears to be only slightly retarded with respect to the TCE plume, but the PCB plume is significantly retarded, as contamination to the Ontario Drinking Water Objective of 3 $\mu\text{g/L}$ extends only 50 m beyond the leading edge of the DNAPL plume.

An extensive network of off-site monitoring wells shown in Figure 3 has been installed between the site and all privately owned farm and domestic wells in the vicinity to provide early warning of any expansion in the area of groundwater impact. The majority of the private wells are located to the north, east and west, hydraulically upgradient from the site, and not downgradient to the south. However, there are

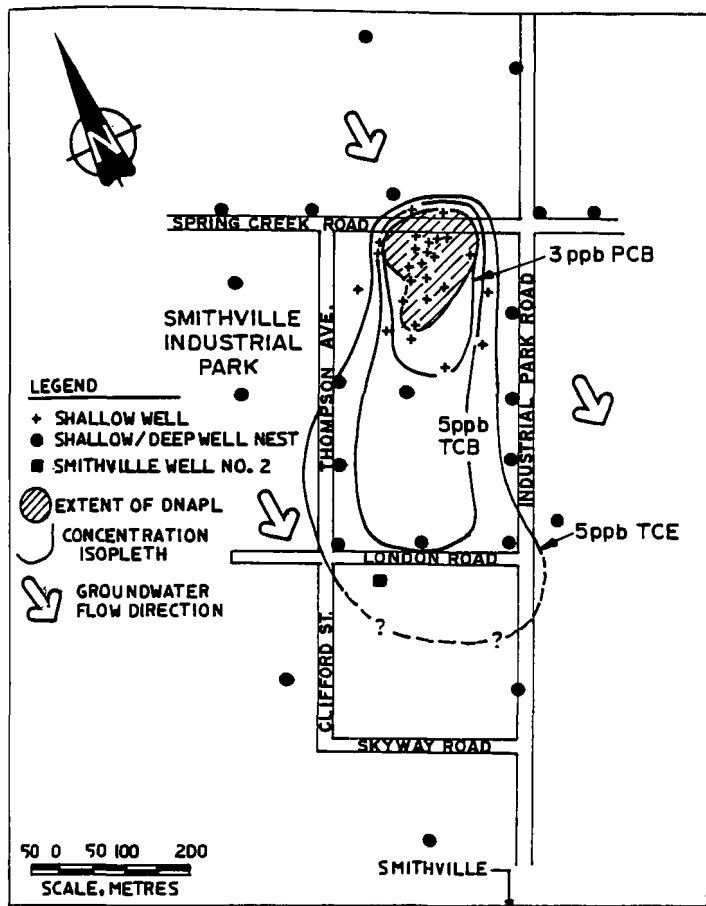


Figure 2
Observed Configuration of DNAPL and
Dissolved Contaminant Plumes Within the
Shallow Aquifer Beneath the
Smithville PCB Site

a few wells located approximately 1.5 km south of the site between the leading edge of the plume and Twenty Mile Creek.

The chemical analytical results of groundwater samples collected from wells installed within the Deep Aquifer are less conclusive than those driven from the Shallow Aquifer. However, there is definite evidence that dissolved contamination plume exists at depth. No direct evidence of DNAPL within the Deep Aquifer has ever been observed, but the relatively high concentrations of TCE and TCB in some wells (several hundreds of mg/l) located only 70 m south of the leading edge of the DNAPL plume contained within the Shallow Aquifer suggests that DNAPL may be present at depth.

The introduction of DNAPL and/or dissolved phase contaminants to the Deep Aquifer is thought to have occurred by downward migration via the regularly spaced vertical fractures and joints in the rock. In these local quarries where the Lockport Formation is exposed, these features occur at intervals as close as 3 m within individual members, and up to 20 m where they penetrate the entire Lockport sequence. A significant downward gradient exists along the minor aquitard between the Shallow Aquifer and the Deep Aquifer, and contaminated groundwater could, therefore, migrate across the aquitard where these joints and fractures occur. Once present within the Deep Aquifer, the dissolved constituents migrate downgradient within the open beddings partings.

Based on well monitoring results, contaminated groundwater reached the Smithville Municipal Well No. 2, located 600 m south of the former lagoon at the site, commencing in mid-1988. Assuming that the DNAPL entered the bedrock sometime between 1978 and 1985, the average linear velocity of the dissolved contaminant plume within the Deep Aquifer actually lies in the range of 50 to 165 m/a.

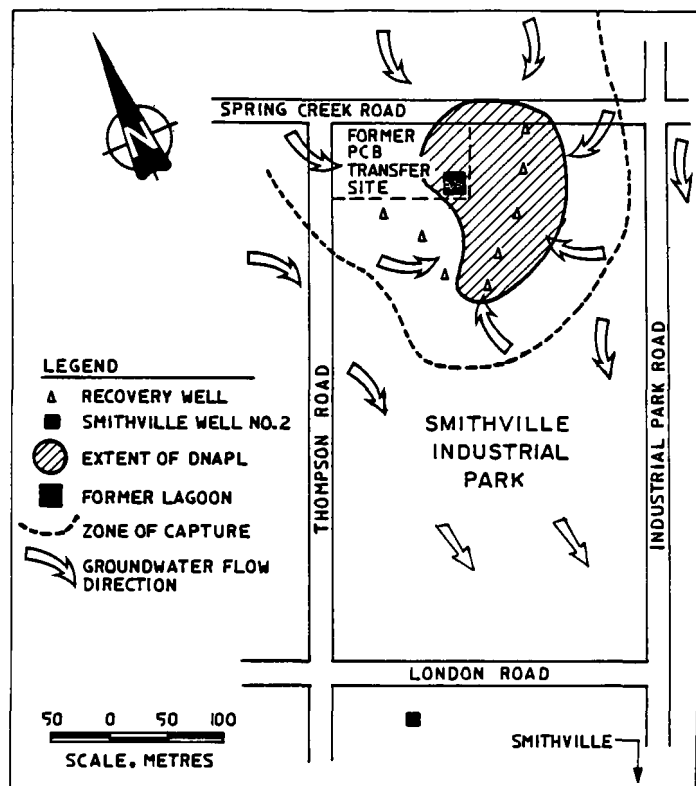


Figure 3
Shallow Aquifer Hydraulic Containment
System Showing Conceptual Operational
Effects at the Smithville PCB Site

INTERIM CONTAINMENT STRATEGY

The hydrogeological investigations completed to date at the Smithville site have identified a large-scale occurrence of bedrock contamination by DNAPL and two separate dissolved phase plumes. A DNAPL occurrence of this nature or magnitude has not been successfully remediated, and the case histories of attempts to deal with smaller scale and more easily accessible occurrences are not encouraging. Nevertheless, every effort will be made to remediate the bedrock at the site if technically feasible. The expenditure of considerable time and financial resources will be required to assess the ultimate feasibility of complete remediation. In the interim, the shallow and deep dissolved contamination plumes identified beneath the site would continue to migrate further downgradient off-site, expanding the scope of the existing problem, unless control measures are implemented.

SHALLOW AQUIFER HYDRAULIC CONTAINMENT

In early 1989, MOE directed the project team to design and implement hydraulic controls to contain the dissolved contaminant plume within the Shallow Aquifer, where clear evidence of off-site migration of relatively high concentrations of TCE and TCB existed. Data derived from a controlled pumping test carried out within the Shallow Aquifer in the vicinity of the DNAPL source of the dissolved plume were used to design a recovery well system.

The system consists of eight 20-cm diameter pumping wells, each equipped with submersible pumping equipment which maintains the hydraulic head within the aquifer at a designed elevation. The well network creates a hydraulic trap, essentially preventing groundwater which contacts the DNAPL from escaping the groundwater sink. The network controls groundwater flow to a point 50 m downgradient from the leading edge of the DNAPL plume by pumping a cumulative total of up to 100 L/min. The recovered water is treated using activated carbon treated on site, and then discharged to the sanitary sewer.

The portion of the dissolved plume in the Shallow Aquifer beyond the zone of capture has, so far, been allowed to migrate uncontrolled,

but another network of recovery wells can be installed beyond the leading edge of this plume in the event that monitoring results indicate a requirement to do so. The recovery system became fully operational in July, 1989, and the early monitoring results indicate successful containment of the shallow plume. The system is shown in Figure 3.

DEEP AQUIFER CONSIDERATIONS

The working hypothesis adopted during the hydrogeological investigations carried out to date at the site, uncertainties remain concerning the occurrence, concentration and mobility of the dissolved plume in the Deep Aquifer.

Planning is underway for a directed investigation to determine the optimum locations (vertical and in plan) for recovery wells to control the deep dissolved plume, should ongoing monitoring results indicate a requirement to do so.

MONITORING

An extensive network of monitoring wells (Fig.3) was installed at the site between 1987 and 1989. The wells are sampled regularly (as often as weekly in some cases), and the samples are analyzed for the suite of constituents associated with the site, including PCB, TCB, TCE, TCA, benzene and chloroform. Plume tracking and concentration trend analysis are undertaken routinely to monitor the three-dimensional configuration of the shallow and deep dissolved plumes.

Monthly groundwater elevation measurements are obtained from all monitoring wells, and five automatic water level recorders collect continuous groundwater elevation data. The monitoring results are used to modify the shallow plume recovery system and to review the need for a deep plume containment system.

LONG-TERM REMEDIAL STRATEGY

A long-term remedial strategy for the site has not been finalized. However, the long-term strategy includes the elimination at the earliest practical time of the estimated 180,000 L of PCB waste currently in secure storage at the site.

This activity is well advanced, and a thermal destruction contractor has been selected to incinerate the PCB-contaminated material. The contractor is preparing for hearings under the Ontario Environmental

Protection Act to obtain approvals to construct and operated a mobile PCB incinerator at the Smithville site. Destruction of the existing stockpiled waste material is expected to be completed by the end of 1990.

Any remedial strategy for the subsurface contamination must include the detailed assessment of potentially applicable technologies to determine the feasibility of application at the site. Assuming that such a technology can be developed, testing of the process at the bench- and field-scales would be required, and, if successful, pilot-scale trials might proceed. At the present time, the only potential remedial technique developed to the point at which a field trial is feasible is excavation, and this option may only be feasible for the Shallow Aquifer. A program of shallow bedrock shaft excavation and testing has been developed which could be implemented at the site.

The costs associated with any effort at remediation, whether in situ or by excavation, treatment and disposal, will be very high, and no precedent for the envisioned scale of remediation exists in North America. Therefore, it will be extremely important to carefully review all possible remediation options and to obtain as much data as may be necessary to arrive at the most appropriate solution to this problem. Despite the best of intentions and technical efforts, it may not be possible to fully remediate the Smithville site in the foreseeable future, and a longer period of secure containment of the site than is currently anticipated may become necessary. In that event, in situ physical containment of the DNAPL plume possibly employing some combination of cut-offs, grout curtains and low permeability covers in association with some level of ongoing groundwater recovery and treatment may have to be considered.

The challenge and opportunities for technical advancement associated with the Smithville site are considerable, and the task of pursuing an effective remedial solution leading to secure site decommissioning continues.

ACKNOWLEDGEMENT

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Panel Discussion: Effectiveness of Groundwater Extraction—Technical Considerations, Field Experience, Policy Implications

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PANEL DISCUSSION

Groundwater contamination is found at over 70% of the sites currently on the National Priority List. The most common method for addressing contaminated groundwater is extraction and treatment. Groundwater extraction can effectively reduce contaminant concentrations in the groundwater where contaminants are primarily present in the dissolved phase. However, research and field experience indicate that it may be more difficult than is often estimated to achieve cleanup concentration goals in portions of the groundwater, particularly those zones near the original source of contamination. Factors limiting the effectiveness of extraction systems include: the presence of non-aqueous phase liquids which lodge in the subsurface and create a continuing source of groundwater contamination as contaminants within the non-aqueous phase dissolve and as the non-aqueous phase itself dissolves into the groundwater, and sorption of contaminants to the soil within the saturated zone resulting in a continuous source of contamination to clean groundwater drawn into the contaminated zone by extraction systems.

In an effort to determine whether these factors are influencing the performance of extraction systems currently in operation, OERR initiated a study to assess the effectiveness of several ongoing groundwater remediation sites. After reviewing data from 19 case studies, it was concluded that groundwater extraction can effectively contain contaminant plumes and that significant contaminant mass can be withdrawn from the subsurface by extracting groundwater. However, in most of the cases, contaminant concentrations in the extracted groundwater tended to level off after an initial decrease, at concentrations that were still above cleanup goals. In many cases, it appeared the factor identified by researchers were playing a role in the performance of the groundwater extraction systems.

As a result of the study, some modifications to the current response approach for contaminated groundwater are warranted. The basic goal of returning groundwater to its beneficial uses, however, will not change. Recommended modifications include: considering containment early to prevent further migration of contaminants and collect information on aquifer response to extraction, providing flexibility in selected remedies to allow for system modification based on data gained during operation, and improving data collection during the remedial investigation to identify situations and processes that may affect extraction performance. Further study of extraction systems is warranted to

identify the signals that indicate cleanup goals cannot be attained and to evaluate the point at which alternate goals should be established.

I. Theoretical Background—Carl Enfield

A. Factors Affecting Groundwater Remediation

1. Hydrogeologic—diffusion through varying geologic material, fractures
2. Chemical—sorption
3. Multi-phase Fluids

B. Need for Improved Data Collection/Methods

1. Characterize Vertical Variations in Geologic Materials
2. Evaluate Contaminant Partitioning in the Saturated Zone
3. Identify Presence of Non-Aqueous Phase Liquids When Practicable

C. Other Cleanup Options/Status of Research

1. Bioremediation
2. Vapor Extraction
3. Solvent Flushing
4. In-Situ Steam Stripping

II. Practical Experience—Jennifer Haley, John Glass

A. Description of Study

1. Identified Groundwater Extraction Sites
2. Selected 19 for Case Studies
3. Evaluated Performance of Extraction

B. Findings

1. Containment Generally Successful
2. Significant Contaminant Mass Removed
3. Contaminant Concentrations Level Off After Initial Decrease
4. Several Factors Limited Effectiveness of Extraction
 - a) Hydrogeologic
 - b) Contaminant
 - c) Adequacy of Source Removal
 - d) Design of Extraction System

III. Implications for Superfund Response Approach to Contaminated Groundwater—Bill Hanson

A. Maintain Overall Goal

B. Initiate Response Early

1. Contain Plume
2. Collect Information on Aquifer Response to Extraction

- C. Provide Flexibility in Remedies
 - 1. Contingency
 - 2. Interim Remedies
- D. Collect Better Data During Remedial Investigation
 - 1. Vertical Variations of Hydraulic Conductivity and Contaminant Concentration
 - 2. Contaminant Sorption to Soils in the Saturated Zone
- E. Guidance Needs
 - 1. Signals Indicating Cleanup to Health-Based Levels Not Practicable
 - 2. Alternate Goals Where Health-Based Concentrations Cannot Be Attained in the Groundwater

CERCLA Sites Affected by RCRA

An Overview of the Corrective Action Process

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ABSTRACT

An overview is provided of the corrective action program (CAP) developed under the RCRA. A description is given of both RCRA and CERCLA program objectives. Basis of the CAP is discussed along with its major components. The proposed codification of the CAP (Subpart S Regulations) are also discussed.

INTRODUCTION

When the Hazardous and Solid Waste Amendments (HSWA) were enacted in 1984 as part of the reauthorization of the RCRA, they set in motion a regulatory vehicle in the form of the Corrective Action Program (CAP), a program designed to address the nation's ever growing concern centering on continuing releases of hazardous wastes or hazardous constituents to sensitive environmental pathways. Since it is not uncommon to encounter RCRA facilities which have or currently are involved with CERCLA activities, under the realm of the CAP, these CERCLA sites would be considered as part of the CAP.

In order to provide timely and appropriate responses when such releases are identified, the complexity of such a comprehensive effort must initially be approached in a systematic or phased manner. Accordingly, the CAP, designed to impact all facilities that received or processed hazardous waste after July 26, 1982, is comprised of three phases:

RCRA Facility Assessments

RCRA Facility Assessments (RFAs) involve the identification of potential hazardous waste or constituent releases requiring further investigation. This is the initial data gathering phase of the CAP, incorporating a comprehensive Preliminary Review (PR) of available facility information and data, a Visual Site Inspection (VSI) of all Solid Waste Management Units (SWMUs) and Areas of Concern (AOCs) within the contiguous boundaries of the facility, and an optional Sampling Visit (SV) of potentially impacted areas.

The information collected during the RFA is considered in making release determinations. This information, therefore, must, at a minimum, include the history of the facility site, the type and design of waste management units, the type and condition of potentially affected soil, surface water, groundwater, subsurface gas and/or ambient air. This RCRA phase parallels the CERCLA Preliminary Assessment/Site Investigation (PA/SI).

RCRA Facility Investigation

RCRA Facility Investigations (RFIs) are designed to provide characterization of releases identified during the RFA. The level of effort performed as part of the RFI involves the comprehensive characterization of suspect area, determination of the extent of releases into the specific environmental media suspected of being impacted and examination of

the nature of the release as related to its impact on human health and the environment.

In consideration of the many various sampling scenarios, the implementation of an RFI may entail a broad range of sampling strategies and techniques. This RCRA phase parallels the CERCLA Remedial Investigation/Feasibility Study (RI/FS).

Corrective Measures

Corrective Measures (CMs) describe remedial measures to be used in the impacted area. If, at any phase of the CAP, conditions are encountered that suggest further action, then Corrective Measures may be required. The nature of these measures depends on the Agency's stance concerning how, in conjunction with the facility response to this condition, they perceive the nature of the suspected release. As mentioned, these Corrective Measures, designed to be developed under RCRA, may pertain to facility CERCLA sites. The interrelation of these phases are illustrated in Figure 1.

Strategies

There are technical strategies available to effectively address release determination issues prior to and during the phases of the CAP. These strategies are based on interpretation of release conditions based on past and ongoing data and involve an active intercommunication between the owner/operators and the Agency. However, the ultimate implementation of owner/operator's strategies depends on the site conditions as perceived by the Agency, the level of supporting information provided by the owner/operators, and the time-frames suggested to address specific CAP phase requirements.

RCRA vs. CERCLA Objectives

It is not unusual for a RCRA facility owner/operator to have an area or unit located on-site which has been associated in the past with the CERCLA program. It is, therefore, important for the owner/operator possessing a CERCLA site to be aware of the difference between RCRA and CERCLA program objectives. Typical RCRA vs. CERCLA concerns are described below.

CERCLA is designed as a response program to deal with environmental contamination that already has been documented. Often, the actions which caused the contamination were legal and non-negligent. Since the facility personnel responsible for these activities did not anticipate that a cleanup would be required in the future, associated cleanup costs were not considered in future budgeting. However, people with prior associations with a contaminated site may be imposed with retroactive liability since the costs of doing so cannot be built into the transactions associated with the disposal, as those transactions took place years ago. Moreover, there is no regulatory/enforcement virtue to

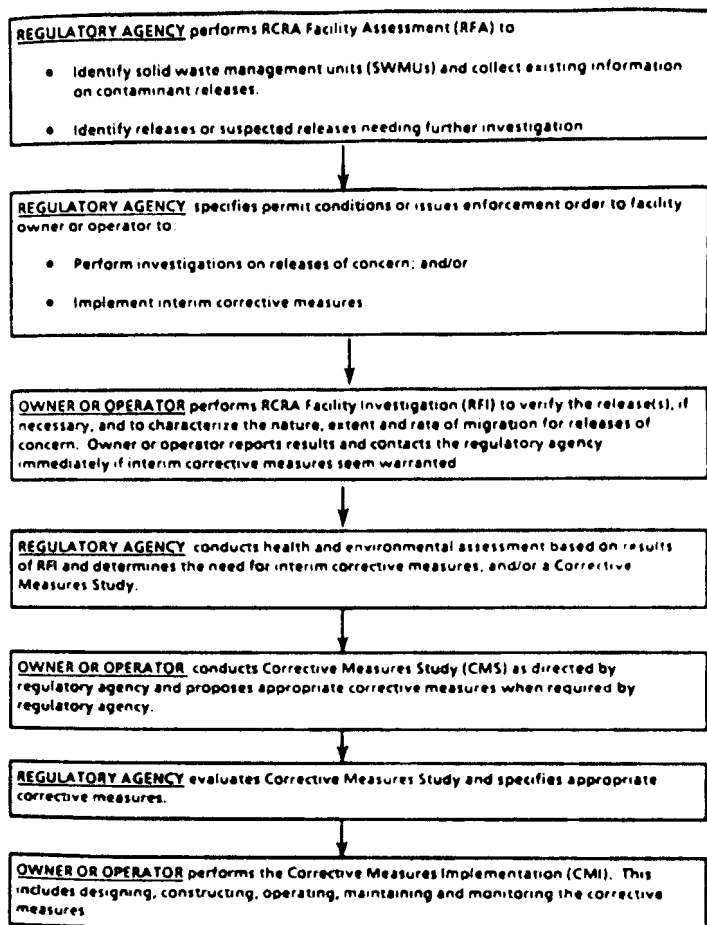


Figure 1

RCRA Corrective Action Process

Note that although certain aspects of the Corrective Action Process are the responsibility of either the regulatory agency or the owner or operator, close coordination between the regulatory agency and the owner or operator is essential throughout the process¹.

imposing "uniform" standards here, as CERCLA does not govern waste management activities.

On the other hand, RCRA is a regulatory program for current and new facilities involved with the management of hazardous waste to prevent releases of hazardous waste or constituents from occurring in the future. RCRA involves nationally applicable standards which are designed to be preventative in nature. Since the facility's environmental manager can predict RCRA required actions, the facility's costs to comply with RCRA may be built into the costs associated with the facility's ongoing hazardous waste management practices. Additionally, since RCRA standards are established on a nationwide basis, these standards must be both uniform and rigorously designed to protect human health and the environment at the many various hazardous waste facility locations throughout the United States.

Are there differences in the scope and/or objectives in the RCRA vs. CERCLA investigation process?

The differences between these investigation processes, most notably, the RCRA PR/VSI and the CERCLA PA/SI, are based on the differing objectives of the two programs. Essentially, RCRA facilities are involved in an ongoing regulatory program. Accordingly, there is information generated in conjunction with the facility's ongoing RCRA monitoring requirements (e.g., particularly on land disposal facilities). Consequently, some facilities are not scheduled for the initial site investigation stages because sufficient historic information exists on the facility to compel a remedial investigation. In the case of the PA/SI, the intent of CERCLA is to provide a response program. Therefore, it may be a single data set which triggers the need for remedial action at the facility.

Nevertheless, both the RCRA PR/VSI and the CERCLA PA/SI have been designed to establish a basis for future corrective measures. However, there are important differences between these two initial investigation efforts. In the case of the RCRA PR/VSI, each unit or similarly related groups of units (e.g., located in close proximity to each other) at the facility is assessed to determine if there has been a release of hazardous waste or constituents. As a result, a framework is developed for determining specific permitting and enforcement actions that should be taken at a facility and which facilities the U.S. EPA should address first.² Since the primary purpose of the CERCLA PA/SI is to develop a hazard ranking score (HRS) which establishes the basis for listing the site on the NPL, the PA/SI does not focus on units, but considers the facility as a whole, as well as off-site releases. The RCRA counterpart to this facility-wide approach would be the RCRA 3008(h).

Following each RCRA PR/VSI, media-specific sampling in the form of an optional RCRA Sampling Visit (SV) may be necessary to make the unit-by-unit release potential determinations. In the case of the CERCLA PA/SI, sampling beyond what is necessary to complete an HRS score is suggested in the following instances³:

- Sampling is necessary in order for the Agency to compel a remedial investigation
- Key data are missing to trigger further investigation.

Are There Any Differences Between The RCRA vs. CERCLA Analytical Approach?

There are distinct differences in the means by which the RCRA or CERCLA program is triggered. In order to trigger RCRA jurisdiction, a substance must first be a waste. Under CERCLA, whether a substance is a waste or a product is irrelevant. At a closer look, the concept of "hazardousness" is recognized to be much broader under CERCLA. For example, under RCRA, a waste must either be "listed" or meet one of the hazardous "characteristics" to trigger jurisdiction based on concentrations of hazardous constituents encountered at a numerical threshold value. However, under CERCLA, a much broader approach prevails. Here, the U.S. EPA says that a substance that contains any amount of a compound included on a much broader "hazardous substance list" will trigger jurisdiction.

Therefore, RCRA owner/operators involved with CERCLA conditions may find that analytical criteria employed under the RCRA program may not be a valid assessment approach under CERCLA. Potential situations such as this behoove the owner/operators to clearly define cleanup goals and criteria prior to initiating any assessment or remedial actions.

Can A RCRA Facility Be Subjected To CERCLA Action Instead Of RCRA Corrective Action?

In an Oct. 14, 1986 memorandum from J. Winston Porter, the Assistant Administrator, Office of Solid Waste and Emergency Response, U.S. EPA, this possible situation was considered⁴. In the case of a facility clearly unable to fulfill its RCRA corrective action, it was suggested that immediate consideration be given to determine if the facility should be managed under the CERCLA program. For example, a facility that has gone bankrupt would be an example of a facility that might be referred to the CERCLA program.

In the CERCLA program, there are several approaches available for dealing with RCRA-associated facilities. In the cases of bankrupt facilities, or at facilities where efforts to secure action under RCRA have been unsuccessful (e.g., due to the lack of viable responsible parties), CERCLA action, as described in CERCLA Section 104, is suggested. Generally these actions are taken in situations which represent more serious environmental threats. Fund-financed remedial action is suggested at these unresponsive RCRA facilities that are listed on the NPL. The U.S. EPA has issued final criteria for listing RCRA facilities on the NPL and has proposed additional criteria for listing these facilities (see 51 FR 21054 and 51 FR 21109, June 10, 1986)⁴.

In addition, it is not unusual to encounter a RCRA facility whose regulated unit is not involved in a hazardous waste or constituent release situation (e.g., container storage area), but which possesses an on-site area involved in the CERCLA program. Although this facility's involve-

ment with the broad-based, CERCLA corrective action approach (i.e., facility-wide), the regulatory triggering of the RCRA CAP investigations may bring about unanticipated conditions of compliance. For example, new units or areas of concern may be identified through the initial stages of the RCRA CAP; these new units may be considered on a unit-by-unit basis, disregarding the facility-wide environmental considerations already established under CERCLA.

For those RCRA owner/operators with CERCLA affected, on-site areas, the following delineates the objectives and scope of the CAP. Whenever appropriate, additional noteworthy RCRA-CERCLA comparisons will be identified.

BASIS OF THE CORRECTIVE ACTION PROCESS (CAP)

The basis of the Corrective Action Process (CAP) originates from the Hazardous and Solid Waste Amendments of 1984. Currently, the Agency has taken steps to have the salient conditions of the CAP codified, namely in the form of the proposed Subpart S ruling. The Hazardous and Solid Waste Amendments (HSWA) The Corrective Action Process (CAP) has evolved from its initial authority as issued under the authority of the Solid Waste Disposal Act as amended by RCRA, and finally, as amended by the HSWA of 1984². Providing a more focused approach than the earlier environmental programs, the primary objective of the RCRA corrective action program is to clean up releases of hazardous waste or hazardous constituents that threaten human health or the environment. The program applies to all operating closed or closing RCRA facilities.

Although HSWA provides the authority to implement the CAP as part of the current RCRA program, corrective action at hazardous waste facilities is also considered under other authorities². These additional authorities include the following:

- *7003 of RCRA* - The Agency has the authority to take action where there is solid or hazardous waste that may present an imminent and substantial endangerment to human health or the environment;
- *3013 of RCRA* - The Agency has the authority to require investigations where there is the presence of hazardous waste or where releases of hazardous waste that may present a substantial hazard to human health or the environment; and
- *40 CFR Part 264, Subpart F* - The Agency has the authority to address releases of hazardous wastes and hazardous constituents to groundwater from units which are "regulated" under the RCRA program.

Nevertheless, HSWA has established new authorities that are even more broad and far-reaching than these other authorities in the RCRA program, that enable the U.S. EPA to accomplish their corrective action objectives. The new authorities are:

- *3004(u) - Corrective Action for Continuing Releases* - This authority requires that for any permit issued to a RCRA treatment, storage or disposal facility after Nov. 8, 1984, corrective action at that facility is required for all releases from their solid waste management units (SWMUs). This provision also requires that facility owner/operators must demonstrate financial assurance capabilities for any corrective action which may be required. This provision also indicates that schedules of compliance be used in permits where the required corrective action cannot be completed prior to permit issuance.
- *3004(v) - Corrective Action Beyond Facility Boundary* - This authority directs the Agency to require corrective action beyond the facility boundary where it would be necessary to protect human health and the environment. This HSWA provision would not be invoked if the owner/operator can demonstrate that, despite the best of efforts, the necessary permission to perform these off-site corrective action activities cannot be obtained. In cases such as this, the Agency still has the authority to issue corrective action orders which, in turn, require the necessary corrective action.
- *3008(h) - Interim Status Corrective Action Orders* - This HSWA provision provides the Agency authority to issue enforcement orders or bring about legal action when there is or has been a documented release of hazardous waste or hazardous constituents at RCRA facilities operating under conditions of interim status. These administrative orders or court action would compel either corrective action

or some other form of response measures in a manner that would serve to protect human health and the environment. In addition, this provision provides the U.S. EPA with the authority to take civil action against facilities in order to obtain the appropriate relief. In providing an interim status "response," this provision more closely parallels CERCLA objectives than the other HSWA corrective action authorities.

Approach to Corrective Action in the Proposed Subpart S Rule

Since the CAP was first developed in 1984, the U.S. EPA has had the opportunity to implement the initial CAP stages, namely the PR and VSI as part of the RFA. As a result, the Agency has experienced a myriad of facility conditions where there have been or are releases of hazardous waste or constituents. In order to provide an effective CAP, proposed to be promulgated under the authority of Subpart S, the Agency must first draw on this experience and establish their priorities and management philosophy as they see appropriate for the implementation of the RCRA CAP. The Agency view of the types of RCRA facilities and the noteworthy conditions involved with environmental impacts, and, therefore, influencing the development of the proposed Subpart S rules, are discussed below.

At some facilities, the type or level of contamination or the release potential associated with the environmental setting may indicate to the Agency that this facility is a high priority for the implementation of corrective action. Most facilities where there are or have been continuing releases of hazardous constituents usually have point source similarities in the conditions involved with the releases [e.g., unlined impoundment(s) or landfill(s)]. Therefore, it would be in the best interest of all parties that corrective actions be performed at the most environmentally significant facilities (i.e., those with documented hazardous waste or constituent releases) and on the most significant problems (i.e., documented continuing releases) at RCRA facilities. Experience has indicated that U.S. EPA also might place a high priority on corrective action performed at those facilities which have demonstrated an unwillingness to provide timely and appropriate response to their environmental problems in the past.

The Agency also has encountered RCRA facilities where the level of contamination is either documented to exist over a wide-spread area or the geographic location of the facility is such that there would be little likelihood of a release causing significant impact to human health or the environment. An example of the latter would be a hazardous waste release overlying an already contaminated aquifer and/or located many miles from the nearest town or residence. In cases such as this, the Agency has, in the past, acceded to "conditional" remedies (e.g., immediate containment of the release). The Agency has recognized that prompt action of this kind can reduce the risk to levels which would be acceptable for the current related uses, or where final cleanup is impracticable. Moreover, if the Agency intends to expedite the CAP, then the types of investigative and remedial activities at all RCRA facilities must be streamlined to focus on plausible concerns and likely remedies. Therefore, if the proposed Subpart S rule is to provide the Agency with a means to effectively manage the CAP, the Agency must emphasize early actions and expeditious remedy decisions.

It would not be unusual for non-RCRA facilities, encountering environmental problems similar to those encountered under RCRA, to seek guidance in the remediation needed at their site. Although the non-RCRA facility owner/operators would be expected to first explore specific program objectives, lest the facility become burdened with an overbearing regulatory yoke, it is becoming more apparent that the liabilities and costs associated with an undefined corrective action approach continue to increase. These increased costs often include the unnecessary corrective action tasks dictated by either facility personnel who are unaware of, or unresponsive to regulatory requirements, or the differing corrective action approaches developed during the turnover of Agency personnel, a common occurrence in both State and Regional EPA offices. In such cases, it is often in the best interest of the facility and the Agency to promote voluntary and independent action by the facility.

PROPOSED SUBPART S REGULATIONS

In order to provide an effective regulatory vehicle for the implementation of the CAP, the Agency has proceeded to develop the final codification of the HSWA amendments, namely the Subpart S regulations as part of 40 CFR Parts 264⁶. Since numerous RCRA facilities currently are involved in various types of investigative and/or cleanup activities, the corrective action guidance provided by the proposed legislation would be both timely and appropriate.

The U.S. EPA's objective in providing such a rule would be expected to establish a framework by which their RCRA corrective action objectives may be implemented. This corrective action framework would serve to provide the following:

- Protection of human health and the environment
- Control of the sources of hazardous waste or constituent releases to reduce or eliminate, to the maximum extent practicable, any further releases that may pose a threat to human health and the environment
- Development of standards, pursuant to the provisions of Subpart S, involving acceptable levels of cleanup for environmental media
- Development of standards, pursuant to the provisions of Subpart S, establishing specific waste management compliance criteria

Scope

There are varied scopes of corrective action which might be required at an impacted RCRA facility. The Agency has recognized that the types and degree of ongoing corrective action at a RCRA facility are based on the complexity of the conceptual model, developed in response to the CAP.

The proposed Subpart S provisions include the corrective action remediation program objectives of the Agency. These objectives include the environmental cleanup standards for remedies that represent a combination of technical measures and management controls for addressing the environmental problems at the facility. These objectives include:

- Reduction of toxicity, mobility or volume of wastes
- Provision of long-term reliability and effectiveness
- Provision of short-term effectiveness
- Implementability
- Realistic cost

In the case of CERCLA sites, the degree of corrective action (and the associated remedial costs) usually is dictated by the Hazardous Ranking Score (HRS), where, the level of required corrective action is based on a numerical score. Generally, the U.S. EPA has encountered two basic types of corrective action approaches to the many different types of impacted RCRA facilities encountered under the auspices of the CAP:

- Streamlined or focused corrective action
- Complex or interdisciplinary corrective action

Under the RCRA CAP, the U.S. EPA has encountered scenarios where it would be in the best interest of both the facility and the Agency to develop a streamlined or focused corrective action plan. For example, such facilities would be expected to include the following:

- *Facilities considered to be a "low risk"* - These facilities are typified by contaminant release problems which are relatively small, and where releases present minimal exposure concerns. Often, facilities such as these merely require a "band-aid" approach to remedial action; for example, development of adequate secondary containment or physical removal of a low volume of waste or contaminated soil.
- *Facilities providing a high quality CAP remedy* - Since more facilities are realizing that the costs associated with an ineffective remedial plan can escalate, high quality remedies are being considered in response to corrective action problems. Certainly, it is not uncommon to encounter situations where the final conceptual approach to corrective action proposed by a facility would result in a remedy which is highly protective. For example, many facilities have opted for corrective action equivalent to a RCRA "clean-closure." It should be noted that a high quality corrective action remedy need not necessarily be cost-prohibitive, and the Agency will only accept a plan which remains fully consistent with all other remedial objectives of the CAP (reliability, etc.).

- *Facilities where there are limited remedial options* - The Agency has encountered several types of RCRA facilities where there may be only limited remedial options. One example of such a type of RCRA facility is one whose waste management practices preceded, and, therefore, did not address the waste management operating requirements of RCRA. It is not uncommon for these facilities to possess old fill or dump areas with appreciable volumes of uncontained waste material (e.g., a large unlined landfill). The associated remedial approach to such a situation would be limited by few practicable cleanup solutions.

Another type of RCRA facility where the types of remedial options may be limited are those where the anticipated future uses of the property, in turn, dictate a high degree of treatment to achieve very low levels of residual contamination. An example of such a facility is one in proximity to vulnerable environmental resources (e.g., wetlands, human exposure); and, at a minimum, requiring cleanup to a level where the contamination must be proven to ensure continuing protection for human health and the environment.

- *Facilities with straightforward remedial solutions* - Many RCRA facilities have similar types of contamination problems and, therefore, require similar types of remedial approaches. In these cases, the most effective remedial alternative considered acceptable by both the facility and the Agency is one which applies standard engineering solutions that have proven effective in similar situations. The equivalent to "clean-closure" under RCRA, or the construction of a RCRA protective cover or liner are examples of straightforward remedial approaches which may be considered effective remedial solutions to Agency personnel under certain conditions.

- *Facilities providing well-developed, phased remedies* - It is becoming apparent that most environmental contamination problems encountered during the CAP involve facilities where the nature of the environmental problem often dictates a singularly focused corrective action approach (e.g., cleanup of groundwater contamination). In these cases, the Agency has recognized that the most effective remedial plan must consider the milestone information gathering process (e.g., assessment of ongoing monitoring data) developed as part of the requirements of the CAP.

Another example of a facility requiring a phased approach is one where there is one particular area of the facility that deserves immediate measures to control further environmental degradation or exposure problems. In these situations, it is in the best interest of all concerned parties that the corrective action phases focus first on that specific element of the overall remedy requiring immediate attention (e.g., providing immediate and adequate containment of the contaminant source), with follow-on corrective action developed as appropriate to deal with the remaining lower priority remedial needs at the facility.

The other type of basic corrective action approach is one which would likely need relatively extensive, interdisciplinary environmental studies to be done to support sound remedy solution decisions. Facilities falling in this category include the following:

- *Facilities considered to be a "high risk"* - These RCRA facilities are marked by environmental conditions where the scope of the anticipated corrective action is expected to involve complex remedial solutions. These types of facilities typically have large volumes of uncontained, concentrated wastes impacting any or all of the environmental release pathways (e.g., soils, groundwater, surface water, soil gas or air). Therefore, the most effective means to remediate such a complex contaminant release scenario is to apply several different treatment technologies in order to achieve the varying degrees of remedial effectiveness (i.e., reduction of toxicity or volume) in each of the affected environmental release pathways. In conjunction with this effort, different types of containment systems must be considered for each pathway for whatever residual contamination is expected to remain during the treatment process.
- *Facilities with various appropriate remedial concepts* - These facilities possess environmental problems for which there may be several distinct technical approaches, all of which are considered practicable. While each of these remedial strategies may offer varying degrees

of long-term reliability, and would be implemented in a phased manner over different time-frames, the costs associated with these substantially different remedial approaches also would be, in turn, expected to be substantially different. In cases such as this, the final remedial selection decided upon by the Agency and the owner/operators will necessarily involve a highly interactive information transfer process, involving a balance of competing goals and interests. Such decisions must be supported with adequate information.

Components

The proposed rule includes various information collection milestones throughout the duration of the RCRA CAP process, most notably the RFI and CM phases. In order to provide an effective corrective action framework, these components would be expected to include the following elements:

- *Permitting procedures and permit schedules of compliance* - As part of the current RCRA permitting process, owner/operators are finding, as part of their final operating permit, an attachment which calls for specific corrective action measures. Most land disposal facilities underwent the initial CAP investigative phase (i.e., RFA) prior to issuance of the permit. The corrective action required as part of final permit conditions usually entail the initiation of the RFI. These attached permit conditions include specific milestones (e.g., reporting requirements) and associated schedules of compliance.
- *Trigger or "action levels"* - During the investigation process (i.e., RFI), enormous amounts of media specific, environmental data are likely to be generated. The ultimate interpretation of the RFI may come down to the comparison of a single data point to another background, standard or reference number. Extreme care should be taken at this stage of the CAP since a significant difference between the two numbers may also represent the difference between costs associated with no further action and costs stemming from development of further corrective action (e.g., CM).
- *Corrective measure study and remedy selection* - If a trigger or action level has been significantly exceeded, as the initial part of the CM phase of the CAP, the owner/operators would have to conduct a Corrective Measures Study (CMS). The recommendations of the CMS (i.e., an evaluation of the potential cleanup remedies) should allow the owner/operators to propose a single, acceptable remedial alternative. However, the owner/operators of large sites with diverse waste management operations, and hence, potentially more complex environmental problems, may need to pursue several varied, remedial alternatives.
- *Cleanup levels* - It is the goal of the CAP to clean up releases of hazardous waste or constituents to levels determined to be protective of human health and the environment. In response to the "How clean is clean?" question, the revised draft rule defined levels, specific for each of the environmental release pathway medium, that are safe for both current and future land use. Although media specific cleanup levels remain a goal of the CAP, there may be cases, however, where these cleanup levels are not achieved. Obviously, in cases such as this, owner/operators must expect to be involved in continuing and sometimes long-term management until the appropriate cleanup levels are reached.
- *Standards for management of corrective action waste* - During the implementation of the field tasks at an impacted RCRA facility, it is expected that hazardous wastes will be generated as a result of these various investigative tasks (e.g., wastewaters, contaminated media). The revised draft rule has performance standards for conducting proper waste handling during the CAP. Certainly, if corrective action waste meets the RCRA regulatory definition of hazardous, it would have to be managed as a hazardous waste. It is anticipated that some facilities may elect to construct new waste management units in order to achieve CAP cleanup goals. In cases such as this, these new units also would be required to comply with necessary performance standards (e.g., 40 CFR Part 264). In addition, only RCRA permitted Subtitle C facilities would be able to receive off-site shipments of hazardous waste.
- *Completion of remedy* - In order to verify that remedial action at

a RCRA CAP site has been successfully completed, the Agency must utilize a recognized approach. Similar to other closure operations under RCRA, an independent engineer or other qualified professional would have to certify completion of the remedy. However, in some cases, cleanup goals as defined in the permit may not be achieved. In cases such as this, the Agency has opted in the past for additional investigation to determine if the key factors in the interpretive process (e.g., validity or representativeness of the cleanup standard) are defensible. If not, new standards as the result of subsequent CMS derived data are a realistic consideration to the owner/operators who cannot achieve each of the media specific cleanup standards. Certainly, if the environmental contamination remained at levels unprotective of human health and the environment, other long-term release controls are likely to be considered in order to prevent continuing human and environmental exposure.

RCRA FACILITY ASSESSMENT

The initial phase of the RCRA CAP is comprised of the RCRA Facility Assessment (RFA). The objective of the RFA is to identify releases or potential releases or hazardous waste or constituents requiring further investigation.

Purpose of the RFA

The RFA is a three-stage process, the purpose of which is to provide the following:

- The identification and gathering of information on hazardous waste or constituent releases at RCRA facilities
- The identification and assessment of SWMUs and other areas of concern for releases to all environmental pathway media; assessment of regulated units for releases to media other than groundwater
- The development of preliminary determinations regarding releases of concern and the need for further actions and interim measures at the facility
- The determination of those SWMUs which do not pose a threat to human health or the environment

During the RFA, Agency or Contractor investigators gather information on SWMUs and other AOCs at RCRA facilities. They evaluate this information and determine whether there are releases that warrant further investigation or other action (e.g., structural integrity testing) at these facilities. Following the completion of the RFA, Agency personnel expect to have sufficient information to determine the potential for the likelihood of release from any SWMU or other AOC. Consequently, the completion of the RFA is an information milestone, whose conclusions and recommendations are designed to indicate if there is a need to proceed to the second phase (RFI) of the CAP.

The RFA has been developed as three distinct phases. All three phases of the RFA require the collection and analysis of data to support initial release determinations:

- *The Preliminary Review (PR)* - This phase focuses primarily on evaluating available existing information, such as inspection reports, permit applications, historical monitoring data and interviews with Agency personnel who are familiar with the facility.
- *The Visual Site Inspection (VSI)* - This phase of the RFA entails the on-site collection of visual information to obtain additional evidence of release. The VSI typically is comprised of personnel from the Regional EPA office, the State office and supporting contractors.
- *The Sampling Visit (SV)* - This optional RFA phase is designed to fill any data gaps that remain upon completion of the PR and VSI by obtaining sampling and field data. This phase may be by-passed in the RFA phase and reintroduced as the initial step in the RFI, namely the "verification investigation."

Scope of the RFA

The scope of the RFA includes all areas of potential release at RCRA facilities and includes the investigation of releases to all environmental pathway media, namely:

- Soil
- Groundwater

- Surface waters
- Air
- Subsurface gas

However, as previously mentioned, groundwater releases from regulated units are not addressed in the RFA.

The types of units requiring investigation under the RCRA CAP are based on the HSWA 3004(u) provision which focuses on investigating releases from SWMUs at RCRA facilities. SWMUs are defined as:

- Any discernible waste management unit at a RCRA facility from which hazardous wastes or constituents might migrate, regardless of whether the unit was ever intended for the management of solid and/or hazardous waste.

The SWMU definition includes:

- Containers, tanks, surface impoundments, waste piles, land treatment units, landfills, incinerators and underground injection wells, including those units defined as regulated units under RCRA
- Recycling units, wastewater treatment units and other units which the U.S. EPA has generally exempted from standards applicable to hazardous waste management units
- Areas contaminated by "routine and systematic" releases from process and product storage areas

It should be noted that the SWMU definition does not include accidental spills from production areas and units in which wastes have not been managed (e.g., product storage or process areas). Routine and deliberate releases from process areas are defined under the RFA as other areas of concern.

The RFA is not intended to routinely address releases that are either permitted discharges (e.g., NPDES) or required to be permitted under other environmental programs. Where such discharges are of concern, the investigators refer the case to the original permitting authority.

However, the RFA does address releases from SWMUs to media other than the one covered by the unit's discharge permit. For example, where there is a cause for concern, the U.S. EPA can use the HSWA authority (and as proposed, the Subpart S rule) to control the release of volatile organic compound from NPDES-permitted wastewater treatment units where there is a cause for concern.

The U.S. EPA purposely designed the RFA to be limited in scope; that is to say, determining the potential for only the likelihood of release. Nevertheless, the RFA framework emphasizes the need to focus data collection and analysis efforts (i.e., historical documentation and/or field sampling data) that are required to support specific permit or enforcement order conditions. Typically, if the Agency encounters suspect areas during the RFA (i.e., PR/VSI) but cannot verify it even though visual conditions supported the likelihood of a hazardous waste or constituent release, then an SV is employed as a "final verification" to the RFA. A broad-based, analytical contaminant list (e.g., priority pollutants) is often requested by the Agency since the investigator must make a strong case to compel owner/operators to conduct an RFI or to convince the public that a SWMU does not pose a threat.

The information requirements needed to trigger an SV will differ on a case-by-case basis. The type and extent of sampling will depend on the amount and quality of information gathered in the PR and VSI and the investigator's professional judgment regarding the amount of information necessary to support an initial release determination. If an SV is initiated, it is likely that the investigators will sample those areas most visibly affected (e.g., stained areas, areas of stressed vegetation).

As the CAP is currently set up, the U.S. EPA and/or the states are responsible for conducting RFAs. Because of the subjective nature of these investigations, the Agency believes that it is appropriate for a regulatory agency to conduct the RFAs. These initial release determinations will provide the basis for requiring further action ranging in scope, for example, from no further action to a multimillion dollar interdisciplinary hydrogeologic investigation. The U.S. EPA and the states have used contractors to assist them in conducting these investigations, but the Agency has retained overall responsibility for the RFA decisions. In some instances, however, the facility owner/operator has participated in the SV (e.g., obtained split samples).

Technical Approach

The technical approach of the RFA requires the investigator to examine extensive data on the facility and specific units at the facility. These data generally can be divided into the following categories:

- Facility and unit characteristics
- Waste characteristics
- Environmental setting
- Pollution migration pathways
- Evidence of release
- Environmental receptors
- Regulatory history
- Previous release events

Specific factors in each category that must be considered will vary depending on which environmental pathway medium is most vulnerable. For example, unlined, in ground units are more likely to have soil and groundwater releases than lined, above ground units. Also, certain wastes tend to volatilize and cause air releases, while other wastes are soluble in water and tend to migrate via surface or groundwater. A facility's environmental setting may determine which media are of concern (e.g., shallow groundwater or fractured subsoils). In addition, further investigation at a facility may be triggered by the facility's poor compliance record or unwillingness to cooperate with the Agency.

The RFA is completed when the Agency has sufficient information to make a determination regarding releases or likely releases at the facility and the need for further investigations. Upon completion of the RFA, a summary RFA report is prepared integrating the findings from all three steps in the RFA. This report generally includes the following components:

- A description of the facility, its waste management practices and regulatory history
- Release information for all SWMUs or groups of SWMUs and other AOCs
- Sampling plan and results
- Final release determinations and recommendations

This RFA report indicates those areas of the facility that require further investigation during the RFI and contains the key information (e.g., contaminant characteristics) to be used to focus these investigations.

RCRA FACILITY INVESTIGATION

As already noted, the RCRA Facility Investigation (RFI) is generally equivalent in scope to the CERCLA remedial investigation. Units or areas of concern that are determined in the RFA to be a likely source of significant continuing releases of hazardous wastes or hazardous constituents may be selected for an RFI. The regulatory means of requiring the RFA is either through RCRA permit conditions (operating or closure/post-closure) or via enforcement orders [e.g., 3008(h)]. Because of the HSWA statutory language, the agencies must focus the RFI requirements on specific solid waste management units or known or suspected releases that are considered to be routine and systematic. The HSWA permit conditions or enforcement orders may include supporting fact sheets, and they can range from very general (e.g., "characterize the groundwater at . . .") to very specific (e.g., a specified number, depth, location and frequency of samples analyzed for a given set of constituents).

Since the Agency, in the RFA, is not required to positively confirm a continuing release, but merely determine that the "likelihood" of a release exists, the scope of the RFI can range from a limited, specified activity to a complex multi-media study. The investigation may be phased, initially allowing for verification or rebuttal of the suspected continuing release(s). If verified, the second phase of investigation consists of release characterization. This second phase, much like an RI, includes: (1) the type and quantity of hazardous wastes or constituents within and released from the SWMU, (2) the media affected by the release(s), (3) the current extent of the release and (4) the rate and direction at which the releases are migrating. Inter-media transfer of releases (e.g., evaporation of organic compounds from contaminated soil to the atmosphere) is also addressed during the RFI, where applicable.

In completing the investigative effort, the regulatory agency, in concert with the owner/operators, interprets the release findings. The first emphasis of the investigation is on the data quality (i.e., were sampling and analytical data quality objectives defined and accomplished?). The findings are then compared against established human health and environmental criteria. These criteria or "action" levels are available for each environmental medium and exposure pathway, taking into account the toxicological properties of the constituent and standardized exposure assumptions. At this stage, if the continuing release of hazardous wastes or constituents is determined to present a potential short-term or long-term threat to human health or the environment, interim corrective measures or a corrective measures study may be required. This evaluation is a crucial stage in the corrective action process.

Identifying and implementing interim corrective measures may be conducted during the RFI. This would occur in a case where, in the process of conducting the investigation, a condition is identified that indicates that adverse exposure to hazardous constituents is presently occurring or is imminent. Where interim corrective measures may be needed, both the owner/operators and the regulator agency have a continuing responsibility to identify and respond to emergency situations and to define priority situations. If first identified by the owner/operators, the need for interim corrective measures should be communicated to the regulatory agency at the earliest possible time. As indicated earlier, the need for close interaction between owner/operators and the regulatory agency is very important, not only for situations discussed above, but also to assure the adequacy of the data collected during the RFI and the appropriate interpretation of those data. Of course the owner/operators benefit from this exchange by allowing efforts to focus on salient issues and minimizing costly misinterpretations or unneeded characterization efforts.

General RFI Implementation Strategy

An investigation of releases from SWMUs requires various types of information. This information is specific to the waste managed, unit type, design and operation, the environment surrounding the unit or facility and the medium to which contamination is being released. Although each medium will require specific data and methodologies to investigate a release, a general strategy for this investigation can be described. This strategy can consist of two elements: one is "desk top" in nature and the other focuses on the field:

- *Conceptual Model Development* - Collection and review of data to be used in developing a conceptual model of the release that can be used to plan and develop monitoring procedures. These data could include existing information on the facility/unit or related monitoring data, data which can be gathered from outside sources of information on parameters affecting the release, or the gathering of new information through such mechanisms as aerial photography or waste characterization.
- *Phased Field Investigations* - Formulation and implementation of field investigations, sampling and analysis, and/or monitoring procedures designed to verify or rebut suspected releases (Phase 1) and to evaluate the nature, extent and rate of migration of verified releases (Phase 2). The latter phase can in turn be divided into logical technical steps.

Varying amounts of information will exist on specific releases and units at the start of the RFI process. In some instances, suspected releases may have been identified based on strong evidence that releases have occurred, but with little or no direct data confirming their presence. On the other end of the spectrum, there may be enough existing data at the start of the RFI for the investigator to begin considering whether some form of corrective measure may be necessary. This potentially broad spectrum of situations which may exist at the beginning of the RFI often calls for a flexible approach for the release investigation. Thus, the steps given above allow a logical progression from general knowledge of a unit and its potential for a continuing release toward a detailed (or "adequate") knowledge of the situation.

The value and role of the conceptual model element of the RFI is in providing a foundation upon which to design subsequent characteri-

zation efforts. The conceptual model may be as simple as a tabular and graphical depiction of the perceived situation. On the other hand, this model can include realistic and worst case fate and transport modeling of known contaminants under the given site conditions. Regardless of its complexity, the conceptual model consists of the following:

- SWMU or area description and an estimate of waste distribution in that unit
- Estimated quality and quantity of waste present, including specific constituents
- Environmental setting of the unit (e.g., soils, surface and subsurface hydrogeology and climate) and its vulnerable contaminant transport pathways
- An estimation of how, how fast and where known or suspected contaminants would be transported and transferred between compartments
- An evaluation of what media would be most likely to be monitorable for detecting any releases

The role of this model is, of course, to determine in broadest terms whether significant release potential is present and, given a significant potential, how to design an investigation/monitoring program capable of release verification and/or characterization.

As already noted, the release characterization may be conducted in phases, if appropriate, with each monitoring phase building on the findings and conclusions of the previous phase. The overall level of effort and the number of phases for any given characterization effort depends on various factors including:

- The nature of the potential contaminants
- The level of data and information available on the site
- The complexity of the release (e.g., number of units, release pathways, affected media)
- The overall extent of the release

Field Investigation Strategies and Techniques

Entire books can be, and indeed have been, written on the topic of field investigations for environmental characterization. Furthermore, the colossal task of discussing RFI methods is multiplied by the fact that any medium (e.g., soil, air, groundwater, etc.) might be involved in a given RFI. Rather than give limited and clearly inadequate coverage to these concerns, the focus here is on selecting an appropriate approach to investigation in the context of corrective action program objectives.

The first effort following identification of the significant hazardous constituents present in the unit or release area is an evaluation of the likely compartment in which a given constituent will be found. Based on chemical, physical and biological properties of the constituent relative to environmental media (e.g., air:water partition coefficient), the evaluation of environmental compartment or medium helps to determine which media should be sampled to characterize whether a release is occurring. A simple example would be to use soil gas monitoring to detect migration of volatile organic compounds. The remaining aspect that may be determined from the compartmental evaluation would be the detection or analytical methods to be used, the expected detection limits and the data quality objectives.

The next effort should entail selection of sampling and/or testing tools or techniques. Various methods exist for obtaining acceptable samples of waste and for each medium. The following criteria should be considered in choosing such methods:

- *Representativeness* - The selected methods should be capable of providing a true representation of the situation under investigation.
- *Compatibility with Analytical Considerations* - Sample integrity must be maintained to the maximum extent possible. Errors induced by poorly selected sampling techniques or equipment can result in poor data quality. Special consideration should be given to the selection of sampling methods and equipment to prevent adverse effects during analysis. Materials of construction, sample or species loss, and a chemical reactivity are some of the factors that should receive attention.
- *Practicality* - The selected methods should stress the use of practical, proven procedures capable of being used in or easily adapted

to the given situation.

- **Safety** - The risk to sampling personnel and others, intrinsic safety of instrumentation and safety equipment required for conducting the sampling should be carefully evaluated.

Finally, the specific sampling/monitoring design may be chosen. This amounts to selection of sample numbers, locations, depths and timing. Because conditions present in the unit or in the contaminant release will change both temporally and spatially, the design of the sampling program or monitoring network should be developed accordingly. Spatially, sufficient samples should be collected to adequately define the extent of the contamination. Temporally, the plan should address spreading of the release with time and variation of concentrations due to factors such as changes in unit operations, the environment surrounding the unit, and the composition of the waste. For example, when possible, sampling and supplemental measurements (e.g., wind speed) should be conducted when releases are most likely to be observed.

It must be emphasized that investigations must consider and include relevant physical and descriptive data and information associated with the samples or the media sampled. This evaluation process is especially critical where computer modeling of fate and transport is to be included in the evaluation. Lack of sufficient pertinent physical and descriptive data can render an investigation almost useless.

RFI Decision Points

As monitoring data become available, both within and at the conclusion of discrete investigation phases, they typically are reported to the regulatory agency as directed. The regulatory agency will compare the monitoring data to applicable health and environmental criteria to determine the need for

- Interim corrective measures
- A Corrective Measures Study

In addition, the regulatory agency will evaluate the monitored data with respect to adequacy and completeness to determine the need for any additional monitoring efforts. Notwithstanding this process, the owner/operators have a continuing responsibility to identify and respond to emergency situations and to define priority situations that may warrant interim corrective measures. For these situations, it is suggested that the owner/operators obtain and follow the RCRA Contingency Plan requirements under 40 CFR Part 264, Subpart D.

As a final note, the same is true of both the CAP and CERCLA investigations. The owner/operators and the responsible parties, respectively, should maintain a significant presence throughout the process and not rely on varied and inconsistent oversight from the agency. This is especially true in providing realistic interpretations of findings, especially where transport and fate considerations may affect the interpretation of what constitutes a "continuing release."

CORRECTIVE MEASURES

In addressing releases from SWMUs to the environment, the RFI is followed by Corrective Measures. That is, a release, and hopefully, a source of contamination, have been identified, and the owner/operator must initiate a remedial response. As in the Superfund program, remedial action objectives of corrective action are site-specific and quantitative goals that define the level of cleanup are required to achieve the response objectives. These goals include any preliminary cleanup levels for environmental media affected by a release, the area of attainment and the remedial time-frame.

The mentioned objectives are accomplished through the Corrective Measures Study (CMS) and the Corrective Measures Implementation (CMI) by identifying, designing and implementing the appropriate remedial strategy, all in accordance with published CM guidance. The CMS serves as a recommendation to the U.S. EPA or the State, while the CMI is the allowed time frame for the actual corrective measures.

Corrective Measures Study

The first step in the CM phase is the development and implementation of the CMS to determine the most effective remedial option to correct potential environmental impact and human exposure threats

posed by releases of hazardous wastes or constituents. Regardless of whether the remedial response effort is conducted under CERCLA or RCRA authority, the objectives of the CMS, or feasibility study, are to utilize technical knowledge and propose actions to control the source of the contamination (by preventing or mitigating the continued migration of contamination by removing, stabilizing and/or containing the contaminants) and/or actions to abate problems posed by the migration of substances from their original source into the environment.

Through the CMS, the owner/operator must technically demonstrate that the response action proposed effectively abates the threats to human health and the environment posed by the release(s). This typically requires the analysis of several remedial technologies in detail sufficient to show that the recommended measures effectively remove the threats posed by the release. To do so, the owner/operators must assess these alternatives in terms of their technical feasibility (including reliability and requirements for long-term operation and maintenance), their ability to meet public health protection requirements and their ability to protect the environment and any adverse environmental effects of the measures. The owner/operator also should consider any institutional constraints to implementation of the measures, such as off-site capacity problems and potential public opposition.

The RCRA approach to assessing the level of remedial action required for environmental media is similar to that of CERCLA³⁷ and generally is based on the following criteria:

- Overall protection of human health and the environment
- Compliance with regulatory programs (e.g., CERCLA or RCRA)
- Short-term effectiveness
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility or volume of hazardous wastes and/or waste constituents
- Implementability
- Cost
- U.S. EPA and/or State acceptance
- Community acceptance

The first two criteria are the basic regulatory requirements, while the next five criteria are interactively used to analyze and compare the options. The final two criteria are considerations in the overall evaluation.

In some cases, it is possible for owner/operators to analyze and present to the Agency or State only a single alternative that meets public health and environmental requirements. This situation is often the case at facilities that have taken "interim corrective measures" and thus have had an opportunity to evaluate the remedial strategy and the associated operations to determine their effectiveness. This solution is appropriate when the U.S. EPA or the State agree that the remedial alternative the owner/operator proposes is likely to effectively achieve corrective action goals, including health and environmental requirements, and is technically sound. In most cases, however, given the array of feasible technologies, it may be necessary to analyze more than one alternative to determine the appropriate response measure. For example, off-site or on-site alternatives may be considered or there may be a difference of opinion as to whether a particular alternative the owner/operator proposes to analyze would be reliable or effective in abating threats expeditiously. In such cases, the U.S. EPA or the State would require the analysis of several alternatives to ensure that appropriate response measures are completed on a timely basis and that response is not delayed by a sequential analysis of a series of alternatives.

RCRA final remedies will be required to meet applicable, possibly current, health and environmental standards promulgated under RCRA and other laws. For example, at regulated units, groundwater releases are subject to the groundwater protection standards, possibly consisting of the following:

- Constituent specific maximum concentration limits (MCLs)
- The background level of that constituent in groundwater
- An approved alternate concentration limit (ACL) where approval would be based on criterion set forth in the RCRA regulatory framework

For soil, soil gas, surface water, groundwater and air emissions problems that cannot be addressed by existing standards, the Agency currently is assessing the appropriate technical approach. One possible alternative is to establish appropriate health-based standards on a case-by-case basis.

Once the owner/operator proposes the remedial strategy(s) for addressing releases to environmental media and the SWMU itself, the U.S. EPA or the State will evaluate the owner/operator recommendation and approve or disapprove it. During the review process, the owner/operator must be prepared to provide the technical support for his or her proposition and must be open to negotiations. The views of the public on the proposed measures and the financial assurance demonstration also will be considered by the State and U.S. EPA in making these decisions.

Corrective Measures Implementation

Once the U.S. EPA, the State, and the owner/operator agree on the remedial approach, the owner/operators will design and construct the selected response action. After construction, the appropriate measures needed to operate, maintain and monitor the remedy will be taken by the owner/operators. These activities will be required by permit condition or compliance order and will be performed by the owner/operators with oversight by the U.S. EPA or State. Since the actual operations serve to provide data concerning the effectiveness of the corrective action, it is essential that these data are used as criterion in determining whether the operations should be modified over time to meet the cleanup objectives.

Effecting remedies (or interim measures) at facilities that do not have RCRA permits will, in some cases, involve creating new treatment,

storage or disposal units. Rather than going through the actual process of issuing RCRA permits to such new units, which could substantially delay implementation of the remedy, the Agency is considering using enforcement authorities and closure plan regulatory authorities to allow those units to be constructed and operated without a formal RCRA permit. The U.S. EPA may need to amend existing regulations to provide for this proposed approach. Such new units would nevertheless be required to generally comply with applicable Part 264 technical standards, and appropriate public review and comment would be provided.

REFERENCES

1. U.S. EPA, *Interim Final RCRA Facility Investigation (RFI) Guidance*, Vol. I, Waste Management Division, Office of Solid Waste, EPA 530/SW-89-031, May, 1989.
2. U.S. EPA, *RCRA Facility Assessment Guidance*, Permits and State Programs Division, Office of Solid Waste, Aug. 14, 1986.
3. U.S. EPA, *Draft RCRA Preliminary Assessment/Site Investigation Guidance*, Permits and State Programs Division, Office of Solid Waste, Aug. 5, 1985.
4. Porter, W. J., *Memorandum*, Assistant Administrator, Office of Solid Waste and Emergency Response, Subject: National RCRA Corrective Action Strategy, Oct. 14, 1986.
5. U.S. EPA, *Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites*, Office of Emergency and Remedial Response, Dec., 1988.
6. U.S. EPA, *Subpart S: Corrective Action for Solid Waste Management Units 40 CFR 264.500-264.560* (Revised Draft Sep. 12, 1988).
7. Stoll, R. G., *Chapter 3: Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund)*, 10th Ed., Government Institutes, Inc. Rockville, MD.

Improved Methodology for Constructing Soil Liners Using Highly Plastic Clays

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ABSTRACT

Use of highly plastic clays for construction of soil liners in hazardous waste landfills has been discouraged partly due to their adverse shrink-swell characteristics but primarily because it is difficult to eliminate macrovoids between soil clods and along interlift boundaries. The macrovoids and lift laminations cause in situ hydraulic conductivities to exceed the mandated maximum hydraulic conductivity of 1×10^{-7} cm/sec.

Faced with no locally available source of low plasticity clay, it was decided to experiment with various aspects of the compaction process, including the effects of moisture conditioning, compaction effort, clod size, equipment type, lift thickness, sequencing of operations and penetration of compactor feet. This was done to evaluate whether highly plastic clays could be compacted with minimum of macrovoids, thereby increasing the probability of successfully meeting hydraulic conductivity requirements.

This paper outlines an improved methodology for constructing soil liners using highly plastic clays. The methodology was developed by varying eight aspects of the compaction process during construction of two test pads and observing migration of dye. The results of two successful SDRI tests (instrumented for swell and movement of wetting front) also are presented along with suggestions for improving the test procedure.

INTRODUCTION

Historically, below-grade landfills consisted of pits excavated through clayey soils. The depth of the pits often was controlled by the location of groundwater. At times, the landfills were lined with imported clay installed using earthwork techniques similar to those employed in the construction of embankments and roadways.

More recently, the influence of governmental regulations, public sentiment and industry's concerns have led to improved technology in design and operation of landfills. Use of composite liners became widespread. However, research and development of synthetics far outpaced advances in the construction of earthen liners.

Monitoring the quality of clay liners centered around field density testing and laboratory measurement of permeability. By the 1980s, studies by Daniel^{1,6,8} and others^{2,3,9,10,11} suggested that permeability of clay liners may be influenced by the presence of macrovoids and laminations; development of in situ permeability equipment^{5,7} demonstrated that field permeability of compacted clay liners could be several orders of magnitude greater than measured in the laboratory.

Many of the industrial facilities in southeast Texas are situated within the Coastal Plain geological province. The near-surface geologic units of this area consist mainly of Pleistocene Beaumont Formation clays. Derived from backswamp or overbank deposits laid down in quite environments adjacent to ancient riverbeds, the clays are typically highly plastic. Sources of low plasticity, clay, preferred for construction of liners, are few and often located considerable distances off-site.

McClelland's experience with the highly plastic clays of southeast Texas indicated that their compaction to achieve low hydraulic conductivity, particularly the strictly enforced, field-tested permeability of 1×10^{-7} cm/sec as mandated by the U.S. EPA and state environmental agencies, could be difficult. We were concerned that it would be difficult to break down the highly plastic clays into small clods and to adjust their moisture content. Moreover, the clay's toughness would make it hard to eliminate inter-clod voids and lift interfaces. Lastly, the compacted clays would exhibit a high shrink/swell potential.

Our concerns were underscored by published case studies^{2,4,10} and discussions with colleagues in industry, which demonstrated that field testing of clay liners constructed employing conventional earthwork techniques failed to meet maximum permeability requirements.

We realized the economic benefits of using locally available sources of highly plastic clay, but we also realized how difficult it would be to work with these clays to meet hydraulic conductivity requirements. Cognizant of the consequences in terms of schedule delays and/or reduced waste containment capacity if field testing failed to meet requirements, it was decided to investigate the effectiveness of additives to improve workability of the clays by reducing their plasticity.

The laboratory study led to full-scale field observations of various aspects of the compaction process, from which an improved methodology of constructing soil liners was developed. The methodology was employed successfully at several sites in southeast Texas using clays of high plasticity.

CLAY MODIFICATION STUDY

Recognizing that elimination of macrovoids and interlift laminations hinged on the workability of clay, which in turn depended on its plasticity, our laboratory study was aimed at modifying clay plasticity. An additive commonly used in the Gulf Coast area to reduce plasticity is lime. Although relationships between lime content, plasticity and shrink/swell potential are well documented, data regarding permeability of lime-modified

clay are limited.

Lime was added in varying concentrations to two different sources of highly plastic clay. Pertinent properties of the two clays are shown in Table 1 below.

Table 1
Properties of the Clays Used in this Study

	Brownish Yellow	Dark Gray
	Clay	Clay
Liquid Limit, %	68-79	96-120
Plastic Limit, %	21-25	29-32
Plasticity Index, %	47-54	67-89

After addition of lime, the soil-lime mixture was allowed to "mellow" for three days before initiating laboratory testing. Samples subjected to strength and permeability testing were first compacted to specified density at selected moisture content and allowed to cure in a humid room for 7 days. The mellowing and curing periods were selected to simulate actual field conditions.

The effects of lime content on strength, plasticity, pH and moisture-density relationships are shown for both clays on Figures 1 and 2. As expected, addition of lime improved workability and strength and reduced the shrink/swell potential.

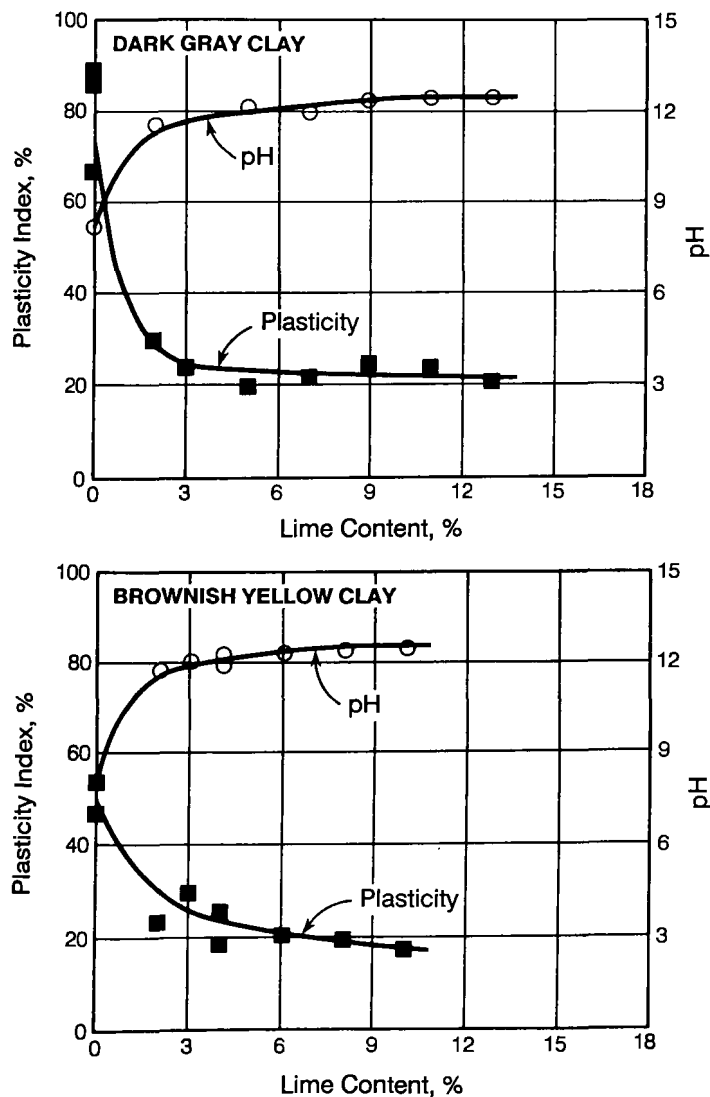


Figure 1
pH and Plasticity Index Versus Lime Content

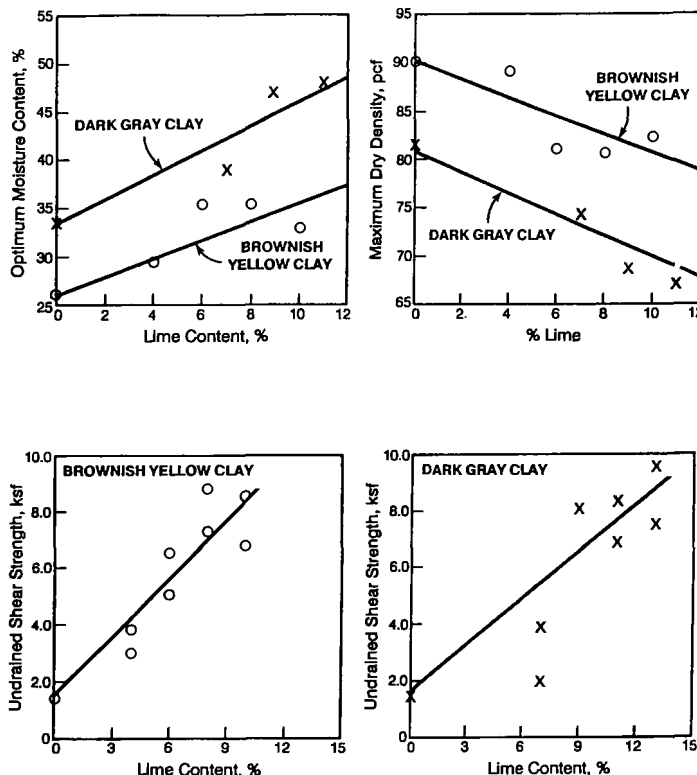


Figure 2
Variation in Soil Properties with Lime Content

Addition of even small amounts of lime increased the permeability of the brownish-yellow clay by one to two orders-of-magnitude. The permeability of the more plastic dark gray clay increased by as much as 10,000 times. The results of the permeability tests are shown in Figures 3 and 4.

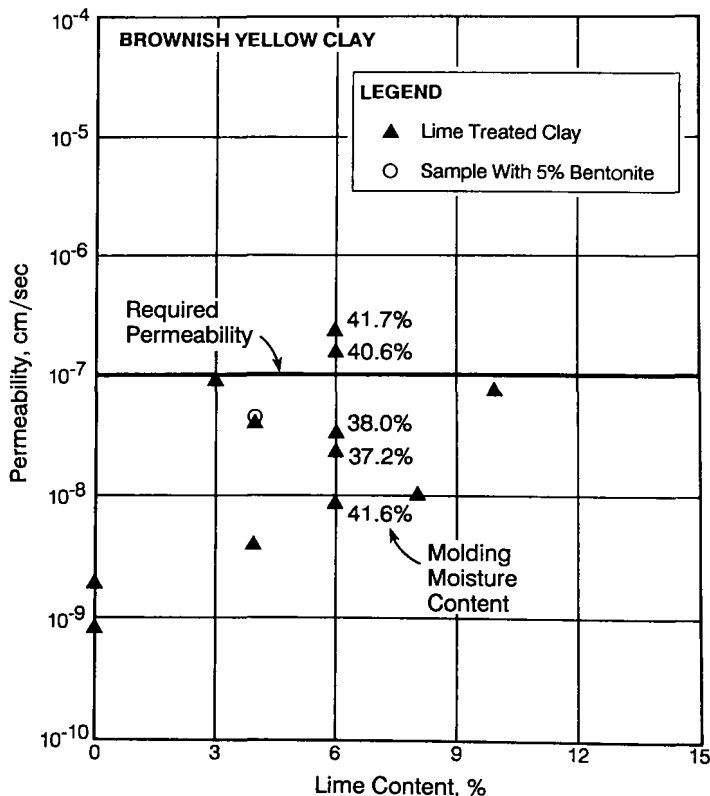


Figure 3
Permeability Versus Lime Content

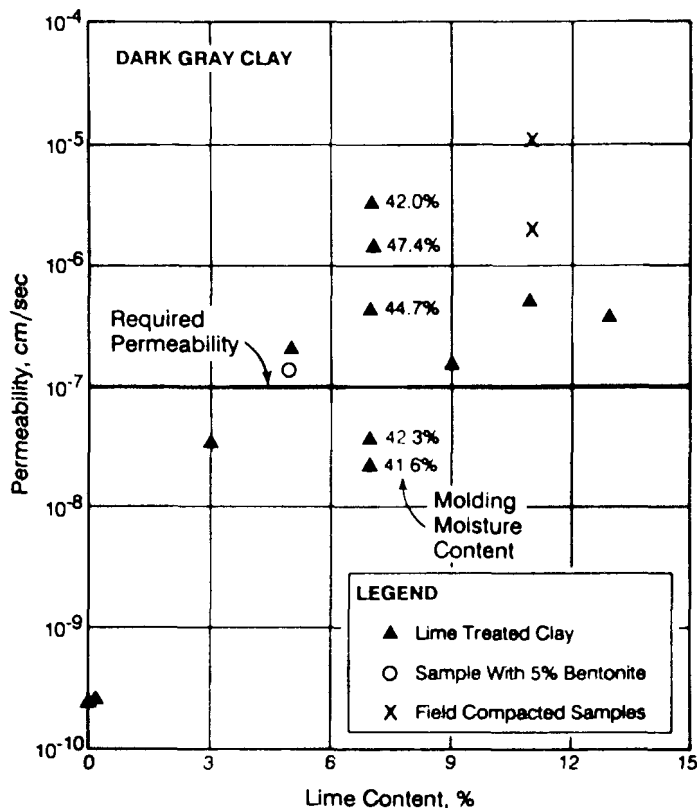


Figure 4
Permeability Variation with Lime Content

A majority of lime-modified samples of the brownish yellow clay met the required permeability benchmark of 1×10^{-7} cm/sec, but by a narrow margin. This was not true for the dark gray clay.

Of greater concern to us was the scatter (one to two orders-of-magnitude) in measured permeabilities at a given lime content.

We hypothesized that this observed increase in permeability upon addition of lime could be attributed to the "granulation" of the mixture during mellowing and possibly be due to the formation of macrocracks in the more brittle lime-modified clay.

Our study showed that addition of lime significantly improved workability. However, considering the scatter in data measured under controlled laboratory conditions, and realizing that variations in the field would be greater, we did not have confidence that the lime-modified clays would successfully meet required field permeability.

FIELD STUDY OF COMPACTION PROCESS

Over a period of 2 mo, we studied various aspects of the compaction process, guided by the goal of reducing the presence of prominent interconnecting macrovoids and lift interfaces which various investigators^{4,9} believed were responsible for the observed high permeability.

Two different sources of highly plastic clay were used in the study. The clay obtained at the study site, termed "On-site", was more plastic than the "Off-site" clay obtained from a borrow source located roughly 1.5 mi away. Pertinent properties of the two clays are summarized in Table 2.

The following aspects of the compaction process were investigated:

- Lift Thickness—the loose lift thickness was varied from 3 to 9 in.
- Moisture Content—moisture content was varied between 2% below to 5% above optimum moisture content.

Table 2
Properties of Clays Obtained at Study Site

	ONSITE	OFFSITE
Classification:	Brown and Yellow Clay With Silt Pockets and Some Calcareous Modules	Gray to Light Brown Sandy Clay With Silt
Liquid Limit, %	70 to 80	50 to 60
Plastic Limit, %	21 to 24	15 to 17
Plasticity Index, %	48 to 56	35 to 43
Sticky Limit, %	26 to 27	22 to 23
Specific Gravity	2.72	2.70
Percent Passing No. 200 Sieve	95	64
Optimum Moisture Content, %	21	18
Maximum Dry Density, pcf	99	107

- Compactive Effort—three different compactors were used, namely: (1) Caterpillar 815B, (2) double-drum sheepsfoot towed by track-type tractor and (3) tamping foot compactor.
- Method of Reducing Clod Size—a disc and pulvimixer were utilized. Number of passes of pulvimixer, depth of cut and shield opening were varied.
- Coverage—number of equipment passes was varied to produce coverages of 100, 150 and 200%.
- Effects of sequencing operations on uniformity of blending and moisture conditioning.
- Location of Discing and Pulverizing—reducing clod size was performed both on the trial pad and at an off-site location.
- Penetration of Compactor Feet—moisture content was varied to produce compactor foot imprint of various depths.

Each of the eight factors described above was studied independently and in various combinations. Variations in technique were applied to both clay types. Careful observation and documentation, along with testing of density and moisture content, were performed along each step.

The trial lifts were dissected routinely and inspected for macrovoids and interlift laminations. Absence of macrovoids and laminations was considered to be paramount to the formation of a successful technique.

It quickly became apparent, too, that compaction techniques were bound by such factors as the "sticky limit" of the soil, a little used Atterberg limit, the bearing capacity required to support compactors and the consistency of clay required for trafficability of various other earthwork equipment.

After repeated trials, a method of placing, processing and compacting the highly plastic clay, in a way that macrovoids and prominent laminations were not observed, was developed. This methodology is described in the following section.

METHODOLOGY DEVELOPED

The methodology developed by this study for construction of liners using highly plastic clays significantly varies from conventional earthwork techniques, yet follows an approach which is expedient, practical and verifiable. The methodology considers clod size, moisture conditioning, lift thickness, compactive effort, coverage and tamping foot penetration. Each of these six concepts is described in detail below.

Clod Size

The effective clod size of the clay is broken down to an effective diameter of less than 3 in. using a pulvimixer, preferably working off the pad. At least one pass of the pulvimixer is required. Discing alone was proven ineffective, but may be considered before pulvimixing. Maintaining proper shield opening greatly affects both productivity and clod size.

Lift Thickness

The loose lift thickness is maintained at less than 6 in., producing a final compacted lift thickness of 4 in. As the plasticity of the clay increases, consideration should be given to reducing maximum loose lift thickness to 4 in. Our experience suggests that use of laser mounts on grader produces consistent and verifiable results.

Compactive Effort

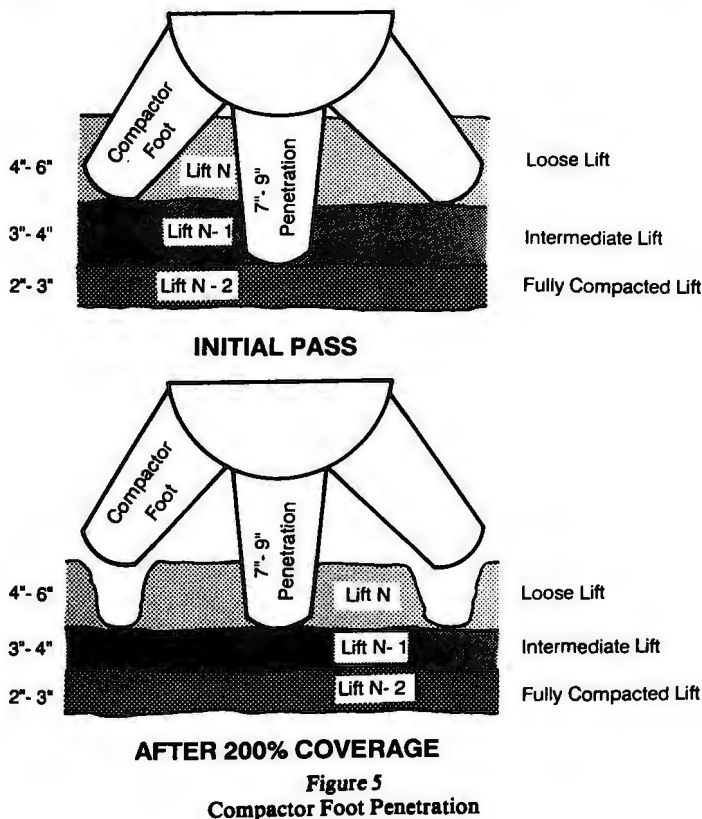
A heavy-duty compactor (Cat 815B or equivalent with a gross weight of 20 to 25 tons) is specified with a tamping foot projection of at least 7 in. and preferably 9 in. Sheepfoot or medium to light-duty compactors are considered ineffective in working with the tough, highly plastic clays.

Coverage

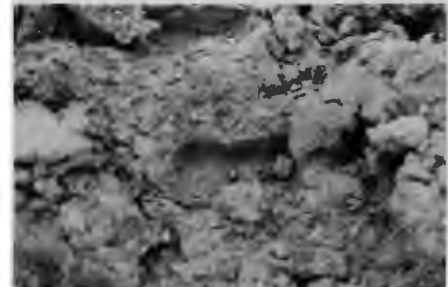
Compaction should be controlled by the number of passes required for 150% coverage. Coverage, not density, should control the number of passes (our experience indicates that minimum density requirements usually will be met with the coverage and compactive effort specified). Uniform coverage by the compactor is essential.

Moisture Conditioning and Tamping Foot Penetration

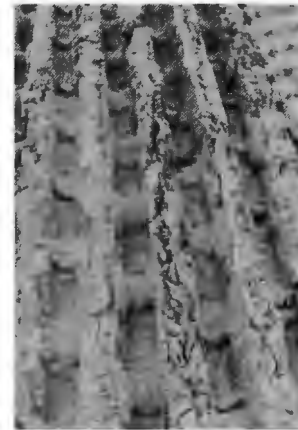
The moisture content should be adjusted to above Compactor's Optimum, defined as moisture at which tamping feet produce at least 4-in. imprint following 150% coverage, but do not fully penetrate (i.e., the drum is not in contact with soil). The desired tamping foot penetration at initial pass and following 200% coverage is illustrated in Figure 5. A rule-of-thumb which we found useful in estimating the compactor's optimum moisture content can be stated as follows: moisture content should be above optimum moisture content (ASTM D 698) but below the "sticky limit" (so that the clay does not stick to the drum). The "sticky limit" is a little used Atterberg limit, one of seven limits developed by a Swedish soil scientist, A. Atterberg, in the early 1900s: Figure 6 demonstrates the impact of varying moisture on penetrability.



Too Dry
1'-2" Imprint



Proper Moisture
4'-6" Imprint



Too Wet
Clay Sticks
To Drum

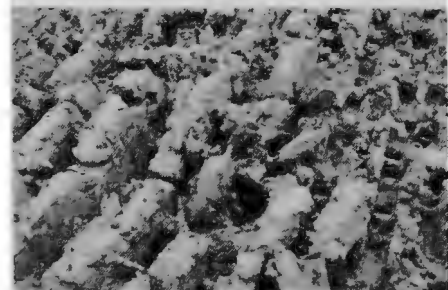
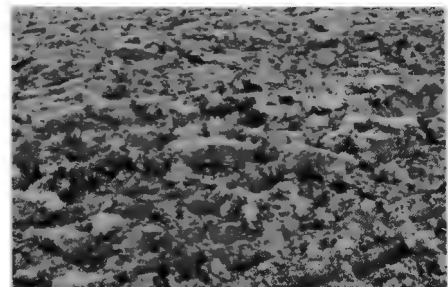


Figure 6
Effect of Moisture Content on Penetration

VERIFICATION OF RESULTS

Extensive field and laboratory studies were performed to check

if the newly developed methodology was successful. Field studies included test trenches and dye penetrant testing. Laboratory tests were performed to study overburden pressure versus swell relationship.

Test Trenches

Test trenches were excavated through the compacted trial pads to check for the presence of macrovoids, laminations, lift interfaces, homogeneity of the soil mass and any other construction defects. To remove smearing caused by the backhoe during trench excavations, portions of the trench were carefully trimmed with a pocket knife. Typical trench cuts are shown on Figure 7. The trenches revealed a homogeneous soil mass with extensive mixing of soil colors and mosaic-like patterns. There was a conspicuous absence of lift interfaces and other construction defects.



Figure 7
Cut Through On-Site Clay Pad

Dye Penetrant Testing

Dye penetration tests were made to evaluate the extent of large, interconnecting macrovoids which may not have been apparent under visual inspection. Four square prefabricated steel rings measuring 6 ft by 6 ft were installed in the pads to observe vertical defects: Seven 4-in. diameter PVC standpipes were installed in boreholes to evaluate the extent of interconnecting horizontal voids. The dye consisted of powdered methylene blue dissolved in water at a concentration of 3 gm/gal. The rings and boreholes were dissected approximately 1 wk after the dye was introduced.

These tests showed that the dye only penetrated a thin veneer of soil (about 1/8 in.); the soil below this veneer was not stained. Penetration along lift interfaces or interconnecting channels also was not observed. The extent of dye penetration is typified on Figure 8.

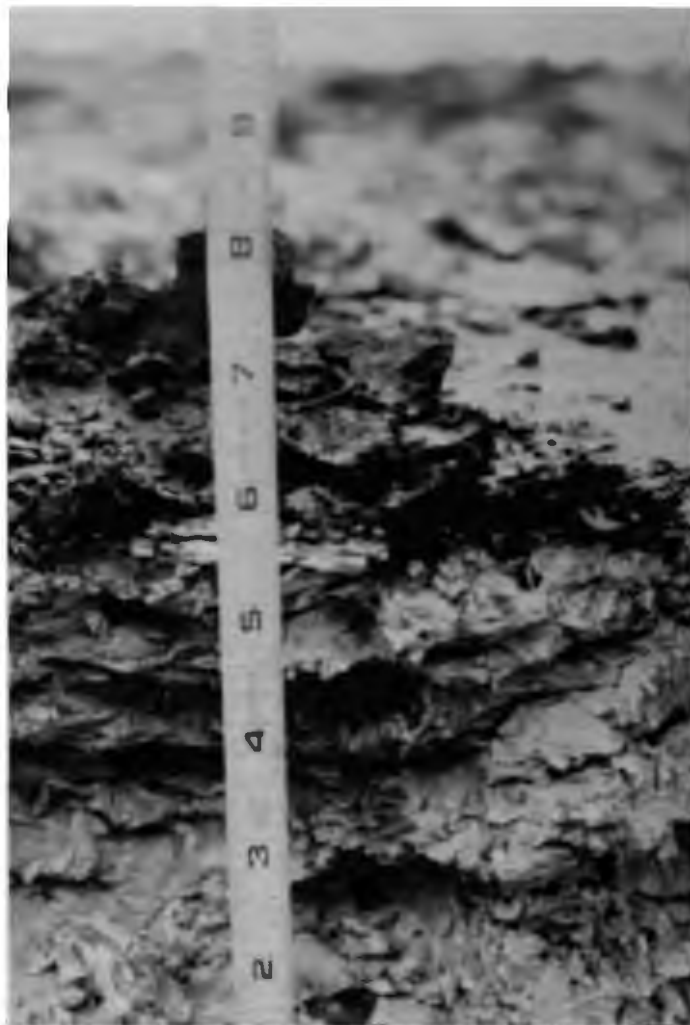


Figure 8
Cross-Section—Dye Penetrant Test

IN SITU TESTING

The rate of infiltration of water into the test fills was measured using the sealed double ring infiltrometer (SDRI) technology described by Daniel and Trautwein.^{5,7} Nine tensiometers at three different depths were used to estimate the advance of the wetting front and, thereby, to obtain a better estimate of the hydraulic gradient during performance of the test. Four swell monitors were used to estimate the quantity of water being held by the soil to enable calculation of the quantity of water flowing through the soil. A schematic diagram of the testing apparatus is presented on Figure 9.

Results of SDRI Tests

The computed hydraulic conductivity values are presented on Figure 10 as a function of time for both the on-site clay and the off-site clay. The dashed curves represent hydraulic conductivity corrected for temperature, but uncorrected for swell. Hydraulic conductivity corrected for both swell and temperature is plotted as a solid line.

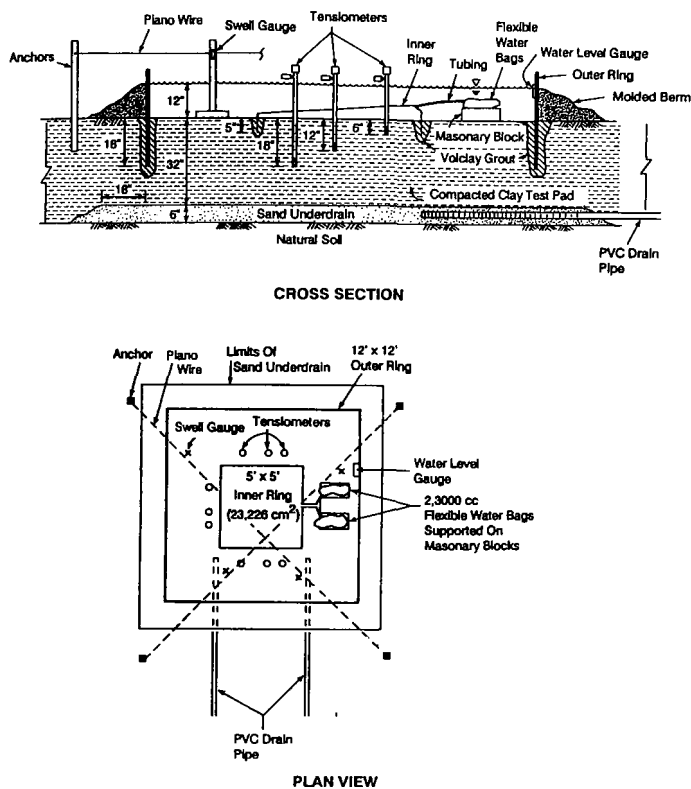


Figure 9
Sealed Double Ring Infiltrometer Layout

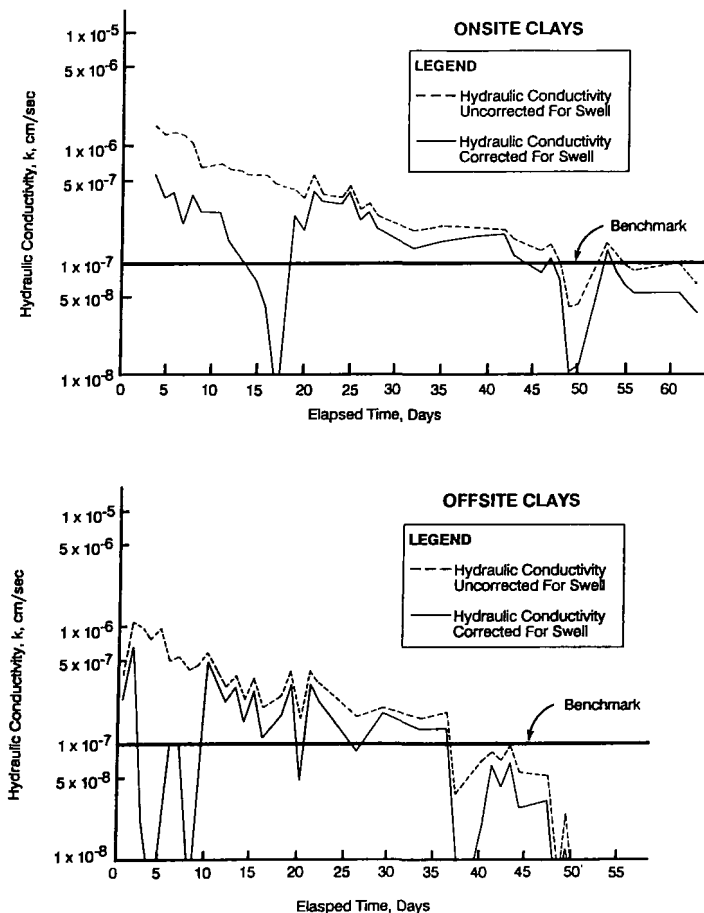


Figure 10
Hydraulic Conductivity vs Elapsed Time

The curves show decreasing permeability with time; this trend is typical of other SDRI tests we have performed. We believe that initially the computed permeability is high due to swelling of the soils and disintegration of the upper few inches of the clay. As the wetting front advances, the overburden pressure increases, reducing swell which we attributed to be responsible for fracturing of the compacted mass, and permeability decreases. Figure 11 shows the rate of swell and the rate of advance of the wetting front with time.

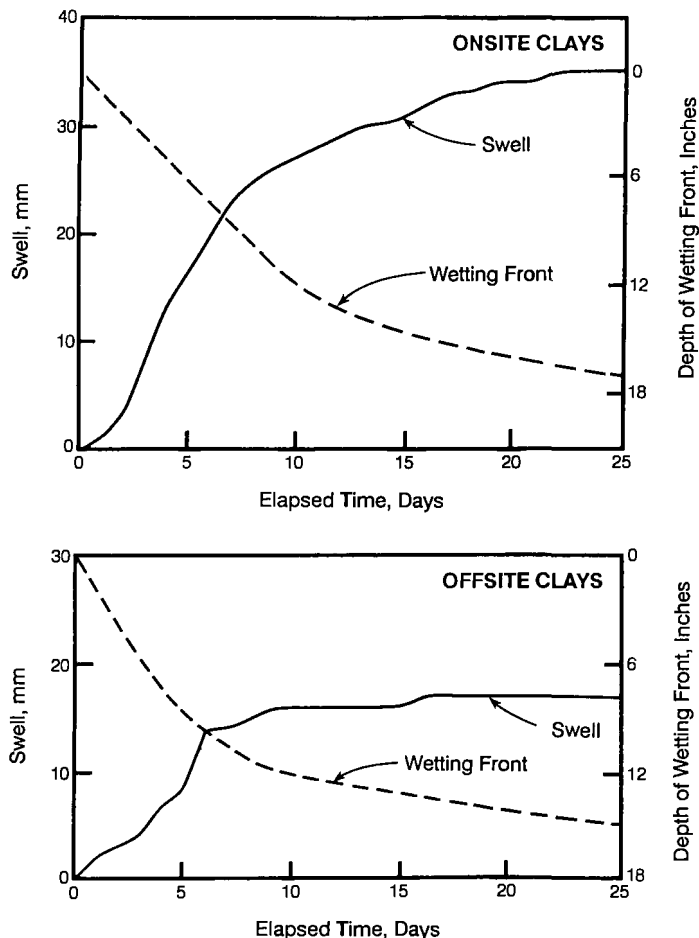


Figure 11
Swell and Movement of Wetting Front vs Time

Laboratory permeability tests were performed on compacted samples prior to the start of the SDRI tests. These tests gave permeability values on the order of 1×10^{-9} cm/sec or less. Laboratory permeability tests also were performed on undisturbed thin-walled tube samples recovered from the test fill after the completion of the SDRI tests. These laboratory tests gave values ranging from 2.3×10^{-7} to 1.2×10^{-9} cm/sec. These results agree well with the SDRI hydraulic conductivity data.

Limitations of SDRI Test

Although the SDRI test is useful in estimating the in situ hydraulic conductivity of a clay liner or cap, the SDRI test has several shortcomings. Further research and modifications to the SDRI equipment should be considered to make it more useful and representative of actual field conditions.

Swell and Overburden Considerations

A typical clay liner or cap will have some overburden. The liners are generally overlain by a 1-ft thick leachate collection layer; a cap may have top soil or other covering. However, the

SDRI setup does not account for any overburden. Lack of overburden results in swelling of high plasticity soils which destroys clay structure in the upper few inches of the liner.

In addition, there is controversy as to how the swell correction should be applied. We feel that the SDRI equipment should be modified so that overburden pressure representative of actual field conditions can be applied. Alternately, a thicker test fill should be constructed and the upper portion (for example, 1 ft) of test fill should be considered as the overburden.

Ideally, correlations should be established where SDRI data with no overburden can be corrected for overburden effects. Laboratory studies suggest that an increase in overburden pressure reduces the hydraulic conductivity and a small amount of overburden (for example, 1 psi) significantly reduces swell of soils compacted wet of optimum moisture content.

Wetting Front and Hydraulic Gradient

Accurate methods are needed to estimate depth of wetting front during performance of the SDRI test. We utilized tensiometers to estimate the depth of wetting front. Tensiometers only indicate when the wetting front reaches the tip depth and do not give a continuous measure of the depth of wetting front. Moreover, if not inserted and grouted properly, the tensiometer can leak around its sides giving erroneous results. A continuous read-out device based on moisture changes, perhaps soil resistivity, should be considered. The final moisture content profile of the soil, after the test is completed, is a reliable method but it is after-the-fact datum and cannot be used during performance of the test.

Cost and Duration of Test

The SDRI is a very expensive and time-consuming test when compared to a laboratory permeability test. In addition, only a small area which may not be representative of the test fill is tested. We believe that consideration should be given either to laboratory tests performed on large diameter samples or expediting the field test.

Miscellaneous Factors

Miscellaneous factors influencing SDRI tests include the growth of algae in the test equipment and the changes in volume of the water and the ring due to temperature fluctuations SDRI.

Misuse of SDRI Test Data

The quality of a liner depends in part on the clay (i.e., whether a particular clay meets permeability requirements as measured by the SDRI) used in its construction. Of equal if not greater importance in determining liner quality is the compaction methodology, the compaction equipment, the experience of construction personnel and the quality assurance program.¹¹ Highly plastic clays can meet the 1×10^{-7} cm/sec permeability requirement provided a proper compaction methodology has been developed for the particular clay.

CONCLUSIONS

The following conclusions were drawn as a result of this study:

- Highly plastic clays are difficult to compact and their use as soil liner material has been discouraged. Yet, these soils are the pre-

dominant near-surface geologic unit in southeast Texas and their use presents economic benefits.

- Addition of lime greatly enhances the workability of highly plastic clays but increases permeability by 10 to 1000 times.
- A methodology has been developed for construction of liners using highly plastic clays. This new methodology differs from conventional earthwork techniques, yet follows an approach which is expedient, practical and verifiable. The methodology considers clod size, moisture conditioning, lift thickness, compactive effort, coverage and tamping foot penetration.
- The SDRI test is useful in estimating in situ hydraulic conductivity. However, the SDRI test has several shortcomings which particularly affect the outcome of tests performed on liners composed of highly plastic clays. Most importantly, the test does not account for overburden or swell.
- The compaction methodology, the equipment and experience of its operators, and the QA/QC program are factors as important to the quality of an earthen liner as the type of clay used in its construction.

REFERENCES

1. ASTM "Annual Book of Standards: Silt and Rock, Building Stones; Peats," Part 19, Philadelphia, PA, 1986.
2. Boynton, S.S. and Daniel, D.E. "Hydraulic Conductivity Tests on Compacted Clay," *J. Geotech. Eng., ASCE*, 111 (4), pp 465-478, 1985.
3. Brown, K.W., Green, J.W., and Thomas, J.C. The Influence of Selected Organic Liquids on the Permeability of Clay Liners," *Proc., Ninth Annual Research Symposium on Land Disposal of Hazardous Waste*, EPA-600/9-83-018, Cincinnati, OH, pp 114-125, 1983.
4. Daniel, D.E., "Predicting Hydraulic Conductivity of Clay Liners," *J. Geotech. Eng., ASCE*, 110(4), pp 285-300, 1984.
5. Daniel, D.E., "Hydraulic Conductivity Tests for Clay Liners," *Proc., Ninth Annual Symposium on Geotechnical and Geohydrological Aspects of Waste Management*, Feb. 1987, Fort Collins, CO, 1987.
6. Daniel, D.E., "Earthen Liners for Land Disposal Facilities," *Proc., Geotechnical Practice for Waste Disposal '87*, ASCE, pp 21-39, 1987.
7. Daniel, D.E. and Trautwein, S.J., "Field Permeability Test for Earthen Liners," *Proc., Use of the In Situ Test in Geotechnical Engineering*, ASCE, New York, NY, pp 146-160, 1986.
8. Day, S.R. and Daniel, D.E., "Hydraulic Conductivity of Two Prototype Clay Liners," *J. Geotech. Eng., ASCE*, 111(8), pp 957-970, 1985.
9. Elsbury, B.R., et al. "Field and Laboratory Testing of a Compacted Soil Liner," Unpublished document prepared for the U.S. EPA, 1988.
10. Gordon, M.E., Huebner, P.M. and Kmet, P. "An Evaluation of the Performance of Four Clay-Lined Landfills in Wisconsin," *Proc., Seventh Annual Madison Waste Conference*, University of Wisconsin, Madison, WI, pp 399-460, 1984.
11. Herrmann, J.G. and Elsbury, B.R. "Influential Factors in Soil Liner Construction for Waste Disposal Facilities," *Proc., Geotechnical Practice for Waste Disposal '87*, ASCE, pp 522-536, 1987.
12. Lahti, L.R., King, K.S., Reades, D.W. and Bacopoulos, A., "Quality Assurance Monitoring of a Large Clay Liner," *Proc., Geotechnical Practice for Waste Disposal '87*, ASCE, pp 640-654, 1987.

Compatibility of Soil-Bentonite Slurry Wall Backfill Mixtures With Contaminated Groundwater

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ABSTRACT

The interactions of solutes found in leachates from uncontrolled landfills with the components of a soil-bentonite (SB) slurry wall are capable of causing swelling or shrinking of the SB backfill material which alters the hydraulic conductivity of the slurry wall. The effect of solutes in contaminated groundwater from the Ninth Avenue Superfund Site in Gary, Indiana, on the hydraulic conductivity of two SB slurry wall backfill mixtures was evaluated using rigid-wall permeameters.

Groundwater samples taken from three observation wells from the Ninth Avenue site contained solutes that could cause increases in the hydraulic conductivity of a SB slurry wall. One groundwater sample contained salt concentrations as high as 20,000 mg/L. A second sample contained total priority pollutant volatile organic compound (VOC) concentrations as high as 2,300 mg/L. A third sample contained approximately 50 mg/L of total base neutral-acid extractables (BNAs) included on the Priority Pollutant List.

Free swell tests using organic solvents, salt and tapwater were conducted on four commercially available bentonites. Sodium chloride showed the most impact on the free swell capacity of the bentonite samples by always reducing the free swell capacity of the samples as compared to the control tap water samples. The organic solvents produced variable results with the bentonite samples, sometimes increasing their free swell capacity over the controls and sometimes decreasing it. From the free swell testing, one bentonite was chosen for use in preparing the SB slurry wall backfill mixtures.

Six clay borrow sources from the Gary, Indiana, area were screened using Atterberg limits and grain size analysis. A high plasticity soil (CH) and medium plasticity soil (CL) were chosen as borrow materials used in the preparation of the two SB slurry wall backfill mixtures.

The backfill mixtures were prepared by adding enough 6.04 bentonite slurry to the two clay borrow samples to achieve at least a 4.0-in. slump. The water contents of the backfill materials were 49.5 and 41.1% for the CH and CL clay backfill, respectively.

Each backfill mixture was loaded into eight rigid wall permeameters. Sidewall leakage inside the permeameters was controlled by the application of bentonite paste along the inside of the permeameter cell walls. All 16 permeameters were run in Phase I with tap water; then in Phase II, six permeameters for each backfill mixture were permeated in duplicate with the three contaminated groundwater samples (i.e., two permeameter per groundwater sample), while the remaining two permeameters, or control cells, continued to be permeated with tap water. The three permeants from the wells produced varied hydraulic conductivity results. However, the solutes had little or no effect on the hydraulic conductivities of the backfill mixtures.

INTRODUCTION

The Ninth Avenue Dump Site is listed on the NPL of hazardous waste

sites scheduled for cleanup under the Superfund Acts of 1980 and 1986 (CERCLA and SARA). The site is a 17-ac inactive chemical waste disposal area located in Gary, Indiana.

The site is situated in an industrial area, although properties adjacent to the site are relatively undeveloped. The site topography is a relatively flat area with poor drainage and is characterized by small depressions and mounds from past disposal and/or cleanup activities.

Both solid and liquid wastes are reported to have been disposed on the site. Solid wastes deposited there include industrial construction and demolition wastes. Liquid wastes deposited there include oils, paint solvents and sludges, resins, acids and other chemical wastes. Waste disposal operations took place between 1973 and 1980.

The groundwater is contaminated with a variety of inorganic and organic contaminants. Inorganic contamination is mainly in the form of sodium chloride (road salt). Organic contaminants are present in significant concentrations in the groundwater, with ketones, benzene, ethylbenzene, toluene, xylene (BETX), polyaromatic hydrocarbons (PAHs) and total chlorinated ethenes being detected in significant concentrations.

In order to eliminate the continual spread of contaminants through groundwater transport and to facilitate site cleanup, a SB slurry wall was proposed as a means of contaminant containment. Proposed placement of the wall will key into the aquiclude and completely surround the site.

SB Slurry Wall Construction

SB slurry walls typically are installed by first digging a 2- to 4-ft wide trench, using either a drag-line or a back-hoe, around the area containing the contaminated material(s) and aquifer. During the excavation of the trench, bentonite slurry is pumped into the excavated area in order to support the sides of the trench. Typically, the trench depth reaches at least 2 to 3 ft into an aquiclude. As the excavation equipment moves along excavating the trench, borrow material is mixed with bentonite slurry to form a bentonite slurry/borrow material mixture referred to as the SB backfill mixture. The SB backfill mixture is added to the trench once the excavation equipment has moved far enough along so that the addition of the backfill mixture does not interfere with excavation activities. The final product is a wall of backfill material that has a very low hydraulic conductivity. Typical SB slurry wall construction methods are shown in Figure 1.

In most cases, the borrow material used during slurry wall construction is simply the soil that is excavated from the trench. However, the soil to be excavated from the Ninth Avenue Site has relatively high percentages of sand and gravel thus requiring trucking in an alternative borrow material with more suitable characteristics for use in slurry wall construction.

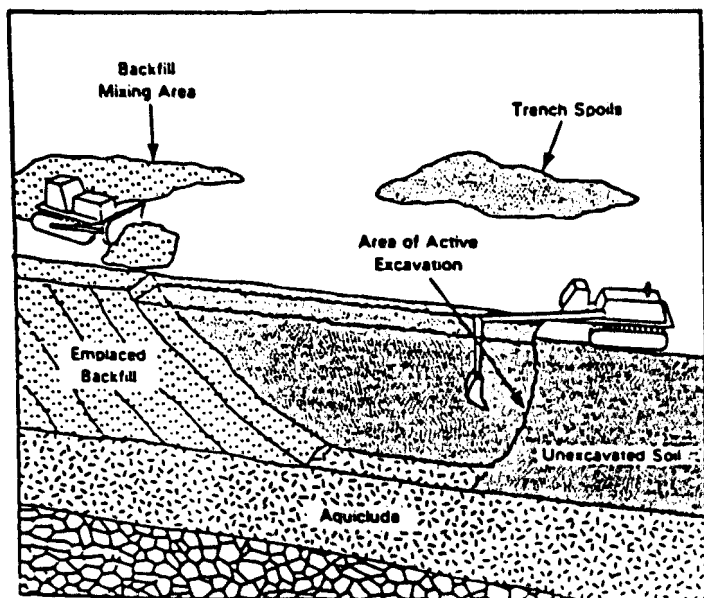


Figure 1
Excavation and Backfilling Operations

Potential Compatibility Problems

Many of the contaminants found in the site ground-water samples have been identified through past research efforts as potentially having adverse chemical interactions with clays, resulting in an increase in hydraulic conductivity¹⁴. Although these contaminants are present in the site groundwater, their concentrations are not nearly as high as those tested in the above mentioned research efforts. In fact, most of the research efforts to date involving chemical interaction between contaminants and clay particles have been performed using either pure or highly concentrated solutions. The contaminant concentrations in the site groundwater are high in terms of an environmental pollution problem, but may not be significantly high in terms of possible chemical interaction between the contaminants in the groundwater and the SB backfill mixtures. Because little or no research in the area of chemical interactions of moderately contaminated solutions with clay particles has been documented, compatibility testing must be performed to assess if the contaminants in the groundwater will adversely change the hydraulic conductivity of the SB slurry wall.

Study Objective and Scope

The objective of this study was to determine through laboratory testing if the contaminants in the site groundwater will increase the hydraulic conductivity of a soil-bentonite slurry wall.

The scope of this study included permeameter testing of two SB backfill mixtures that were formulated as part of this study. The SB backfill mixture formulations were based solely on technical considerations and not on an analysis of the projected costs associated with the construction of a SB slurry wall at the site. Compatibility of the proposed SB slurry wall with the contaminated site groundwater was determined through permeability testing of two SB backfill mixtures with test permeants consisting of tap water from the City of Gary, Indiana (CGI) and contaminated ground-water from three site observation wells (X-1, X-14 and X-25). The concentrations of the major chemical constituents detected in water samples from each of the three wells are presented in Table 1.

Bentonite Selection

Bentonites used in the construction of SB slurry walls to contain contaminated groundwater should exhibit a hydration volume that will not be significantly reduced when exposed to the contaminants present in the site groundwater. Any significant decrease in hydration or free swell volume could increase the hydraulic conductivity of the SB slurry wall. Therefore, a bentonite that exhibits a significant decrease in free swell

Table 1
Groundwater Samples Permeants Analytical Data

Constituent	Observation Well Number		
	X-1	X-14	X-25
Total Ketones	ND	503.3	1452.0
Total Phenols	ND	27.9	2.1
BETX Compounds**	ND	139.3	3.7
Methylene Chloride	ND	25.0	20.0
Sodium	13000.0	47.4	656.0
Iron	18.8	323.0	574.0
Calcium	992.0	1040.0	836.0
Magnesium	217.0	180.0	574.0
Manganese	1.5	4.9	17.6
Potassium	35.7	23.1	34.0
Chloride	22700.0	1450.0	1200.0
Hardness	2480.0	2760.0	3440.0
Alkalinity	429.0	403.0	578.0
pH	7.5	5.8	6.8
Total Organic Carbon	4.4	1764.0	2970.0

* All concentrations in mg/l

** Benzene, Ethyl Benzene, Toluene, and Xylene

ND Not Detected

volume when exposed to the site contaminants should not be considered suitable for use in the construction of a SB slurry wall.

Bentonite samples from four commercial sources were evaluated for use in the bentonite slurry used in the preparation of the two SB backfill mixtures. Samples from each source were labelled as Bentonite Samples B-1, B-2, B-3 and B-4. Evaluations were based on results from free swell testing of the bentonites. The free swell test involves the addition of 2 g of bentonite to 100 mL of a test solution containing levels of contaminant(s) at or above the levels found in the site groundwater. Free swell tests usually are performed in 100 mL graduated cylinders. The volume occupied by the bentonite or free swell (hydrated volume) is measured at 2 and 24 hr. For this study, tap water and laboratory-prepared solutions of tap water mixed with various solvents and sodium chloride at concentrations greater than those found in the site groundwater were prepared and used as hydration fluids.

The results of the free swell testing of the four bentonite sources are presented in Table 2. The table lists the test solutions and the respective free swell volumes at 2 and 24 hr. The free swell tests using tap water as test solutions were used as a test control. Table 3 presents the percent of control for each solution and bentonite. The percent of control is a comparative value that is calculated by dividing the free swell volume of the bentonite for each test solution by the free swell volume of the bentonite sample for tap water then multiplying by 100.

Table 2
Bentonites Free Swell Data

Contaminant (Concentration)	Time (hours)	Free Swell Volume (ml)*			
		Sample B-1	Sample B-2	Sample B-3	Sample B-4
Acetone (1000 mg/l)	2	27.3	34.8	34.6	31.9
	24	33.5	35.9	36.4	32.9
Acetone (3000 mg/l)	2	30	29	30.9	27.9
	24	32.7	31.1	31.9	30.2
Acetone (6000 mg/l)	2	27	30.3	31.3	32.7
	24	34.2	31.8	32.1	34.1
MEK (3000 mg/l)	2	27.8	31.3	27.6	28.9
	24	32	33.3	28.5	30.2
NaCl (4000 mg/l)	2	26.3	28.6	23.5	25.8
	24	27.9	29.8	24.81	26.5
NaCl (10000 mg/l)	2	19.6	22.8	16.9	18.3
	24	19.6	22.8	16.9	18.3
Toluene (2000 mg/l)	2	23.3	29.7	30.6	33
	24	28.9	32.1	32.4	34.3
Tap Water** (Uncontaminated)	2	25.3	27.8	29.7	34.1
	24	29.3	29.7	30.3	34.6

* Average of three replicates

** Test Control

Table 3
Summary of Percentage of Controls for Bentonite Sources

Contaminant	Sample B-1	Sample B-2	Sample B-3	Sample B-4
Acetone (1000 mg/l) (1000 mg/l)	114	121	121	95
Acetone (3000 mg/l)	112	105	106	87
Acetone (6000 mg/l)	117	107	106	99
MEK (3000 mg/l)	109	112	94	87
NaCl (4000 mg/l)	92	100	82	77
NaCl (10000 mg/l)	67	77	56	53
Toluene (200 mg/l)	99	108	107	99

Percent of control values were used to determine the degree of interaction, if any, between the various bentonites and test solutions. Therefore, if a bentonite sample has a percent of control value (POCV) less than 100%, then adverse interactions between the contaminants in the test solutions and the bentonite particles are occurring. It is possible to have POCVs greater than 100%. Some contaminants in solution at lower concentrations will actually increase the swell capacity of some bentonites. This phenomenon was observed by Hettiaratchi and Hrudley⁵. They concluded that acetone solutions at concentrations of less than 25 mole percent of acetone (approximately 52% acetone so-

lution) increased the free swell capacity of the bentonite-soil mixture tested.

All three acetone concentrations (1,000 mg/L, 3,000 mg/L, and 6,000 mg/L) increased the POCVs for all the bentonites tested except for bentonite sample B-4. MEK increased the POCVs for both bentonite samples B-1 and B-2. The POCVs for B-3 and B-4 for the MEK tests were 94 and 87%, respectively. All of the free swell testing using sodium chloride (salt) as test solutions resulted in POCVs less than 100%, except sample B-2 4000 mg/L NaCl test which had a POCV of 100%. Sample B-2 performed the best with respect to the sodium chloride free swell tests followed closely by the performance of the B-1 sample. Toluene did not have a detrimental effect on any of the bentonite samples tested. Bentonite samples B-2 and B-3 had toluene POCVs greater than 100%, while bentonite samples B-1 and B-4 had POCVs of 99% for the toluene free swell tests.

Bentonite yield is a rough measure of the solids content based on the viscosity and swell capacity of the bentonite. A comparison of the yields of bentonite samples B-1 and B-2 indicated that bentonite B-2 is an extremely high yield bentonite that was developed for use as a liner material for industrial waste lagoons. Bentonite B-1, on the other hand, is an average yield bentonite that is more suitable for use in formulating bentonite slurries for SB slurry wall construction. Therefore, based on the results of free swell testing and a comparison of the respective yields of samples B-1 and B-2, bentonite sample B-1 was chosen as the bentonite source for use in formulating the SB backfill mixtures.

SELECTION OF BORROW MATERIALS

Six sources of borrow materials located within the CGI vicinity were

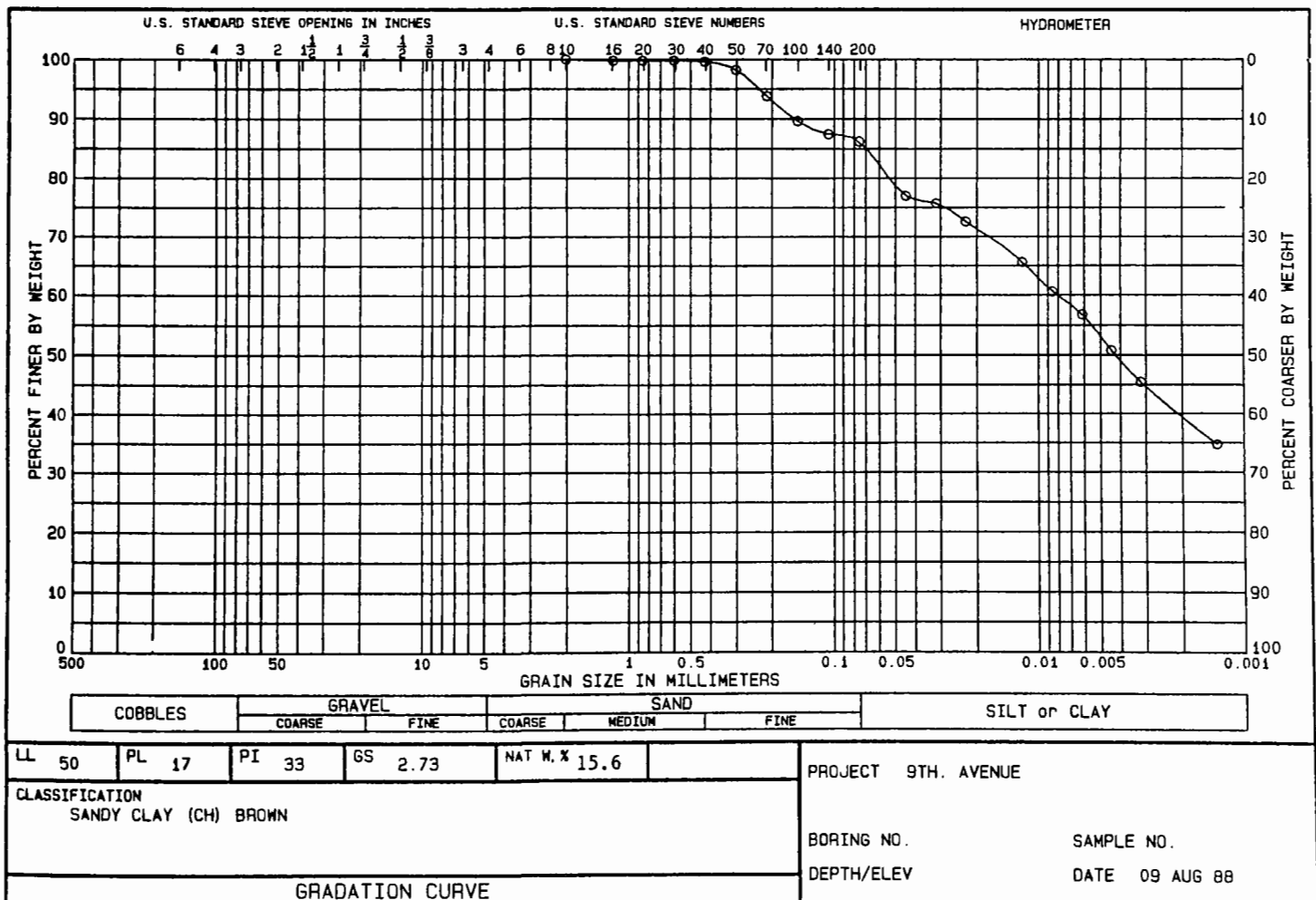


Figure 2
Sample No. BM-1

evaluated based on Atterberg limits, classification under the Unified Soil Classification System (USCS) and percent fines (determined through both sieve and hydrometric gradation analysis). The six sources were identified as samples BM-1, BM-2, BM-3, BM-4, BM-5 and BM-6. According to D'Appolonia², SB slurry wall hydraulic conductivity is a function of the percent fines (percent of material that passes through a No. 200 sieve) of the borrow material used in the formulation of the SB backfill material. The greater the percentage of fines, the lower the hydraulic conductivity of the SB backfill mixture.

Based on the USCS, sample BM-1 was a CH soil, samples BM-2, BM-3 and BM-4 were CL soils, and samples BM-5 and BM-6 were SC soils. The CH soil (sample BM-1) and CL soil (BM-2) were selected for use in formulating the two SB backfill mixtures evaluated in permeability testing. Soil sample BM-2 was chosen from the CL group of sources because it had the second highest percentage of fines of the CL class of soils. Therefore, source BM-2 was considered representative of the CL group of borrow material sources. Gradation curves for the selected borrow materials are presented in Figures 2 and 3. Physical and chemical properties of the two selected borrow sources are presented in Table 4.

A 6.0% bentonite and CGI tap water slurry with a Marsh Funnel reading of 48 sec. was mixed with the two borrow materials to formulate two SB backfill mixtures. One SB backfill mixture was prepared using the BM-1 material, while the second SB mixture was prepared with the BM-2 material. The porosities (n) of the two SB backfill mixtures were determined in order to calculate the pore volume of the backfill mixture samples loaded into each permeameter. The slumps of the BM-1 and BM-2 SB backfill mixtures were 4.0 and 4.5 in., respectively. The water contents of the BM-1 and BM-2 SB backfill mixtures

Table 4
Physical and Chemical Characterization of Clay Samples
Formulation of SB Backfill Mixtures

Parameter	Clay Samples	
	BM-1	BM-2
pH	5.37	7.71
CEC (meq/kg)*	2260	1960
Ca (mg/l)	15200	1270
Mg (mg/l)	9970	5470
K (mg/l)	3690	4120
Na (mg/l)	246	149
TOC (mg/l)	4307	1081
Liquid Limit (%)	50	39
Plastic Limit	17	17
Plasticity Index (%)	33	22
Water Content (%)	15.6	8.0
Specific Gravity	2.73	2.73
Clay Type**	CH	CL

* Method 8081 USEPA SW-846 (Sodium Method)

** Unified Soil Classification System

were 49.5 and 41.1%, respectively. The percentages of bentonite in the SB backfill mixtures BM-1 and BM-2 were 2.30 and 2.33%, respectively.

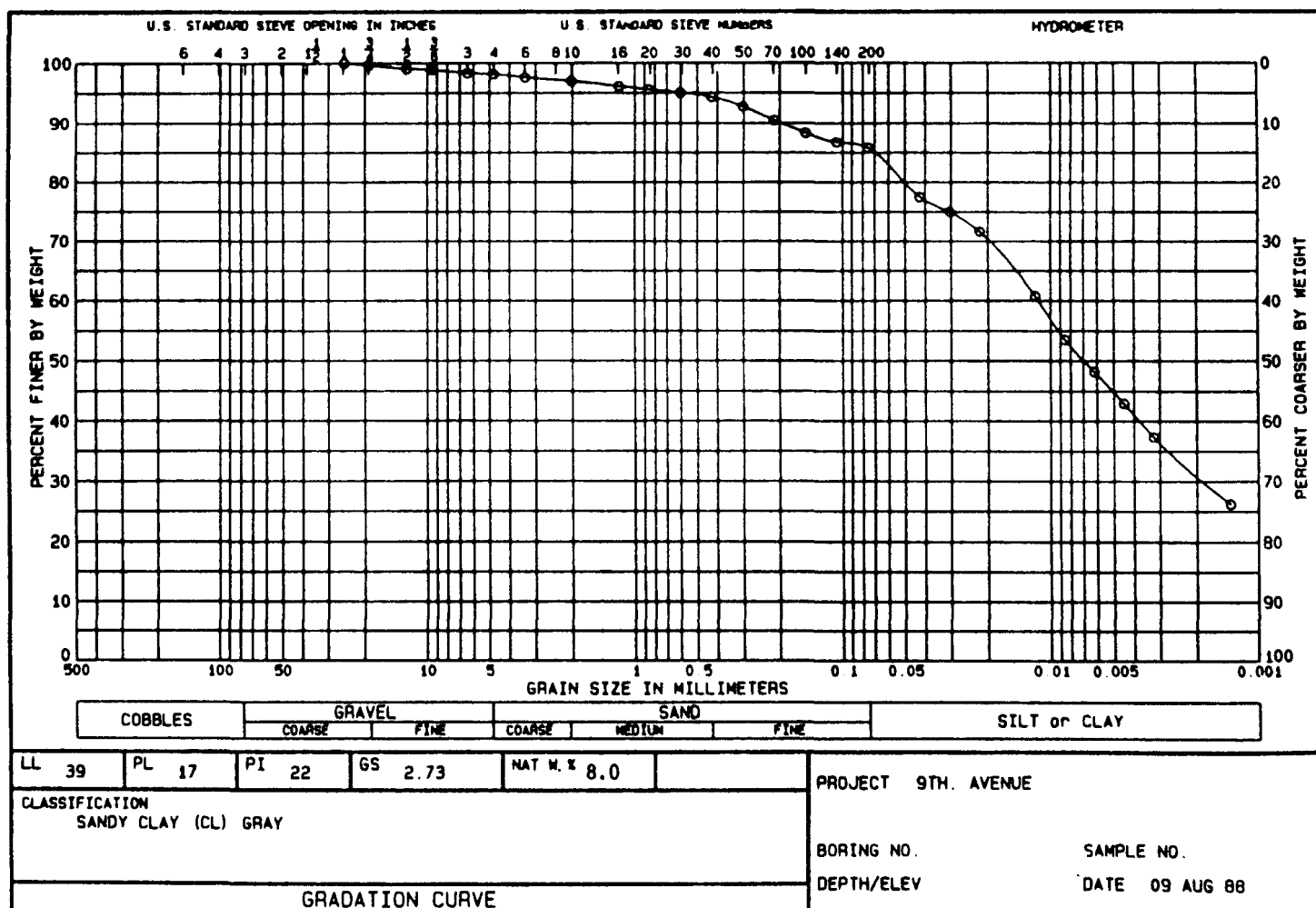


Figure 3
Sample No. BM-2

Permeameter Testing

Eight of the 16 permeameter cells were loaded with one of the two SB backfill mixtures while the remaining eight cells were loaded with the other SB backfill mixture. Initially, all test cells were permeated with CGI tap water in order to determine the hydraulic conductivity (K) of the SB backfill mixture sample in each cell. Although eight replicate cells contained the same SB mixture, slight differences in packing each of the cells could produce differences in the observed hydraulic conductivity for each cell. For this reason, CGI tap water was permeated in all cells so that a baseline hydraulic conductivity could be determined for each cell.

After at least one pore volume of tap water was permeated through each cell, six of the eight cells for each SB backfill mixture were permeated with contaminated groundwater collected from the three site observation wells. Samples from each of the three site observation wells were permeated through two replicate cells for each SB backfill mixture. Two of the eight cells for each SB backfill mixture continued to be permeated with CGI tap water throughout the course of permeability testing. These four cells (two cells for each SB backfill mixture) served as test control cells. The control cells were used to help determine if any changes in hydraulic conductivity were due to physical changes in the SB backfill mixture samples caused by operational adjustments made during testing (i.e., increased hydraulic gradient) and not due to chemical interaction between the backfill mixtures and ground-water contaminants.

The test cells were downflow rigid wall permeameters constructed as illustrated in Figure 4. SB backfill samples used for permeability testing were 2.25 in. long with 4-in. diameters. The inside walls of the permeameters were roughed up with a stainless steel brush and coated with a 0.06-in. layer of bentonite paste to reduce sidewall leakage. Porous stones, saturated with CGI tap water, were used to support the samples inside the permeameters. The permeameters were setup as illustrated in Figure 5. The average hydraulic gradients (i) used in permeability-testing of the SB backfill mixtures BM-1 and BM-2 were 45 and 27 ft/ft, respectively.

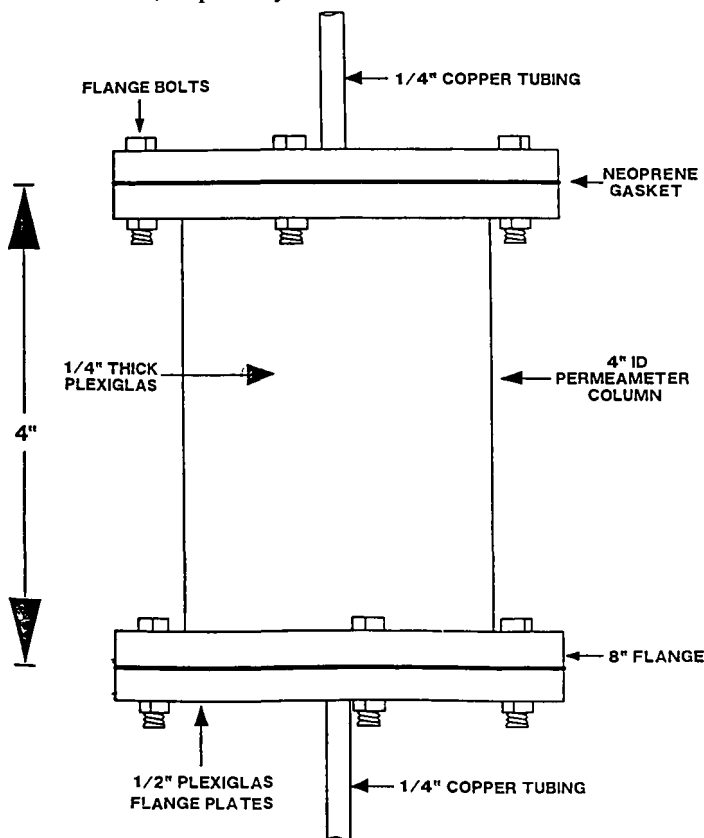


Figure 4
Rigid Wall Permeameter

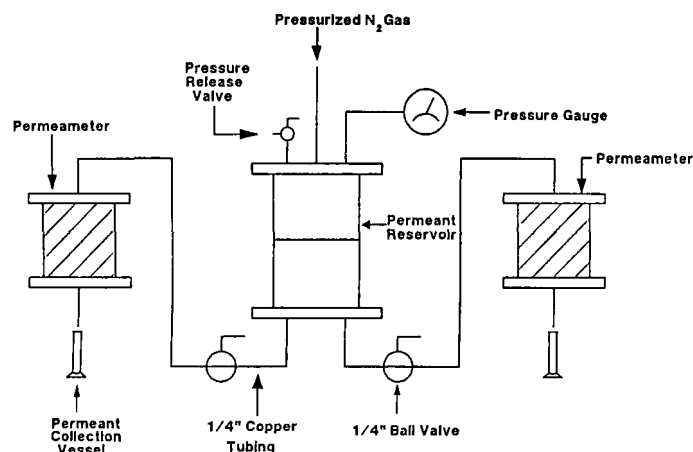


Figure 5
Rigid Wall Permeameter System

Bottled nitrogen was used as the pressure source for the permeant reservoirs. One pressure reservoir was used to pressurize and deliver the permeants to two separate permeameters. This arrangement served as duplicate permeameter sets for each SB backfill mixture sample and respective permeant. Copper tubing (0.25 in. OD) was used to connect the reservoirs to the permeameters. Permeant volumes were collected and measured daily in 100-mL graduated cylinders.

Table 5 summarizes the results of the permeability testing of the two SB backfill mixtures. The period of permeability testing in which CGI tap water was used as the permeant in all cells was identified as Phase I. Phase II of permeability testing was the period of permeability testing when contaminated groundwater samples were used as permeants in some of the cells. Table 5 also lists the K ratio for each cell which is simply the ratio of the average Phase II K over the average Phase I K. A K ratio of unity indicates a test cell with no K deviation over the course of permeability testing.

A K ratio of less than unity indicates a cell with decreasing K's. This situation can occur when the sample within the cell slowly consolidates over time. An example of this is best illustrated in Figure 6 which is a plot of the number of pore volumes of permeant that flowed through cell No. 5 versus the respective K. The K values in Figure 6 gradually decrease over the course of permeability testing as the sample consolidates over time thus closing off pore channels. Another example of less than unity K ratios observed is illustrated in Figure 7 which presents the K data for one of the two BM-2 control cells. In this case, during the initial stages of Phase I permeability testing, the cell was very

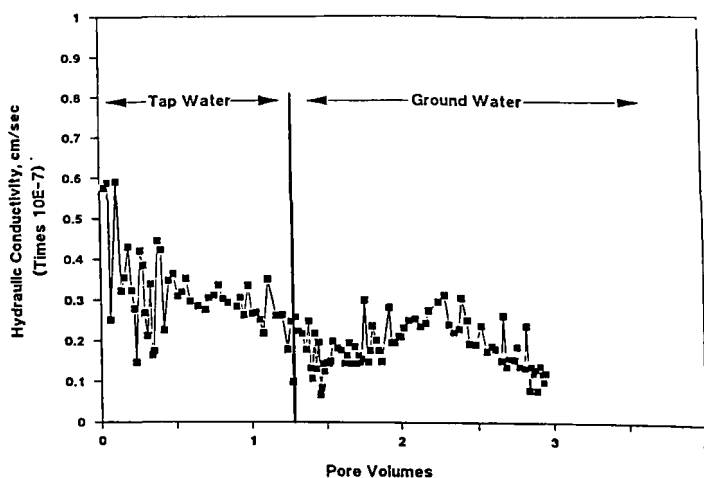


Figure 6
Cell Number 5 Hydraulic Conductivity Data

Table 5
Summary of Preliminary Permeameter Results

Permeameter Number	Phase I* Permeant	Number of Pore Volumes Permeated During Phase I	Average K During Phase I (cm/sec)	Phase I K Standard Dev. (cm/sec)	Phase II# Permeant	Number of Pore Volumes Permeated During Phase II	Average K During Phase II (cm/sec)	Phase II K Standard Dev. (cm/sec)	Ratio Phase II to Phase I K†
BM-1 Backfill									
1	Tapwater	1.33	3.07E-08	9.73E-09	Tapwater	2.60	2.48E-08	6.93E-09	0.80
2	Tapwater	1.73	3.90E-08	7.92E-09	Tapwater	3.48	3.02E-08	5.32E-09	0.77
3	Tapwater	1.56	3.94E-08	9.62E-09	X-1	3.71	4.08E-08	1.24E-08	1.03
4	Tapwater	1.27	3.09E-08	1.02E-09	X-1	2.16	2.45E-08	4.80E-09	0.79
5	Tapwater	1.27	3.13E-08	1.06E-08	X-14	1.68	1.81E-08	5.59E-09	0.58
6	Tapwater	3.21	8.67E-08	8.98E-08	X-14	---	---	---	---
7	Tapwater	2.72	6.34E-08	3.34E-08	X-25	6.48	1.84E-07	1.15E-07	2.90
8	Tapwater	1.87	4.67E-08	3.29E-08	X-25	2.73	5.12E-08	8.12E-08	1.10
BM-2 Backfill									
9	Tapwater	10.81	5.47E-07	4.26E-07	Tapwater	9.33	2.22E-08	8.16E-08	0.04
10	Tapwater	5.94	2.39E-07	1.56E-07	Tapwater	6.25	1.27E-07	3.64E-08	0.53
11	Tapwater	4.94	2.13E-07	7.52E-08	X-1	10.27	2.55E-07	9.64E-08	1.20
12	Tapwater	4.43	1.90E-07	9.81E-08	X-1	6.09	1.55E-07	3.23E-08	0.82
13	Tapwater	5.02	2.61E-07	3.02E-07	X-14	6.23	1.58E-07	1.17E-07	0.61
14	Tapwater	4.88	2.15E-07	1.23E-07	X-14	8.64	2.26E-07	1.78E-07	1.05
15	Tapwater	5.07	1.87E-07	1.02E-07	X-25	6.09	1.38E-07	7.08E-08	0.74
16	Tapwater	5.66	2.03E-07	7.70E-08	X-25	5.73	1.49E-07	3.45E-08	0.73

* Phase I is when all permeants were tapwater

Phase II is when contaminated permeants were run in non-control test cells

† Calculated using average K's

--- Permeameter failure

dynamic with inconsistent Ks. After a period of variable Ks, the cell stabilized with very consistent Ks (hence the extremely low K ratios for both BM-2 control cells). Most of the cells experienced variable Ks at the initiation of permeability testing (the early stages of Phase I testing).

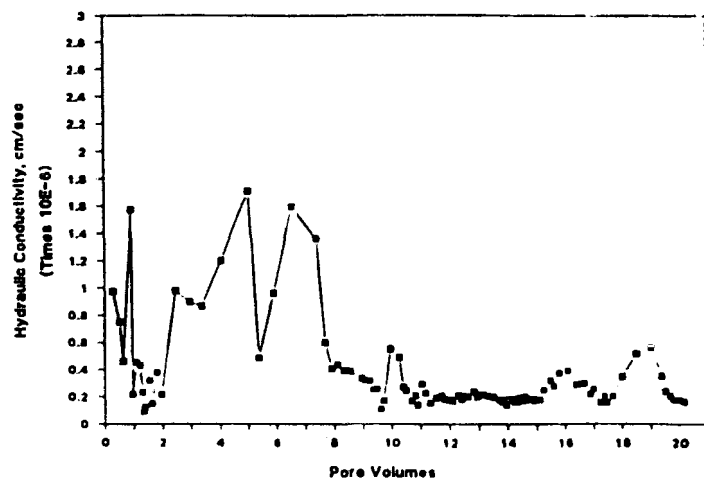


Figure 7
Cell Number 9 Hydraulic Conductivity Data

Greater than unity K ratios were also observed. Greater than unity K ratios observed for this study are indicative of those permeameters that were experiencing increased variability in K over time. Greater than unity K ratios can be an indication of adverse chemical interaction between the contaminants in the groundwater and the SB backfill materials. None of the greater than unity K ratios observed during this study were believed to be caused by chemical interaction. Permeameter operations, such as permeant change out and reservoir refilling, were believed to be the cause of the greater than unity K ratios.

None of the BM-2 SB backfill permeameters had K ratios significantly higher than unity. Cell No. 11, with a K ratio of 1.2, had the highest K ratio of all the BM-2 SB backfill permeameters. After approximately seven pore volumes of contaminated groundwater from well X-1 had permeated through Cell 11, an increase in K was observed as shown in Figure 8. This increase in K was only temporary, because the Ks began to gradually return to within the range of Ks previous

to the elevated values. The cause of the increase is believed to be due to the sample shifting during the removal of the pressure head while refilling the permeant reservoir.

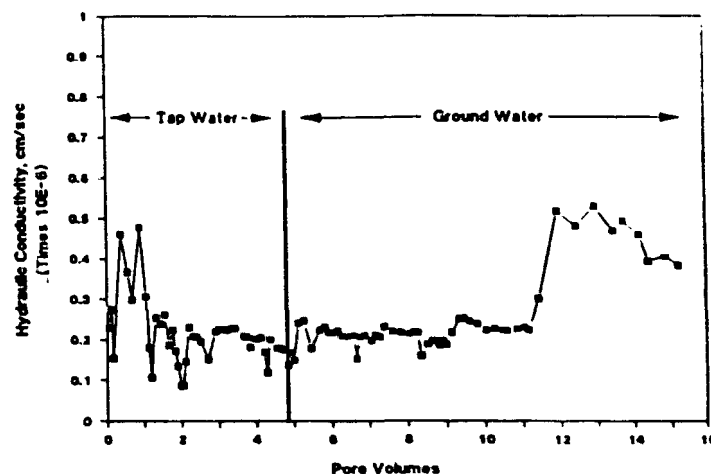


Figure 8
Cell Number 11 Hydraulic Conductivity Data

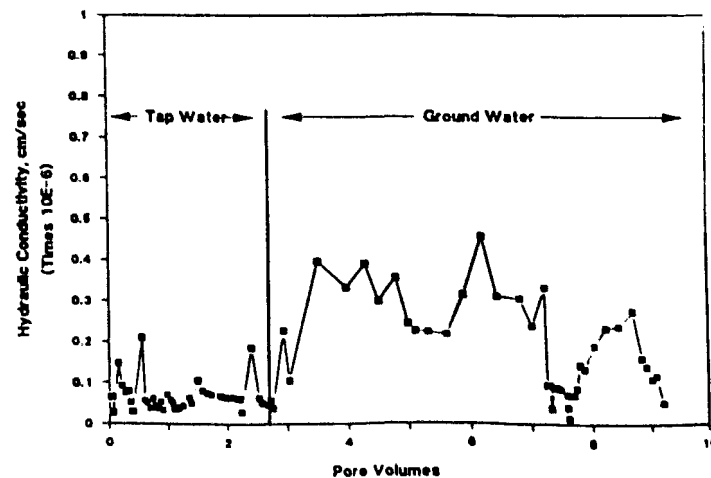


Figure 9
Cell Number 7 Hydraulic Conductivity Data

The BM-1 SB backfill mixture cells had two cells with K ratios significantly higher than unity. Cell No. 6 data were not used to evaluate groundwater compatibility with the SB backfill mixture because significant sidewall leakage was observed at the end of Phase I testing. Cell No. 7, with a K ratio of 2.9, experienced variable Ks at the end of Phase I, as shown in Figure 9. The variable Ks continued throughout all of Phase II, however, no trend toward an increase in K was observed. The high Phase II standard deviation listed in Table 5 for cell No. 7 is indicative of the variability of cell No. 7 K data.

CONCLUSIONS

Acetone increased the free swell volume of all the bentonites tested except for bentonite sample B-4. Bentonite samples B-1 and B-2 had increased free swell volumes when exposed to MEK during the free swell tests, while samples B-3 and B-4 both exhibited reduced free volumes when exposed to MEK. Sodium chloride reduced the free swell volumes of all the bentonite samples. Toluene did not have a detrimental impact on the free swell volumes of any bentonite samples.

SB backfill mixtures BM-1 and BM-2 were compatible with groundwater samples from site well X-1, X-14 and X-25. Permeameter testing demonstrated that hydraulic conductivities for the SB slurry mixtures selected for this study were not affected by contaminants in groundwater from the Ninth Avenue site. Elimination, or at least reductions, in the on/off cycling of the pressure head that occurs during refilling the permeant reservoir and permeant change out should reduce the amount of K variability observed during permeability testing. The overall average hydraulic conductivities for SB backfill mixtures BM-1 and

BM-2 throughout both phases of permeability testing were 4.7×10^{-8} cm/sec and 2.1×10^{-7} cm/sec, respectively.

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REFERENCES

1. Anderson, D.C. and Jones, S.G., "Clay Barrier-Leachate Interaction," *National Conference on Management of Uncontrolled Hazardous Waste Sites*, HMCRI, Silver Spring, MD, p 154, 1983.
2. D'Appolonia, D.J., "Soil-Bentonite Slurry Trench Cutoffs," *J. of the Geotechnical Engineering Division*, 106, No. GT4, 1980.
3. U.S. EPA, *Slurry Trench Construction for Pollution Control*, EPA 540/2-84-001, 1984.
4. Evans, J.C., Fang, H.Y. and Kugelman, I.J., "Organic Fluid Effects on the Permeability of Soil-Bentonite Slurry Walls," *Proc. National Conference on Hazardous Wastes and Environmental Emergencies*, Cincinnati, OH, HMCRI, Silver Spring, MD, p 267, 1985.
5. Hettiarachi, J.P. and Hrudley, S.E., "Influence of Contaminant Organic-Mixtures on Shrinkage of Impermeable Clay Soils with Regard to Hazardous Waste Landfill Liners," *Haz. Wastes/Haz. Materials*, 4,(4), pp 377-388, 1987.

Solute Migration Control in Soil-Bentonite Containment Barriers

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ABSTRACT

In many cases containment by a soil-bentonite barrier is the most attractive strategy for mitigation of subsurface contamination. Because the hydraulic conductivity of these barriers is generally less than 10^{-7} cm/sec, molecular diffusion can be the dominant transport process. "Effective" diffusion coefficients for low-molecular-weight organic solutes in soil-bentonite barriers are reduced only several factors from those in free aqueous solution. Molecular diffusion can then result in solute breakthrough within a relatively short time as well as in significant solute transport through the barrier when the diffusion process obtains a near-steady-state condition.

Of the several potential means for improving the performance of soil-bentonite barriers, this work examined the addition of class "F" fly ash, which contains a significant fraction of unburned carbon, to soil-bentonite mixtures for enhancement of sorption capacity. The sorption capacity of the unburned carbon fraction of the fly ashes tested was found to be roughly equivalent to that of natural soils and sediments. Simulations of the performance of a typical barrier indicated that the addition of a sorptive phase such as fly ash can significantly retard solute breakthrough.

INTRODUCTION

Several authors¹⁻⁴ have recently claimed that the migration of water soluble contaminants through cut-off barriers can be effectively curtailed by restricting the hydraulic conductivity of such barriers to less than 10^{-7} cm/sec. Given that the magnitude of natural hydraulic gradients seldom exceeds unity, under these conditions the bulk flow of water will not exceed 3.0 cm/yr. The aqueous solution residing within the pores of a soil-bentonite barrier is, then, effectively a stagnant fluid and convection (advection) is insignificant. Under these conditions, molecular diffusion is the dominant transport process. Two studies^{5,6} of dissolved solute transport into natural clay barriers of low hydraulic conductivity concluded that molecular diffusion was the process responsible for the net migration of solutes into the barriers. Another theoretical study⁷ suggested that solutes could migrate through soil-bentonite barriers by molecular diffusion even against an inward directed hydraulic gradient of magnitude equal to 0.50.

Diffusive flux (F_u) and convective flux (J_u) may be represented in mathematical form as:

$$F_u = D_{ix} (\partial C / \partial z) \quad \text{and} \quad J_u = v_i C, \quad (1)$$

where C is the aqueous concentration, v_i is the superficial fluid velocity, z is the coordinate in the gradient direction and D_{ix} is the effective diffusion coefficient for solute i within the porous medium.

An empirical relationship describing D_i in terms of the free aqueous diffusion coefficient (D_i) and the porosity (ϵ) of a porous medium or the hindrance factor (H) is given as^{8,9}:

$$D_i = \epsilon^{1/2} D_i / H \quad (2)$$

Equation 2 has been verified for diffusion in packed beds of lead shot, sand and calcite¹⁰; and diffusion in unsaturated soils^{11,12}. Additionally, diffusion coefficients for chloride in compacted sand-bentonite mixtures¹³ and in natural clay¹⁴ have been found to conform with Equation 2¹⁵.

Sorption within a porous medium can delay or retard transport through reduction of aqueous phase concentration levels and, hence, the macroscopic concentration gradient ($\partial C / \partial z$). The aqueous concentration of solutes within soil-bentonite containments can approach the solubility limit of the solutes in question; thus, the most applicable relationship for describing sorption equilibrium is the non-linear Freundlich sorption model:

$$q_i = K_f C_i^n \quad (3)$$

where q_i is the adsorbed concentration at equilibrium, K_f is the Freundlich capacity parameter, C_i is the aqueous concentration at equilibrium and n is an exponential fitting parameter. In certain cases, it is assumed that the conditions within a given medium very closely approach equilibrium and that equation 3 is applicable throughout (the local equilibrium assumption, LEA). Most systems, however, exhibit rate-limited sorption rendering the LEA quite inapplicable. The combination of non-linearity and non-equilibrium introduces additional degrees of complexity into the mathematical structure of models describing the transport process.

Diffusion, convection and sorption are combined with a pseudo first-order transformation term (k_f) through application of the mass conservation law in one dimension at the differential scale to yield the mathematical model describing solute transport within a porous medium:

$$\epsilon \frac{\partial C_i}{\partial t} = D_{ix} \frac{\partial^2 C_i}{\partial z^2} + v_i \frac{\partial C_i}{\partial z} - k_f C_i - \rho_s (1 - \epsilon) \frac{\partial q_i}{\partial t} \quad (4)$$

where ρ_s is the density of the sorbent phase and t is time. If the LEA is applicable, Equation 4 may be more simply stated as:

$$R \frac{\partial C_i}{\partial t} = D_{ix} \frac{\partial^2 C_i}{\partial z^2} + v_i \frac{\partial C_i}{\partial z} - k_f C_i \quad (5)$$

where $R = \epsilon + \rho_s (1 - \epsilon) n K_F C_i^{-1}$ for a non-linear sorption relationship. Note that for a linear sorption relationship, n equals unity and K_F is replaced by the partition coefficient (K_p). If the LEA is not applicable, the sorption term typeset equation here may take one of many formulations. The simplest of these, considered here, is:

$$\rho_s (1 - \epsilon) (\partial q_i / \partial t) \approx k_F \alpha_s (C_i - C_{s,i}) \quad (6)$$

where k_F is a mass transfer coefficient derived from boundary layer theory, as is the aqueous/solid interfacial surface area per bulk unit volume of porous medium and C_i is the aqueous solute concentration at the aqueous/solid interface. The assumption inherent with this formulation is that intraparticle transport resistance is negligible. The coefficient k_F may be approximated for the case of insignificant convection as^{15,16}:

$$k_F d / D = 2.0 \quad (7)$$

where d is the characteristic dimension (usually the diameter) of a spherical particle. Substitution of Equations 6 and 7 into Equation 4 and de-dimensionalization of the interfacial transfer term leads to the definition of a Damkhler number (N_D):

$$N_{D,i} = k_F \alpha_s d^2 / D_{e,i} \quad (8)$$

Alternative formulations for N_D have been developed for convective systems, and it was found that when the magnitude of N_D was 100 or greater, simulations of solute transport using Equation 6 agreed quite well with those employing the LEA^{17,18}. It would be reasonable to assume that the mathematics of diffusive systems would behave in a similar manner with respect to the appropriateness of the LEA.

The objectives of this work were: (1) to measure diffusion coefficients for low-molecular-weight solutes in soil-bentonite media; (2) to define the applicable relationships among D_e , D_i and definable properties of soil-bentonite barriers; and (3) to investigate the use of high-carbon fly ash as an additive to soil-bentonite mixtures in order to enhance retardation capacity.

EXPERIMENTAL PROGRAM

Materials

Background soil for soil-bentonite mixtures consisted of a mixture containing 77% silica sand, 10.5% silica flour and 12.5% kaolinite. These materials were chosen for their properties of low organic carbon content, high purity and inert mineral surfaces. Grain size distributions for each constituent and for the composite background soil are shown in Figure 1. Sodium bentonite (Slurry Ben 90, American Colloid Co.) was added to the background soil in various quantities to obtain the experimental soil-bentonite mixtures. Relationships between porosity and confining stress were developed for each experimental mixture using a slurry consolidometer and, subsequently, were employed in the analysis of the diffusion data.

Samples of fly ash were obtained from the B.C. Cobb, Karn and Trenton electrical power generating plants owned and operated by the Consumers Power Co. of Michigan. The fly ashes were tested for loss on ignition, carbon content and various other properties. The results of this characterization are shown in Table 1.

Target solutes were chosen to represent the several classes of low-molecular-weight priority pollutants. A listing of these solutes and pertinent properties is given in Table 2. All chemicals used were of reagent grade or better.

Diffusion Experiments

Both quasi-steady-state (QSS) and transient diffusion experiments were conducted to determine the magnitude of effective diffusion coefficients for target solutes in soil-bentonite mixtures. The device

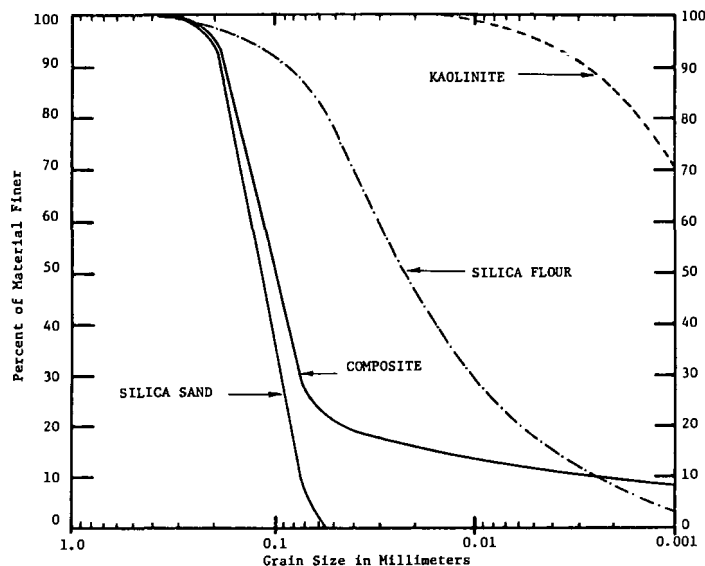


Figure 1
Gradation Curves for Experimental Background Soil Mixture

Table 1
Pertinent Fly Ash Properties

Property	Karn	Fly Ash Trenton	Cobb
Density ² (g/cm ³)	2.25	2.29	2.24
Loss on ignition ² (%)	6.47	9.14	10.23
Percent carbon ³	4.69	6.14	6.52
Iodine number ³	525	562	595
Phenol value ³	nd	nd	39.0
Tannin value ³	3086	951	3501
Specific surface (m ² /g) ⁴			
Raw	1.14	2.65	3.52
Fired	0.78	1.08	1.18

¹Measured as CO₂ recovered during wet combustion

²Bergstrom and Gray (19)

³Normalized to the carbon fraction of the fly ash

⁴Primary surface area by B.E.T. nitrogen adsorption

Table 2
Properties of Target Organic Solutes at 25°C

Solute	Henry's Constant (atm)	log K_{OW}	Aqueous Solubility (mg/L)	Aqueous ² Diffusivity (x10 ⁵ cm ² /sec)	Molecular ³ Radius (Å)
CTET	1659 ⁴	2.64	785 ¹	0.983	3.55
TCE	521 ⁴	2.29	1100	1.068	3.49
TTCE	965 ⁴	2.88	126 ¹	0.961	3.70
1,4-DCB	138 ⁵	3.39	79	0.920	3.79
1,2,4-TCB	190 ⁵	3.98	30 ¹	0.847	3.98
PCP	0.05 ⁵	2.39	27100 ¹	0.930	3.67
lindane	0.00001 ⁶	3.72	7.2 ¹	0.635	4.68

¹Values given at 20° C.

²Hayduk and Laudie Correlation (20)

³Based on LeBas Volume (20)

⁴Gosset (21)

⁵Calculated from vapor pressure and solubility data

⁶Mackay and Leinonen (22)

employed in the QSS experiments is shown schematically in Figure 2. Experiments were conducted by allowing dissolved solutes to diffuse from the upper reservoir through the composite barrier into the lower reservoir. Traces of lower reservoir concentration verses time formed

the basis for the calculation of the magnitude of effective diffusion coefficients. Exact details of the experimental procedures and analyses are given elsewhere¹⁴. The device employed in the transient experiments and the arrangement of the apparatus are shown schematically in Figures 3 and 4, respectively. Experiments were conducted by allowing dissolved solutes to diffuse into the packed columns from the small reservoir located directly below the boundary between the aqueous solution and the column packing. The solute regeneration and recirculation system provided for a known concentration condition at the boundary. Diffusion coefficients were evaluated by matching experimental concentration profiles with those generated by simulation of the process using a time-linearized, implicit finite difference numerical approximation of Equation 4. Additional details of the experimental procedures and analyses are given elsewhere¹⁴.

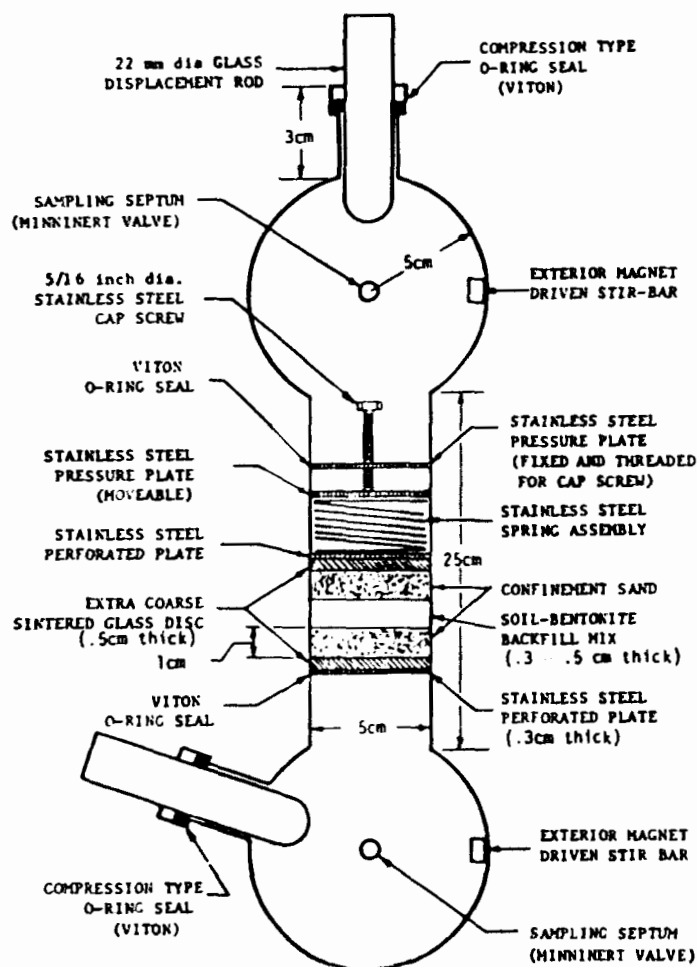


Figure 2
Modified Stokes Diaphragm Cell

Sorption Experiments

Sorption parameters were obtained through completely mixed batch reactor (CMBR) experiments of the tumbled bottle type. A minimum equilibration period of 7 days was used to insure that a functional sorption equilibrium was, in fact, attained. Soil-bentonite mixtures were introduced into the reactors in slurry form while fly ash was introduced in dry form and subsequently wetted. The sorbent mass and volume of aqueous solution were determined gravimetrically. Reactors were filled leaving no head space for experiments using volatile solutes. Aqueous samples were taken from the reactors after liquid/solid separation using appropriately sized syringes ranging in capacity from 10 μ L to 25 mL. Samples thus obtained were then either subjected to

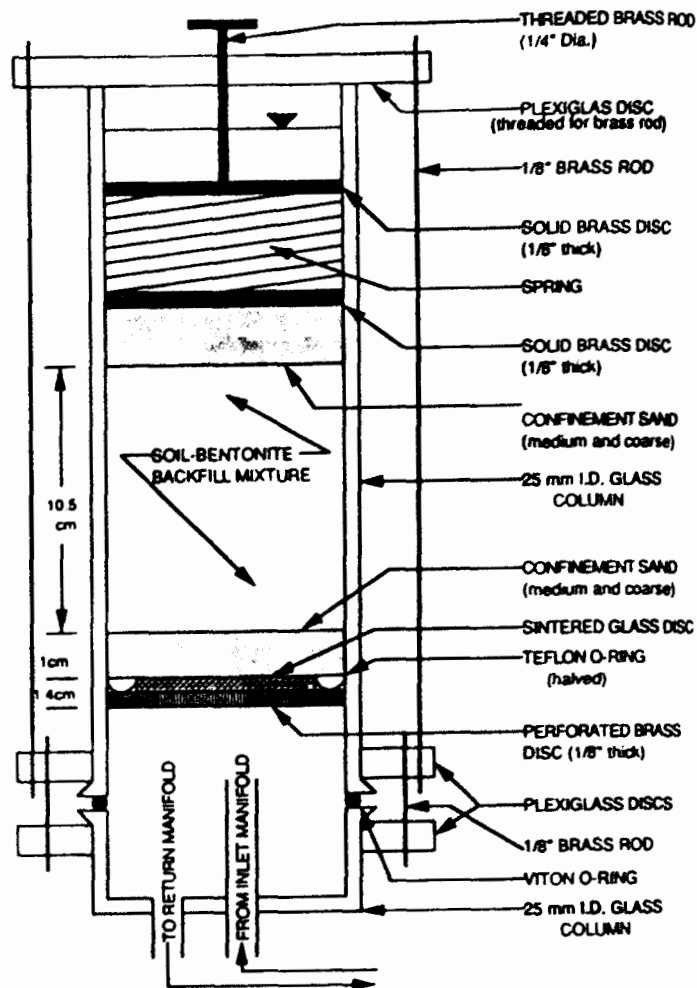


Figure 3
Transient Diffusion Column Schematic

liquid/liquid extraction of organics using hexane or stored as aqueous samples.

Analytical Methods

Aqueous concentrations of CTET, TCE, TTCE, DCB, TCB and lindane were assayed by gas chromatography with electron capture detection. Aqueous samples of PCP were assayed by high performance liquid chromatography using ultraviolet detection at 235 nanometers.

RESULTS AND DISCUSSION

Diffusion Experiments

The quasi-steady-state diffusion experiments were conducted using mixtures containing bentonite fractions of 0.02, consolidated at 7 psi ($\epsilon = 0.40$), and 0.04, consolidated to 4 and 10 psi ($\epsilon = 0.48$ and 0.43, respectively). Separation of the individual resistances of the confinement and soil-bentonite layers within the diaphragm cells proved impossible; thus, a residual minimization technique was used to determine the most probable value of the exponential coefficient (m) of e in Equation 2. The results of the quasi-steady-state experiments are given in Table 3.

Note that the values of H presented in Table 3 were calculated based on the most probable value of m determined from the diffusion experiments. The value of m appears to conform with that suggested by Equation 2. Additionally, it may be noted that the magnitude of D_i is reduced only three factors from D_i .

Transient diffusion experiments were conducted using lindane as a solute and a soil-bentonite mixture containing a bentonite fraction of 0.04 consolidated at 4 psi. Three columns, all containing identical mixtures, were sectioned at three transport times, which resulted in three distinct concentration profiles representative of the progress of

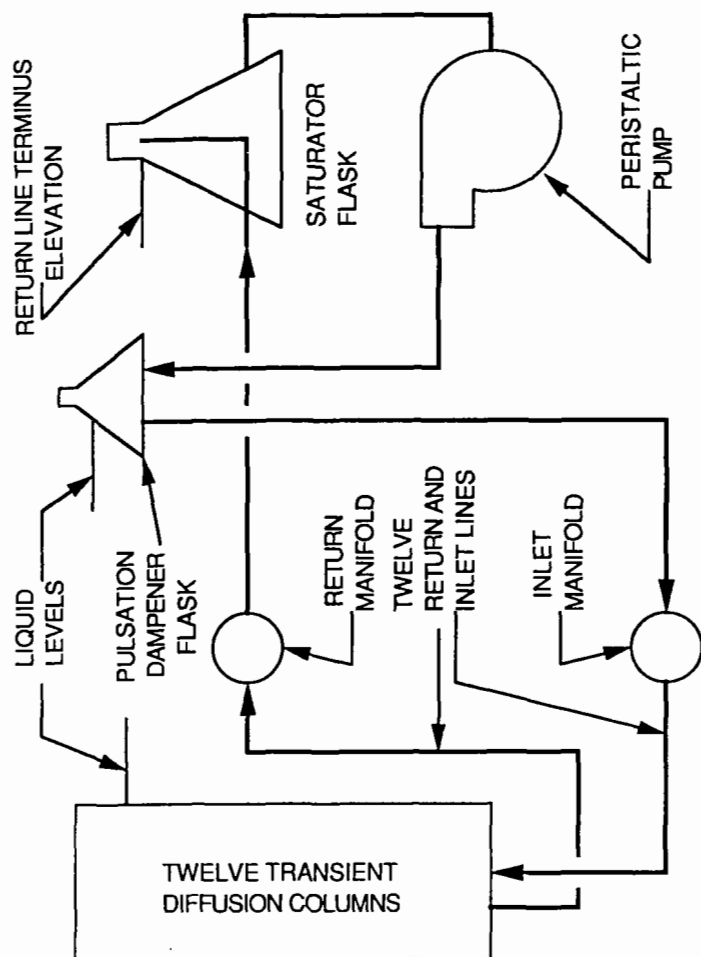


Figure 4
Transient Diffusion Column Experimental Arrangement

Table 3
Results of Quasi-Steady-State Diffusion Experiments

Solute	m	Hindrance Factor (H)		
		$\epsilon = 0.40$	$\epsilon = 0.43$	$\epsilon = 0.48$
DCB	1.31	3.32	3.02	2.62
PCP	1.46	3.81	3.43	2.92

the diffusion process at the three experimental times. The effective diffusion coefficients corresponding to the respective layers were calculated using Equation 2 and used in simulations of the diffusion process.

Lindane is known to undergo solvolysis in aqueous solution; thus, a first-order transformation coefficient (k_t) was determined experimentally and employed in the simulations. The sorption capacity of the background soil for lindane was determined and used in the simulations.

The experimental concentration profiles and two selected simulations are shown in Figures 5, 6 and 7. Note that only the portion within the soil-bentonite is shown. Extrusion of the column contents disturbed the confinement layers and, perhaps, the segments of the soil-bentonite that were situated near the confinement/soil-bentonite interface. Total solute penetration was used to ascertain the correctness of the diffusion coefficients. Effective diffusion coefficients determined from Equation 2 appear to successfully describe the diffusion process which occurred in these experiments.

Sorption Experiments

Karn, Trenton and Cobb fly ashes were tested in raw form for sorption of CTET, TCE, TTCE, DCB, TCB, PCP and lindane. Additionally,

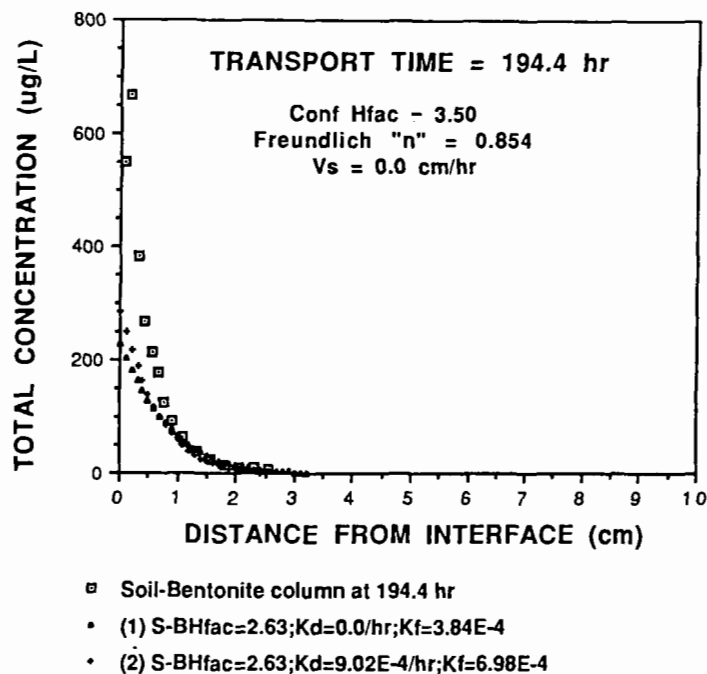


Figure 5
Transient Column Data and Simulations for Transport Parameter Evaluation

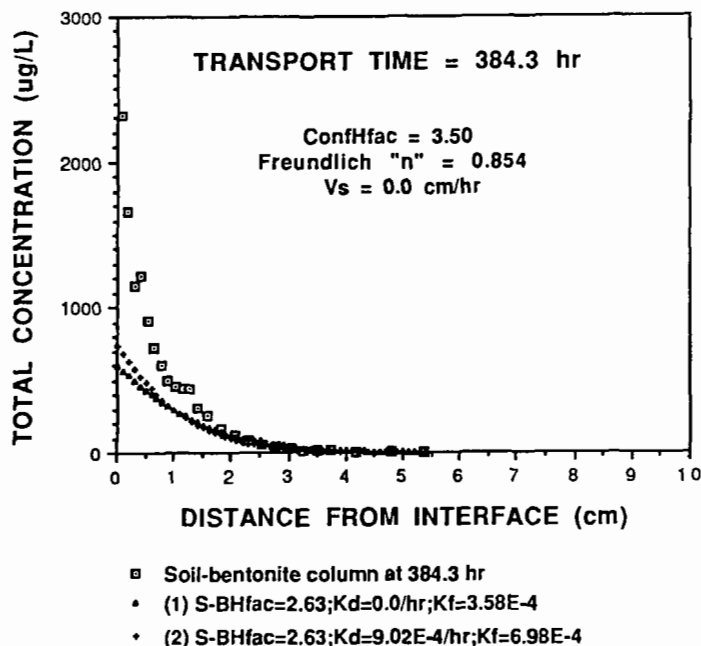


Figure 6
Transient Column Data and Simulations for Transport Parameter Evaluation

the fly ashes were tested for sorption of DCB after firing at 600°C. From these experiments it was concluded that the fraction lost upon ignition was responsible for the sorption capacity of the fly ash. Therefore, the K_F values are based on the carbon fraction of the fly ashes rather than total mass. The resulting parameters based on least squares fitting of sorption data to Equation 3 are listed in Table 4. The K_F data of Table 4 were plotted against octanol/water partition coefficient (K_{OW}) in Figure 8 and against aqueous solubility (S) in Figure 9. Because PCP sorption is not solvophobically driven, data for this solute are not included in Figures 8 and 9. The resulting regression equations and statistics are listed in Table 5. The correlations are highly significant, suggesting that physical relationships exist. Of particular

Figure 7
Transient Column Data and Simulations for
Transport Parameter Evaluation

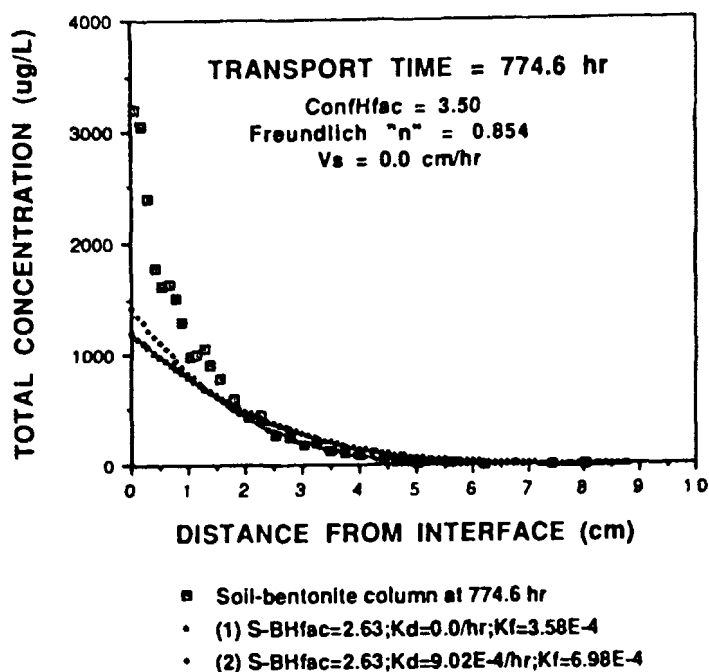


Table 4
Summary of Fly Ash Sorption Capacity (K_f)
and Intensity (n) Parameters

Solute	Fly Ash	K_f^1	95% C.I.	n	95% C.I.	CV^2
CTET	Karn	0.348	0.160-0.756	0.609	0.356-0.863	161
	Trenton	0.387	0.156-0.961	0.745	0.477-1.01	141
	Cobb	1.53	0.777-3.00	0.581	0.258-0.903	48
TCE	Karn	0.658	0.400-1.08	0.477	0.309-0.644	145
	Trenton	0.920	0.581-1.46	0.498	0.343-0.653	111
	Cobb	1.71	1.04-2.82	0.428	0.264-0.593	55
TTCE	Karn	1.37	0.808-2.33	0.466	0.204-0.729	27
	Trenton	2.39	1.70-3.36	0.320	0.142-0.499	12
	Cobb	4.88	3.09-7.69	0.428	0.170-0.685	18
DCB	Karn	4.02	2.82-5.72	0.322	0.181-0.463	20
	Trenton	4.71	3.82-5.80	0.267	0.174-0.361	14
	Cobb	6.20	3.39-11.4	0.386	0.172-0.600	40
TCB	Karn	8.66	6.67-11.2	0.256	0.134-0.378	18
	Trenton	5.85	4.35-7.87	0.360	0.211-0.508	32
	Cobb	14.0	9.07-21.6	0.305	0.180-0.430	42
PCP	Karn	2.95	2.01-4.33	0.267	0.131-0.404	14
	Trenton	3.10	2.43-3.96	0.211	0.121-0.302	8
	Cobb	8.09	6.13-10.7	0.149	0.049-0.250	3
Lindane	Karn	8.05	5.02-12.9	0.348	0.202-0.494	65
	Trenton	7.28	4.35-12.2	0.330	0.192-0.467	81
	Cobb	19.5	8.55-44.3	0.430	0.252-0.607	103

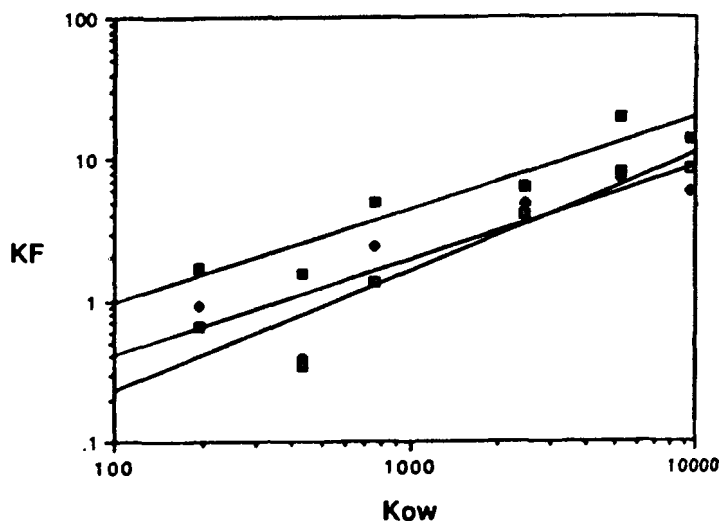
¹The values of K_f correspond to units of $\mu\text{g/L}$ and $\mu\text{g/g}$ for aqueous and solid phase concentrations, respectively.

²Coefficient of variation.

interest is the fact that the carbon associated with the respective fly ashes behaved differently with respect to its sorption capacity. The surface area associated with the fraction of the fly ash lost on ignition was determined from measurements of the surface area of both raw and fired fly ashes. The values were 6.3, 18 and 24 m^2/gr for Karn, Trenton and Cobb ashes, respectively. The pre-exponential coefficients shown in Table 5 are a measure of the base sorption capacity of the fly ash. This coefficient was divided by the surface area lost on ignition to obtain a measure of the specific surface sorptivity. Respective values based on the K_f - K_{ow} relationships for Karn, Trenton and Cobb ashes are 7.6×10^{-4} , 1.0×10^{-3} , and 2.0×10^{-3} . The value of the specific sorptivity increased dramatically from Karn to Cobb ash which suggests that the surface of the Cobb ash has a greater density of sorption sites, due to one or more of many potential factors which cannot presently be identified.

Table 5
Regression Data for K_f - K_{ow} and
 K_f -S Relationships

Fly ash	Regression Equation	R^2	t_{calc}	Significance
Karn	$K_f = 0.0048 K_{ow}^{0.837}$	0.94	5.51	1%
Trenton	$K_f = 0.0187 K_{ow}^{0.667}$	0.87	3.53	5%
Cobb	$K_f = 0.0468 K_{ow}^{0.651}$	0.94	5.51	1%
Karn + Trenton	$K_f = 0.0485 S^{0.521}$	0.90	4.13	1%
Cobb	$K_f = 0.1620 S^{0.474}$	0.98	9.80	0.05%



notes: 1) Parachlorophenol data is omitted from regressions
2) KF has units of $(\text{mg/g})/(\text{mg/L})^n$

Figure 8
Fly Ash Freundlich K_f vs. Octanol-Water Partition Coefficient

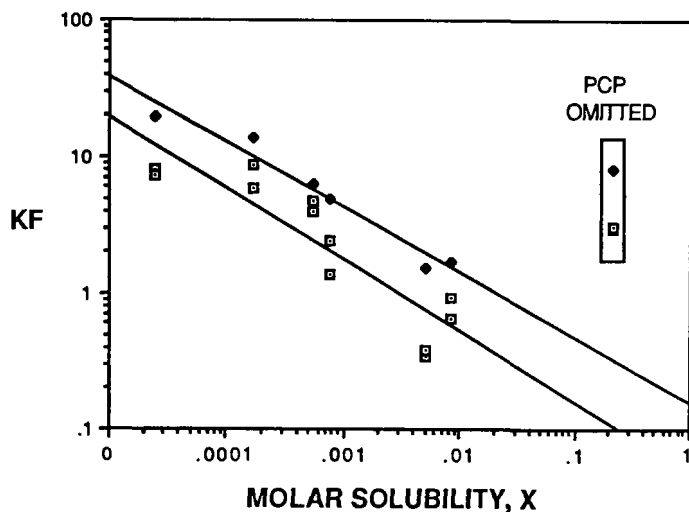
The sorption data discussed above were obtained for non-linear systems. Unfortunately, most other data taken for systems involving organic carbon associated with natural soils and sediments apply to the very low concentration range where partitioning relationships are functionally linear. To compare the sorptivity of fly ash carbon and naturally occurring organic carbon, a partition coefficient (K_c) was defined as:

$$K_c = K_f C_s / C_s \quad (9)$$

The value of C_s chosen was 100 $\mu\text{g/L}$ and the resulting estimated values of K_c were regressed on a log-log basis against both K_{ow} and aqueous solubility in millimoles per liter (X). The results of these regressions based on K_c are compared in Table 6 with representative regressions from the literature that are based on K_{oc} . Upon comparison of the correlations presented in Table 6, the conclusion may be drawn that the sorption capacity of the carbon associated with the fly ashes examined by this investigation is at least as great as that of naturally occurring organic carbon.

Diffusion-Sorption Experiments

Three transient diffusion columns were packed with a soil-bentonite mixture containing 0.31% Cobb fly ash. The experimental concentration profiles were simulated using transport and sorption parameters derived above. It was assumed for the simulations that the LEA applied within



■ KARN & TRENTON ASHES

$$KF = 0.0485 \cdot X^{-0.521}; R^2 = 0.81$$

● COBB ASH

$$KF = 0.162 \cdot X^{-0.474}; R^2 = 0.96$$

Figure 9
The Relationship Between the Freundlich K_F
and Solute Solubility for Sorption by Fly Ash

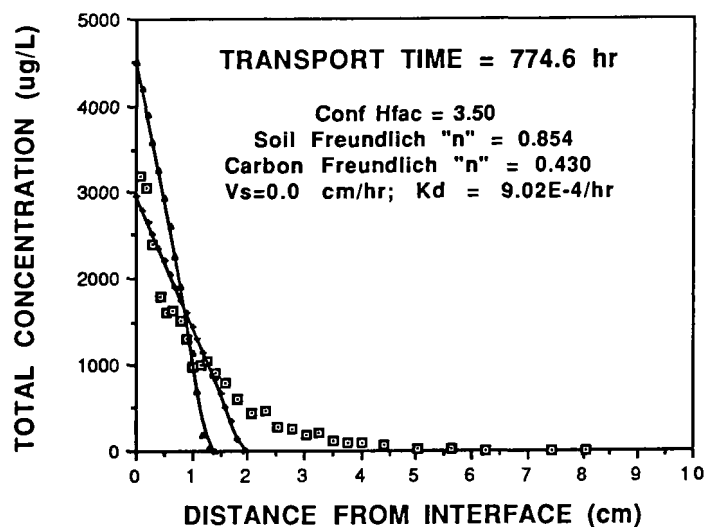
Table 6
Regression of K_C on K_{OW}
and K_C on x

Sorbent	Regression Equation	Rr	Significance
Karn and Trenton ash	$\log K_C = \log K_{OW} + 1.17$	0.84	1%
Cobb ash	$\log K_C = \log K_{OW} + 2.15$	0.90	1%
Natural Sediments (23)	$\log K_{OC} = \log K_{OW} - 0.21$		
Karn and Trenton ash	$\log K_C = 5.65 - 0.451 \log x$	0.87	1%
Cobb ash	$\log K_C = 5.81 - 0.441 \log x$	0.94	1%
Natural Sediments (24)	$\log K_{OC} = 4.28 - 0.561 \log x$		

the columns. The concentration profiles from the experiment and simulations for one experimental time are shown in Figure 10. It may easily be noted that the simulation fails miserably in describing the experimental behavior. Based on the effective diameter of the spherical fly ash particles, N_p was calculated for the system and found to be 0.04, well removed from the value of 100 suggested as appropriate for application of the LEA. The value of N_p for a soil-bentonite mixture containing 40% fly ash was calculated to be approximately 4.0, which also is well removed from the acceptable value of 100. The conclusion may be drawn that successful modeling of solute transport in soil-bentonite barriers that are modified by the addition of high-carbon fly ash must employ non-equilibrium as well as non-linearity in the sorption term.

Simulations of the Performance of Soil-Bentonite Barriers

Two extreme conditions envelope the realm of potential conditions within a soil-bentonite barrier: (1) no sorption capacity; and (2) sorption that may be described by the LEA. Simulations were performed for these two conditions and were based on a hypothetical barrier of thickness equal to 3.3 ft, containing 10 ac and extending 50 ft below an unconfined water table. The target solute considered was CTET and the effective diffusion coefficient was calculated from Equation 2. The barrier was considered planar in geometry and infinite in areal extent. The interior concentration (C_o) was considered constant at 1 mg/L and



■ 0.309% Cobb Fly Ash Column at 774.6 hr

$$\bullet (3) S-BHfac=2.63; Kfs=3.58E-4; Kfc=19.47$$

$$\bullet (4) S-BHfac=2.63; Kfs=3.58E-4; Kfc=9.84$$

Figure 10
Transient Column Data and Simulations for 0.309%
Cobb Fly Ash Experiments

the exterior concentration was considered to be zero. The analytic solution for the solute flux at the exterior face of the barrier which was adapted for the applicable form of Equation 4 and stated boundary conditions is²⁵:

$$F_{iz} = \frac{D_{e,i} C_{0,i}}{T_B} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left(- \frac{D_{e,i} n^2 \pi^2 t}{\epsilon T_B^2} \right) \right] \quad (10)$$

where T_B is the barrier thickness (3.3 ft) and all other terms are as previously defined. The total solute migration (Q_i) through the barrier is simply the integral over time of the flux:

$$Q_i = \int_0^t F_{iz} dt \approx \sum_{i=1}^t F_{iz} \Delta t \quad (11)$$

In the case that the barrier was non-sorbing, D_e was obtained directly from equation 2. For the condition of a barrier with sorption capacity, the LEA was invoked, the partitioning relationship was assumed linear, a retardation factor (R) was defined and the quotient D_e/R was substituted for D_e in Equation 10. The partition coefficient chosen corresponded to that for a mixture containing 40% Cobb fly ash and was calculated using Equation 9.

Plots of F_{iz} versus time for the two limiting cases considered are shown in Figure 11 and plots of Q_i versus time for the two limiting cases are shown in Figure 12. For the case of no sorption capacity, breakthrough is predicted to occur within 2 yr and near-steady-state flux rates are predicted to obtain within 12 yr. Conversely, for the case of barrier modification by fly ash, solute breakthrough is predicted to occur in approximately 30 yr and near-steady-state flux rates are predicted to obtain within approximately 220 yr.

The solute migration rates shown in Figure 12 are based on an aqueous concentration of 1 mg/L within the barrier. To obtain an estimate of total solute escape, these values must be multiplied by the true interior concentration and the exterior area of the barrier (10^8 cm^2). Given that the solubility of CTET is 785 mg/L, the ultimate steady-state solute migration rate through the hypothetical barrier could approach 85 kg/yr. For the case of no sorption capacity, the total solute escape during the

first 12 yr could approach 600 kg. From these simulations it may be concluded that diffusive transport can be quite significant and that the addition of fly ash to soil-bentonite barriers can significantly improve performance.

The true behavior of a barrier will fall between the two extreme cases considered here; thus, for proper evaluation of mitigative strategies, it is imperative that methods be developed to more accurately predict solute transport in these barriers. Moreover, if soil-bentonite barriers are to be viable alternatives for mitigation of subsurface contamination, means of reducing the magnitude of effective diffusion coefficients should be sought.

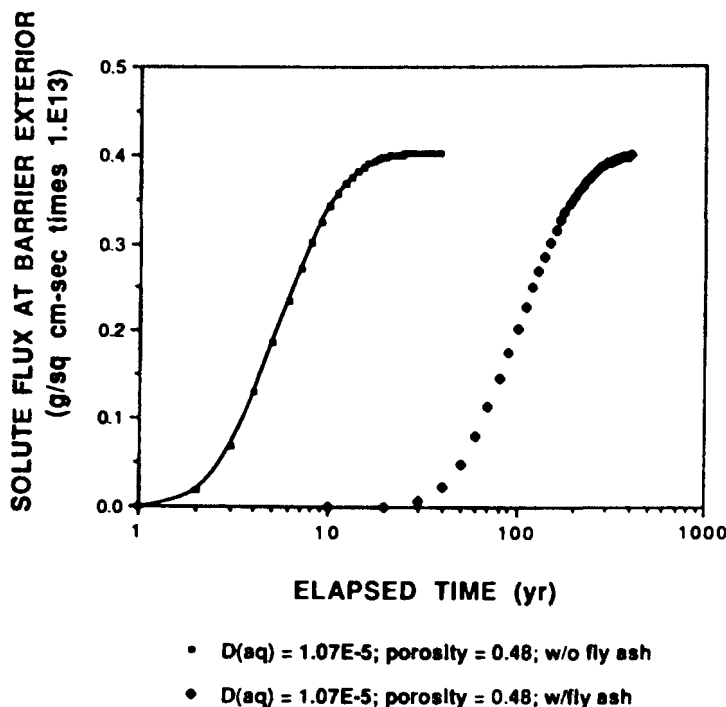


Figure 11
Model Simulations of Solute Flux from a Hypothetical Soil-Bentonite Containment Barrier

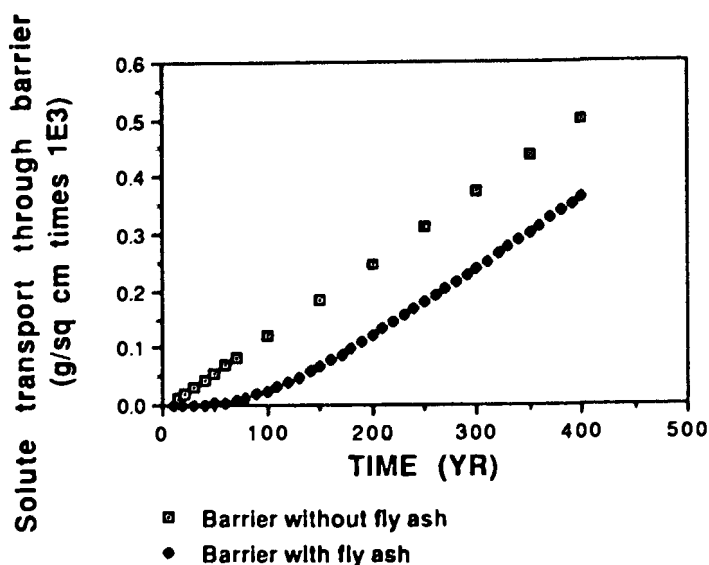


Figure 12
Simulations of Solute Escape from a Hypothetical Soil-Bentonite Barrier

CONCLUSIONS

The results of both quasi-steady-state and transient diffusion experiments suggest that effective diffusion coefficients for low-molecular-weight solutes in soil-bentonite barriers are reduced only several factors from those in free aqueous solution. Effective and free aqueous diffusion coefficients appear to be related through a power function of porosity.

The capacity of carbon associated with fly ash for sorption of representative low-molecular-weight solutes was found to be at least equivalent to that of naturally occurring organic carbon. The Freundlich sorption capacity factor, K_p , was found to correlate well on a log-log basis with both the octanol/water partition coefficient and aqueous solubility.

Simulations based on a hypothetical barrier and performed for two limiting cases suggest that solute migration through soil-bentonite barriers by molecular diffusion can be significant, and that the addition of a sorbent phase such as fly ash to soil-bentonite mixtures can markedly improve the performance of such barriers.

ACKNOWLEDGEMENTS

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REFERENCES

1. D'Appolonia, D.J., "Soil-Bentonite Slurry Trench Cutoffs," *ASCE Jour. Geo-technical Engr.*, 106(GT4), 1980.
2. Schulze, D., Barvenik, M. and Ayres J., "Design of Soil-Bentonite Backfill Mix for the First Environmental Protection Agency Superfund Cutoff Wall," from The Proceedings of the Fourth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring, Columbus, OH, May, 1984.
3. Jepson, C.P., "Sodium Bentonite: Still a Viable Solution for Hazardous Waste Containment," *Pollut. Eng.*, Apr., 1984.
4. White, L.A., Dasgupta, A. and Coia, M.F., "Containment of Uncontrolled Hazardous Waste Sites," *Jour. Haz. Mat.*, 14, 1987.
5. Goodall, D.C. and Quigley, R.M., "Pollutant Migration from Two Sanitary Landfill Sites Near Sarnia, Ontario," *Can. Geotech. J.*, 14, 1977.
6. Johnson, R.L., Cherry, J.A. and Pankow, J.F., "Diffusive Contaminant Transport in Natural Clay: A Field Example and Implications for Clay-Lined Waste Disposal Sites," *Environ. Sci. Technol.*, 23, 1989.
7. Gray, D.H. and Weber, W.J., Jr., "Diffusional Transport of Hazardous Waste Leachate Across Clay Barriers," Presented at the Seventh Annual Madison Waste Conference, University of Wisconsin-Extension, Madison, WI, Sept., 1984.
8. Millington, R.J., "Gas Diffusion in Porous Media," *Science*, 130, July, 1959.
9. Millington, R.J. and Quirk, J.P., "Permeability of Porous Solids," *Faraday Trans. of the Chem. Soc.*, 57, 1961.
10. Kimura, M., Ueda, K. and Ofuka, T., "Effective Diffusivity of Packed Bed," *A.I.Ch.E.J.*, 5(2), 1959.
11. Shearer, R.C., Letey, J., Farmer, W.J. and Klute, A., "Lindane Diffusion in Soil," *Soil Sci. Soc. Am. Proc.*, 37, 1973.
12. Farmer, W.J., Yang, M.S., Letey, J. and Spencer, W.F., "Hexachlorobenzene: Its Vapor Pressure and Vapor Phase Diffusion in Soils," *Soil Sci. Soc. Am. J.*, 44, 1980.
13. Gillham, R.W., Robin, M.J.L. and Dytynshyn, D.J., "Diffusion of Nonreactive and Reactive Solutes Through Fine-Grained Barrier Materials," *Can. Geotech. J.*, 21, 1984, p. 541-550.
14. Mott, H.V., "Diffusive Transport of Low-Molecular-Weight Organic Solutes through Soil-Bentonite Containment Barriers," Ph.D. Thesis, The University of Michigan, Ann Arbor, MI, 1989.
15. Bennett, C.O. and Myers, J.E., *Momentum, Heat and Mass Transfer*, 3rd ed., McGraw-Hill, 1982.
16. Cussler, E.L., *Diffusion: Mass Transfer in Fluid Systems*, Cambridge University Press, 1984.
17. Jennings, A.A. and Kirkner, D.J., "Instantaneous Equilibrium Approximation Analysis," *ASCE J. Hydraulic Eng.*, 110(12), 1984.
18. Bahr, J.M. and Rubin, J., "Direct Comparison of Kinetic and Local Equilibrium Formulations for Solute Transport Affected by Surface Reactions," *Water Resources Res.*, 23(3), 1987.
19. Bergstrom, W.R. and Gray, D.H., "Fly Ash Utilization in Cut-Off Walls: A Progress Report to Consumers Power Company," The University of

- Michigan, Department of Civil Engineering, Ann Arbor, MI, August, 1987.
20. Lyman, W.J., Reehl, W.F. and Rosenblatt, D.H., *Handbook of Chemical Property Estimation Methods*, McGraw-Hill, New York, NY, 1982.
 21. Gossett, J.M., "Measurement of Henry's Law Constants for C_1 and C_2 Chlorinated Hydrocarbons," *Environ. Sci. Tech.*, 21(2), 1987.
 22. MacKay, D. and Leinonen, P.J., "Rate of Evaporation of Low-Solubility Contaminants from Water Bodies to Atmosphere," *Env. Sci. Tech.*, note, 9(13), Dec., 1975.
 23. Karickhoff, S.W., Brown, D.S. and Scott, T.A., "Sorption of Hydrophobic Pollutants on Natural Sediments," *Water Res.*, 13, 1979.
 24. Chiou, C.T., Peters, L.J. and Freed, V.H., "A Physical Concept of Soil-Water Equilibria for Non-ionic Organic Compounds," *Science*, 206, Nov., 1979.
 25. Crank, J., *The Mathematics of Diffusion*, Second Edition, Clarendon Press, Oxford, 1975.

Use of Synthetic Liners in Recent Superfund Cleanup Projects

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ABSTRACT

Many NPL sites for which the Superfund is responsible are finally being cleaned up after several years of engineering studies. Contaminants at a large number of these sites are being contained with the help of flexible membrane liners functioning as barriers to waste migration.

A number of different liner systems are used in the containment process. The current concept in liner system design can be summarized as incorporating redundant layers of liner and using composite liners which takes advantage of the synergism between materials with different mechanisms of barrier activity. Provisions also are made for fluid drainage both above and between liners.

INTRODUCTION

The Superfund program has taken a first step toward addressing one of the most perplexing environmental challenges of all time, hazardous waste and its uncontrolled storage/burial. Future waste disposal will be very expensive and billions of dollars currently are being set aside to rectify past problems. Since we did not pay to properly dispose of the waste in prior years.

But what are proper waste disposal techniques? Many people talk about waste recycling or incineration as though they are the panacea to the problem. Yet neither process is a complete answer to the hazardous waste problem. There still remains non-reusable waste and ash that are often more hazardous than before treatment. Deep well injection, another viable disposal technique, also has limited application. The simple truth is that disposal and containment of waste products on and below the earth's surface must continue for lack of better alternatives.

Since surface containment of waste is necessary, the wisest approach is to provide the best possible barrier for waste containment. If money is spent on appropriate barriers to prevent waste migration, savings will result because future cleanup operations will not become necessary. Also, if costs are increased for traditional surface containment because of better barrier construction, desirable alternatives such as recycling become more cost competitive. An incentive is therefore provided to recycle waste and/or limit waste production. Liners are often used as barriers to containment transport. Examples of liner systems are shown in Figure 1.

LINER TECHNOLOGY

With the advent of copolymer, pipe-grade HDPE technology, synthetic liners in current landfill technology have achieved strength, toughness, durability, chemical resistance and environmental stress crack resistance. The desirable qualities of HDPE as a barrier material can be seen from its increasing applications in the container market. Much growth is expected for HDPE containers of agricultural chemicals, insecticides, herbicides, paint thinners and household chemicals as well as other

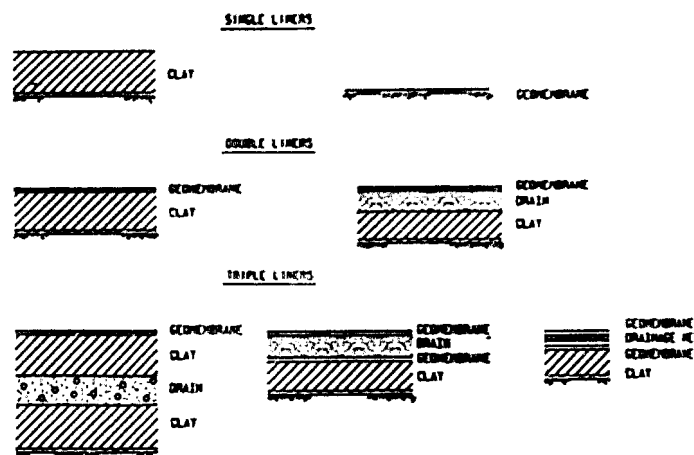


Figure 1
Liner Systems Available

chemical products². HDPE is expected to replace more and more traditional metal and glass containers in the market place. High molecular weight HDPE is also used to contain low level radioactive waste.

A composite liner, formed by a synthetic liner such as HDPE in contact with a clay liner, offers the greatest degree of impermeability. This good performance occurs because the permeability of the synthetic liner is very low and containment transport occurs only by diffusion. Unlike convection, diffusion is driven by a concentration gradient instead of a pressure gradient. The absorptivity and porosity of a clay liner directly underneath a synthetic liner means that the chemical concentration gradient is reduced across the synthetic liner since diffused chemical species accumulate in the clay pores at the clay/synthetic interface. With chemical concentrations approximately the same on both sides of the synthetic liner, the driving force for diffusion is eliminated.

A synthetic/clay liner works well because the synthetic liner is a barrier to pressure-driven mass transfer, while the underlying clay liner forms a barrier to concentration-driven mass transfer. The combination liner comprised of a synthetic liner, drainage layer, synthetic liner and clay, is the liner system required for hazardous waste containment under Subtitle C of the Hazardous and Solid Waste Amendments to the RCRA.

The drainage layer in the landfill can be either conventional sand or gravel, or drainage netting. Drainage netting is a net-shaped material made by overlapping high density polyethylene strands to conduct fluids in the plane of the net. Drainage netting generally has a hundred times more flow capacity than sand or gravel drainage layers.

SUPERFUND CLEANUP STRATEGY

Every Superfund site requires its own special considerations before a cleanup strategy can be mapped out. The goal, however, in every case is to prevent the toxic waste at the site from causing an ecological or human health problems.

Current barrier technology can offer a number of practical approaches to site cleanup. These procedures generally can be classified into the following groups:

- Removal of the contaminated material off-site for containment in a RCRA-approved hazardous waste facility or treatment/cleansing of polluted soils.
- Construction of a RCRA landfill at or adjacent to the site for transfer and proper containment of the polluted soil
- On-site containment of the waste by construction of an impermeable cap and barrier wall to prevent infiltration of surface water/precipitation and the spreading of contamination to the surrounding groundwater

Removal of contaminated material to a hazardous waste facility means the construction of increased capacity at RCRA-approved disposal sites. This option requires the transportation of hazardous waste.

Proper construction of a landfill at or adjacent to the Superfund site would also demand the double liner technology required under RCRA. All the considerations appropriate to hazardous waste facility construction centered around the installation of two layers of synthetic liner would apply.

The construction of caps and barrier walls for on-site containment of Superfund waste will likely be a frequent strategy in cleanup work. The use of synthetic liners for cap construction has been proven effective. Barrier walls are primarily constructed with bentonite slurry.

With SARA setting timetables for cleanup activity at NPL sites, money will be spent for actual cleanup rather than for just paper studies. In the past, the major share of the Superfund money has gone to study the problems rather than clean them up. One exception and an early, now classic Superfund project, is the work at Nashua, New Hampshire.

PUMP-AND-TREAT FLUSHING WITH SYNTHETIC LINERS

Superfund cleanup work at Nashua, New Hampshire, utilized the construction of a cap and barrier wall to meet a fast-moving plume of groundwater contaminated with illegally dumped organic solvents including chlorinated hydrocarbons. The contaminant plume was moving at a rate of approximately 2 ft/day when work began in 1982. The 20-ac synthetic cap was constructed with an HDPE geomembrane liner. The barrier cut-off wall was made from a bentonite slurry; it extended down to bedrock and ringed the site in an oval shape (Fig. 2).

Because of fractures in the bedrock and because of evidence that the organic chemicals in the aquifer would tend to degrade the bentonite by altering the mineral composition of the clay, groundwater interception and treatment was implemented through the use of pumps. Contaminated water is thus being pumped out of the containment area, treated and re-injected so as to flush out remaining contaminants. This innovative and economical Superfund project at Nashua, New Hampshire, likely is indicative of the approach to be used at many sites in the future, i.e., cap and barrier wall construction with pumping of contaminated water to lower the water table within the containment and remove pollutants.

Construction of caps for other Superfund cleanup projects could utilize other geosynthetic materials such as a drainage netting for drainage of surface precipitation above the impermeable geomembrane layer as well as geotextile for separation of cover soil from the fluid flow zones.

Similar pump-and-treat techniques are now available using air as the mobile phase to extract up organic contaminants from soils. Synthetic liner caps are important in such cases to intercept rain water and prevent further movement of the contaminants into and through the groundwater. With a synthetic liner impermeable to the contaminated air being flushed out, funneling, collection and treatment of the air is facilitated.

CAP APPLICATIONS AT SUPERFUND SITES

Four very recent Superfund projects have utilized synthetic liners for

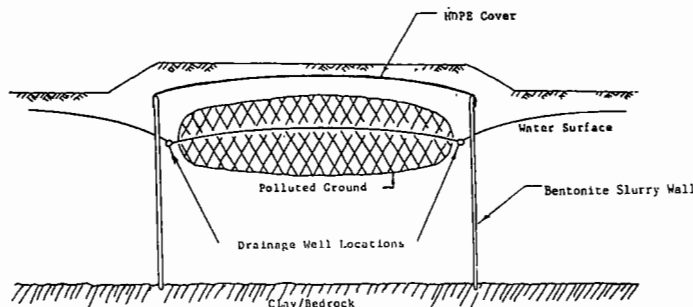


Figure 2
Schematic of Cap and Barrier Wall On-Site Containment System
For Superfund Project

cleanup purposes. They include Pine Bluff Arsenal, Pine Bluff, Arkansas (2.6 million ft² of 40-mil and 80-mil HDPE); Lackawanna Landfill, Old Forge, Pennsylvania (1.3 million ft² of 60-mil HDPE); Charlie George Landfill Cap, Tynsborough, Massachusetts (2.8 million ft² of 60-mil HDPE); and Helleva Landfill Cap, LeHigh County, Pennsylvania (1.8 million ft² of 60-mil HDPE).

Special situations at Pine Bluff Arsenal included the presence of dangerous chemical weapons and the containment of 13 separate sites - two hazardous waste landfills, nine landfill caps and two surface impoundments. Several of the sites used some rather recent geosynthetic product developments such as specially textured sheets for extra slope stability and synthetic drainage netting for fluid flows in the liner system.

OSHA levels B, C and D protection were required for the crews at the various project sites. Installation crews were, in some cases, required to have OSHA training before working around the hazardous waste. Cooperation with unions was necessary at both Charlie George and Helleva Landfills.

LINER INSTALLATION

In all of these Superfund projects, when liner construction began the cell earthworks were already prepared and graded. A front-end loader was used to deploy the HDPE, which was manufactured by Gundle Lining Systems, Houston, Texas, in 22.5-ft. wide seamless rolls, each weighing about 2,800 lb. All field seams were welded by Gundle employees using the company's patented extrusion welding machine with mixing tips to improve heat transfer, or the Gundle automatic dual hot wedge welder. All of the seamed footage was either vacuum tested for voids or air pressure tested in the case of the hot wedge welds. Vacuum testing uses a plexiglass faced, rectangular box placed over a section of the seam. A 5 psi vacuum is pulled on the box. Any voids in the seam will form bubbles in the soap solution sprayed onto the seam before the box is set in place (Fig. 3).

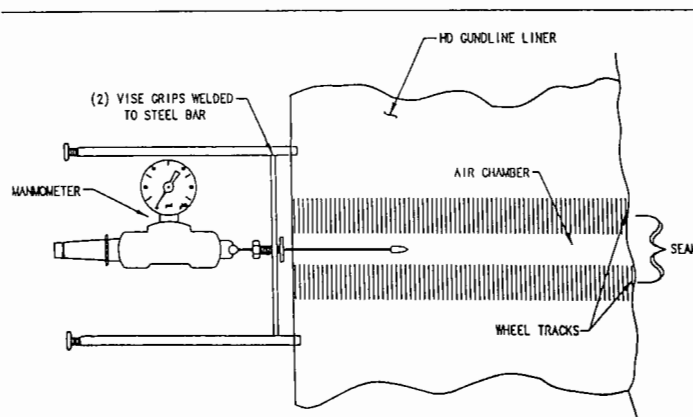


Figure 3
Seam Air Pressure Test

In the case of the hot wedge welding, several advantages of the seaming method should be noted. The Gundle hot wedge welder automatically feeds the sheet across the hot wedge and through the pressure rollers. The welder also automatically positions the wedge accurately at the edge of the top sheet and automatically adjusts the roller gap to accommodate different sheet thicknesses. These features of the hot wedge enable it to achieve welding speeds of up to 15 ft/min.

With the dual hot wedge welder, non-destructive testing is made more efficient because of air pressure testing of the "split" or "dual" wedge of the system. The dual wedge system leaves a gap between two separate wedge weld tracks. In the air pressure test, the gap is pressurized to about 30 psi and possible leaks are noted by the reduction in pressure over 5 min.

Buffing of the sheet is not necessary with the hot wedge, unlike extrusion techniques. This, along with the increased welding rates, makes the hot wedge welder very cost-effective for high quality construction of liner systems in waste containment.

In addition to the non-destructive testing, samples for destructive seam testing were cut from the field seams at regular intervals. The samples were tested for both shear and peel on a tensiometer. In shear testing, one applies a tensile stress across the weld from the top through the

bottom sheet. Peel testing peels the top sheet back against the overlapped section of the bottom sheet to observe how the weld is coming apart. If the weld tears (called a "film tear"), then the weld has formed a homogeneous connection through the seam. This is the desired result. If not, the test signifies a defective seam and it must be repaired.

CONCLUSION

The suitability of high quality geomembranes as barriers in the containment of hazardous waste has been, and is continuing to be, demonstrated on a very wide scale. The adaptability of the products and construction techniques to many different situations is continuing to prove their usefulness and is extending their application to the highly important work of the Superfund.

REFERENCES

1. U. S. EPA, *Minimum Technology Guidance of Double Liner Systems for Landfills and Surface Impoundments—Design, Construction and Operation*, U.S. EPA, Washington, DC, 1985.
2. Leaversuch, R., "HDPE: Resin of Choice for Barrier Functions," *Modern Plastics*, pp. 68-71, May, 1986.

Some Observations of the Influence of Deformation On a Clay Liner

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ABSTRACT

Centrifuge model tests have been performed to study the response of clay barriers subjected to differential deformations. The modes of deformation that have been observed are relevant to those that might occur as the result of differential settlements of waste material—leading to deformation of cover liners—or from non-uniform soil strength profiles or deep sited subsidence—leading to deformations of base liners.

Plane model liners were constructed both from pure kaolin and from a mixture of sand, silica flour and bentonite. The integrity and performance of these model liners was evaluated on the centrifuge at a force of 50 gravities. Physical degradation of the model liners was monitored photographically and their performance as effective hydraulic barriers was assessed throughout the deformation process.

For all the model liners where no overburden was present, tension cracking of the liner surfaces was observed. These tension cracks were very significant in the kaolin models and led to a drastic reduction in liner performance. However, the presence of an overburden suppressed the formation of tension cracks, and no significant reduction in the kaolin liner efficiency was observed.

The sand/silica flour/bentonite liner material proved to be highly resistant to deformation with little evidence of tension cracking and no significant reduction in performance.

INTRODUCTION

Solid waste disposal in shallow landfill depositories has been extensively employed for the permanent disposal of both municipal and industrial wastes. However, this practice has generated much concern over the possibility of environmental contamination. The principal concern is the potential for groundwater contamination resulting from the permeation of leachate out of the landfill. Such leachates are likely to contain concentrations of chemical and biological pollutants produced by the decomposition of the contained wastes. A typical engineered landfill depository is shown schematically in Figure 1a.

The key element to the successful operation of such a landfill is the presence of a hydraulic barrier surrounding the waste material. A further reduction in the possibility of groundwater contamination can be achieved by minimizing the potential for a buildup of leachate within the deposit. This added protection requires the temporary covering of the landfill during filling followed by placement of a permanent cover once filling is complete and an acceptable degree of waste stabilization has occurred. Both the base and cover liner systems commonly are fabricated from compacted clay—usually a few per cent wet of optimum proctor compaction.

However, such compacted clay liners may fail to perform satisfactorily for several reasons. For example, cover liners are susceptible to climatic effects such as dessication cracking¹ and frost action², as well

as deformations of the liner itself³, (Fig. 1b), caused by differential settlements of the contained wastes.

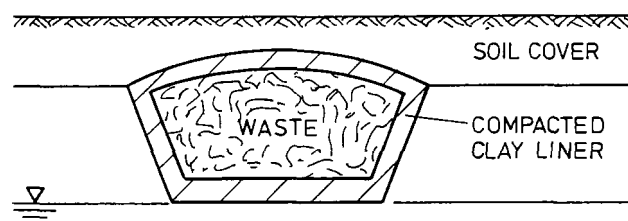


Figure 1a
Schematic Representation Of A Landfill Facility

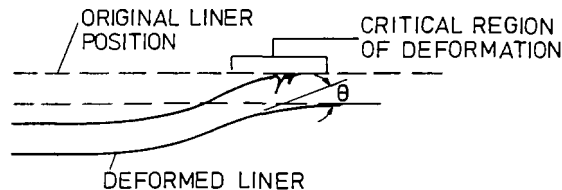


Figure 1b
Illustration Of Liner Deformation Mode.

Similarly, base liners are prone to chemical attack from the contaminated leachate, as well as to differential liner settlements resulting from non-uniform soil strengths below the landfill⁴ or from near surface ground movements associated with deep sited substances.

The tests reported in this paper are concerned with the effect of differential settlements on the performance and integrity of clay liners. Previous studies⁵ where part of an underlying basement has been displayed to introduce a discontinuity of slope, but not of displacement, have shown that such continuous boundary deformations can lead to the formation of discontinuities or ruptures in the overlying soil. It is of interest, therefore, to study the response of clay liners subjected to such boundary deformations and to investigate the parameters which influence the stress dependent liner response. In particular, the evaluation and comparison of pure clay and fine/coarse mixture sand/clay liner materials has been investigated, and their performance as effective hydraulic barriers throughout the deformation process has been assessed.

CENTRIFUGE MODEL TESTS

Introduction To Centrifuge Model Testing

It is well known that the behavior of most soils is very dependent on stress level. In conventional small scale model tests performed in the earth's gravitational field, it is not always possible to maintain similarity

with prototype situations and to ensure that stress levels in areas of interest reach prototype values. A geotechnical centrifuge can subject small models to centripetal accelerations many times the earth's gravitational acceleration. By selecting a suitable acceleration level, the unit weight of the soil being tested can be increased by the same proportion by which the model dimensions have been reduced, and thus stresses at corresponding points in the model and prototype will be the same.

The centrifuge model tests reported here were performed on the Bochum 10 m balanced beam centrifuge at an enhanced acceleration level of 50 gravities. Details of the Bochum Geotechnical Centrifuge can be found elsewhere⁶.

Scaling Relationships

Centrifuge scaling relationships have been extensively described elsewhere⁷. However, if we consider a model where the prototype dimensions have been reduced "n" times such that $d_p/d_m = n$, where d_p and d_m are prototype and model dimensions respectively, and if 'n' is chosen as the gravity scaling factor, then the Table 1 illustrates the basic scaling relationships associated with centrifuge modeling.

Table 1
Centrifuge Scaling Relationships

Parameter	Units	Scaling Relationship
Gravity	m/s ²	n
Length	m	1/n
Stress	P _a	1
Strain	%	1
Force	N	1/n ²
Time*	sec	1/n ²

Note: These relationships apply to laminar flow processes such as consolidation.

If the same material is used in both the model and prototype, then the similarity of stress levels at corresponding points in the model and prototype will result in a model response directly analogous to that of the prototype. Furthermore, the prototype stress gradient present in the model will ensure similarity of the primary permeability distribution⁷.

Centrifuge Model Package

The centrifuge model tests were performed in a rectangular strong box of internal dimensions 395 mm wide x 658 mm long x 395 mm high. The front of the strong box is formed by a 70-mm thick Perspex window through which deformations of the model can be photographically observed while the model is "in-flight" on the centrifuge.

The model test package is shown schematically in Figure 2. In order to generate a displacement profile at the base of the model liner, a rectangular piston is centrally located in the floor of the strong box. This piston extends the full width of the strong box and has a maximum throw of 25 mm. A flange base containing a pair of 95-mm hinged flaps is located across the strong box and so arranged that when the piston is lowered, the flaps rotate and induce a discontinuity of slope at the base of the overlying soil—as represented by the dashed line in Figure 2. Linear variable displacement transducers (LVDTs) are used to monitor water levels and liner deformation.

To minimize the possibility of leakage between the liner and the strong box sides, the overlying water is contained within a shallow trench—

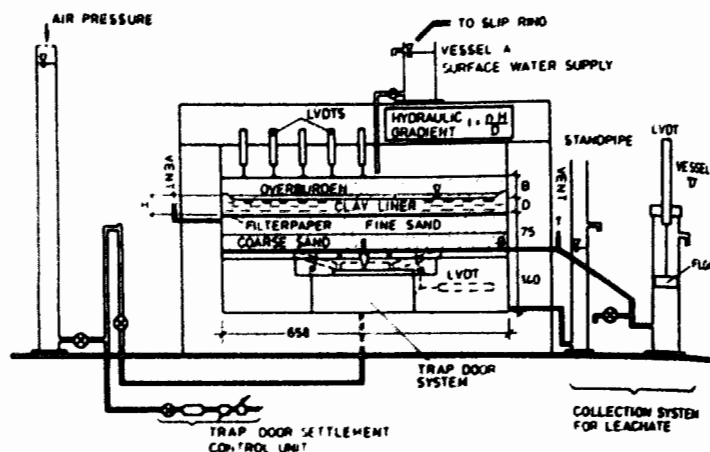


Figure 2
Schematic Illustration Of Centrifuge Model Test Package

model landfill—as illustrated in Figure 4a. The depth of surface water present is monitored by a LVDT and float and can be increased by releasing water from vessel A. The water table below the liner is maintained at the pre-set level of outlet B. The overflow from this outlet B is collected into the cylindrical vessel D. Consequently, by monitoring the rise of the water level in D, the rate of water flow through the liner can be deduced and hence the permeability can be estimated.

MODEL PREPARATION PROCEDURE

Choice Of Liner Materials

Two different liner materials were chosen. The first was a commercially available kaolin clay (2096c kaolin) supplied by Erbsloh & Co., W. Germany. This clay has a liquid limit of 44.4% and a plastic limit of 28.1%. There is much debate as to the optimum design water content that should be used for compacted clay liners, but for the purposes of this experimental study, a moisture content corresponding to 95% saturated Proctor density was adopted.

The second liner material was a sand/silica flour/bentonite mixture (hereafter referred to as the fine/coarse liner material) of the following proportions (Table 2).

Table 2
Composite Model Liner Mixture

Material	Particle size (approx.)	Percentage by weight
Coarse sand	1 - 1.5 mm	64
Silica flour	30 µm	22
Bentonite	80 % < 2 µm	14

This model liner material was chosen to represent the prototype mixture shown in Figure 3. As can be seen in this figure, the prototype mixture contains a large gravel fraction. This gravel fraction has been scaled down and replaced by the quartz sand fraction in the model liner mixture.

Model Preparation

After all the internal components have been fitted into the strong box, a 30-mm layer of coarse sand overlain by a further 45 mm of fine sand was poured into the strong box. A layer of filter paper was placed just below the final sand surface to prevent fine particles of the liner material from being washed out. A row of discrete markers was placed against

PARTICLE SIZE DISTRIBUTION CURVE

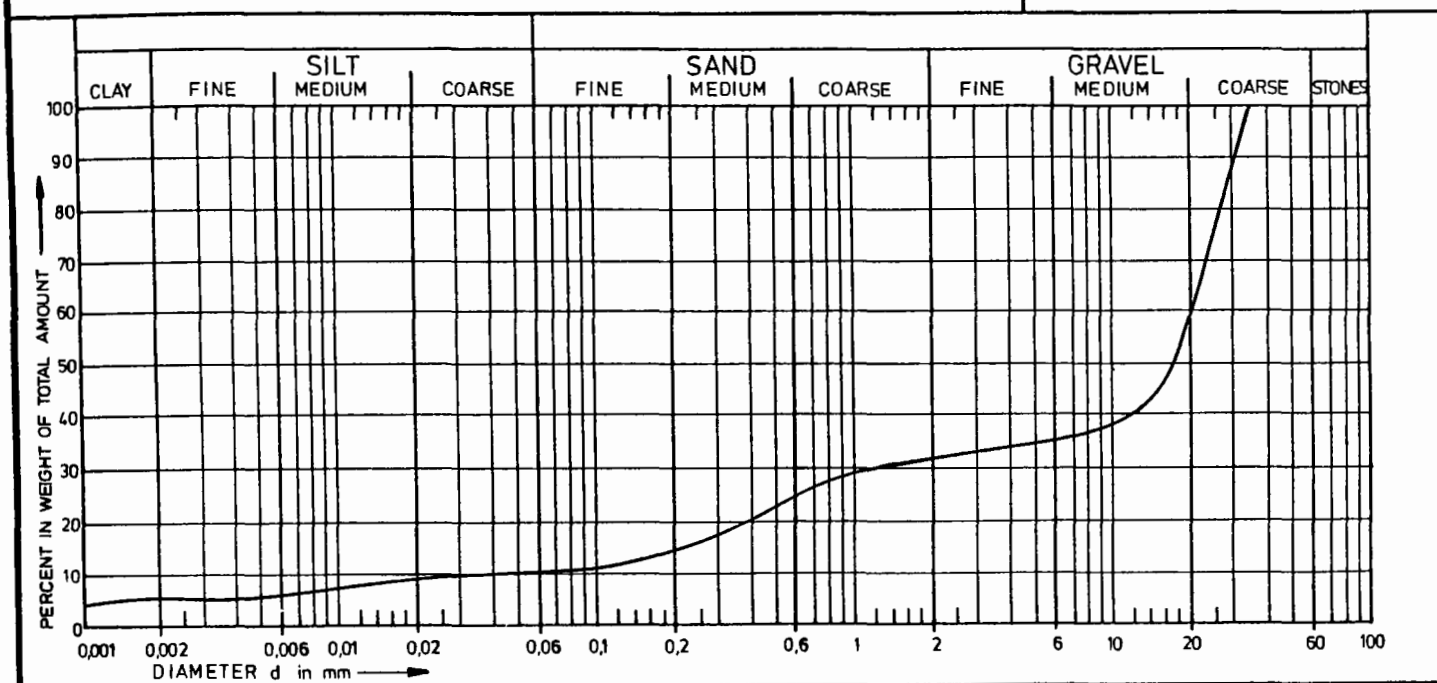


Figure 3
Grading Curve For Prototype Fine/Coarse Mixture Liner Material.

the Perspex window on the sand surface for subsequent digitisation from "in-flight" photographs. The sand was then saturated by the upward percolation of water introduced via a network of drainage holes at the base of the strong box. After greasing the internal sides of the strong box, the model was ready for liner fabrication.

Kaolin Liner Preparation

Kaolin slurry was placed by hand—to avoid air entrapment—to a predetermined depth over the saturated sand. A consolidation unit then was attached to the strong box and the slurry was one-dimensionally consolidated to a final vertical effective stress of 630 kPa. This final effective stress level is consistent with the moisture content associated with a 95% (saturated) proctor compaction density.

After removing the consolidation unit, a shallow landfill was formed in the consolidated liner (Fig. 4a).

Composite Liner Preparation

The preparation of the fine/coarse mixture liner was somewhat arbitrarily arrived at for the test reported here (test KDB1). The material was mixed to a moisture content of 35% and placed by hand to the required depth. The consolidation unit was then fitted and a pressure of 100 kN/m² was applied. This pressure was maintained for 3 days. After removal of the consolidation unit, a shallow landfill was formed again in the consolidated liner. This preparation procedure was simply intended to produce an initially saturated model liner in a reasonably short time. However, for future tests the material will be placed dry and vibro-compacted before saturating by upward percolation. This process is more representative of the prototype placement method, but it has the disadvantage of requiring a very long time for saturation.

4 CENTRIFUGE MODEL TEST RESULTS

The corresponding model and prototype boundary conditions for the tests reported here are given in Table 3.

The principal objective of the model tests was to investigate the physical response of model liners, subjected to various degrees of deformation, as illustrated through the development of cracks and ruptures. The

Table 3
Model and Prototype Boundary Conditions

Test No.	Liner material	Liner thickness		Depth of overburden	
		Model(mm)	Prototype(m)	Model(mm)	Prototype(m)
TD8	2096c Kaolin	35	1.75	0	0
TD9	2096c Kaolin	35	1.75	50	2.5
TD10	2096c Kaolin	40	2.0	0	0
KBD1	Sand/Silica flour/ Bentonite mixture	40	2.0	0	0

effect of overburden and choice of liner material on the model response was observed. In addition, the performance of the liners as effective hydraulic barriers was monitored throughout the deformation process. This test process enabled the effects of losses in liner integrity—such as cracking—to be quantified.

As mentioned earlier, the liner deformations are induced by the vertical translations and rotations of the piston and flap arrangement located at the base of the sand layer. However, it is difficult to relate these movements to the actual degree of deformation suffered by the liner. Consequently, the degree of liner deformation is defined as the degree of rotation, θ , (Fig. 1b) that has occurred at the base of the liner. This angle is deduced from digitized recordings of the discrete markers placed at the sand/liner interface.

Tension Cracking And Rupture

Figure 4b shows a post-test photograph of the model liner surface of test TD10 with a liner deformation of 8°. Severe tension cracks are clearly evident in the regions of maximum liner deformation. The development of such tension cracks was a typical feature of the pure kaolin/clay liner tests where no overburden was present. The degree of liner deformation at the onset of tension cracking will be a function of liner thickness for similarly prepared models⁸.



Figure 4a.
Pre-test Photographs For Kaolin Model Liner

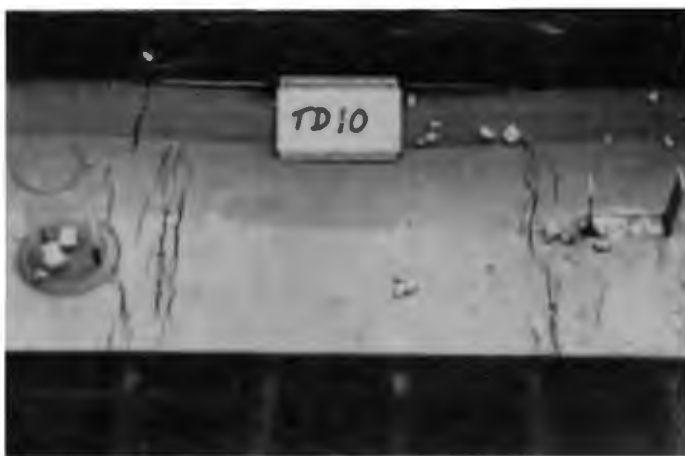


Figure 4b.
Post-test Photographs For Kaolin Model Liner, Test TD10.

For the tests reported, here the onset of tension cracking was observed at 3 to 3.5° for the pure kaolin tests TD8 and TD10. After washing away the sand overburden in test TD9, no tension cracking was evident with a liner deformation of 11°. For the bentonite/sand liner (test KBD1), slight surface cracking was observed at a liner deformation of 7.5°, but no significant cracking developed even after the maximum liner deformation of 16° had been introduced.

After each test, the Perspex front face of the strong box was removed and the model liner was sectioned to examine the depth of tension cracks and the presence of any other internal damage. For tests TD8 and TD10, the tension cracks extended vertically to the base of the liner (Fig. 5a). Careful sectioning of test TD9 revealed no further evidence of tension cracking; however, a series of multiple shear ruptures in the regions of greatest liner deformation was clearly observed (Fig. 5b). These ruptures curved out over the break in slope, indicated an arching type mechanism of material response. Finally, the post-test examination of the deformed bentonite/sand liner did not reveal any significant material degradation, and only shallow surface cracking in the regions of greatest liner deformation was visible.

Assessment of Liner Performance

The performance of the model liners as effective hydraulic barriers is best illustrated through the rate of leachate (water) flow through the liner. This flow rate is directly observed by the rise of the water level in collection vessel D (Fig. 2). However, conversion of this flow rate to an average value of liner permeability is complicated by the non-uniform hydraulic gradient present across the model liner.

This non-uniform hydraulic gradient arises from two conditions. The

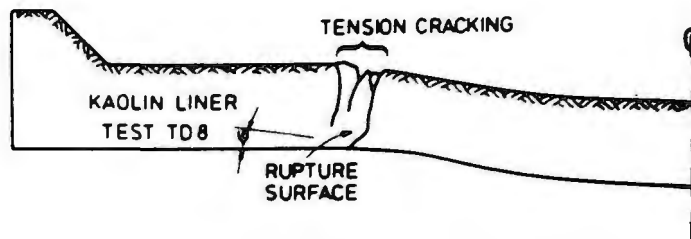


Figure 5a
Trace Of Crack and Rupture Patterns Observed Without Overburden, Test TD8

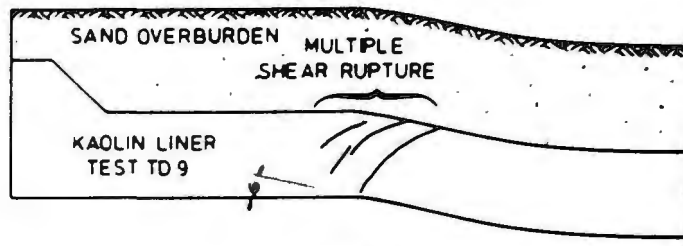


Figure 5b
With Overburden, Test TD9

first condition is unique to centrifuge modeling and is the tendency of water levels in centrifuge models to align along lines of equal radius from the axis of centrifuge rotation. Thus, the surface water level within the model landfill will, at all times, maintain a concave curvature resulting in higher hydraulic gradients away from the center line of the model. Second, the deformations introduced during the test will result in increased hydraulic gradients over areas of liner depression. Thus, in light of these and other complications the values of average permeability stated herein should be treated with caution.

Figure 6 shows the settlement record of the center of the model liner superimposed on the LVDT trace monitoring the water level in the collection vessel D for test TD10. These data are typical test results for a kaolin clay liner with zero overburden, and they illustrate the following characteristic behavior. From A to B the centrifuge is accelerated up to speed and the collection vessel D is rapidly filled and discharged as water in the underlying saturated sand is centrifuge down to the level of connection B (Fig. 2). From B to C there is still quite a rapid flow into vessel D as water continues to be expelled from the sand and also from the self-weight consolidation of the clay liner. From C to C' it can be assumed that no more water is being forced out of the sand and that the amount of water deriving from the liner itself is minimal.

From this flow rate, an initial value of average liner permeability was found to be 1.3×10^{-9} m/sec. From C' to D to flow rate is seen to increase, while a deformation to 3° is introduced at the base of the liner. This increase in flow rate again will be partly due to water being squeezed out of the liner itself, so a realistic calculation for permeability cannot be made during the actual deformation process. However, for the region D to E, the value of average permeability was found to be 1.18×10^{-9} . This value suggests that within experimental error no detectable change in permeability has occurred with a liner deformation of 3°.

Further deformations are introduced (E to F), but again there are no significant increases of flow rate through the liner until a deformation of 6.4° is obtained at F, at which point a dramatic increase in flow rate into vessel D is observed. The subsequent reduction in flow rate (region F to G) before further deformation indicates a self-healing potential of the clay. The behavior of all the kaolin clay liners without overburden exhibited a behavior similar to that illustrated by Figure 6.

The onset of a sudden increased flow rate through the liners can be considered to be a serious failure of the liner and corresponds to the development of deep tension cracks and ruptures forming a preferential flow path through the liner in the regions of maximum deformation. For the test performed with an overburden pressure (test TD9), no such liner "failure" was observed, and it can be concluded that the

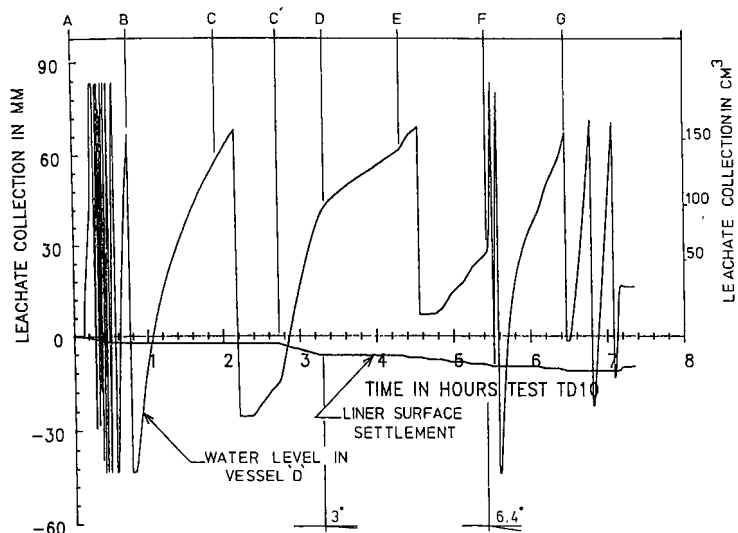


Figure 6
Selected Transducer Records For Test TD10
(kaolin liner, zero overburden).

presence of shear ruptures did not significantly affect the liner's performance.

Comparison of Kaolin and Fine/Coarse Mixture Liner Performance

The fine/coarse mixture liner model was made to the same initial boundary conditions as test TD10 and subjected to a similar time/deformation test history. Figure 7 shows a plot of liner settlement and leachate collection level for the full duration of the test. Comparison of this plot with the corresponding record for test TD10 (Fig. 6) illustrates some fundamental differences.

First, the initial flow rate reduces to virtually zero (region A to B) indicating extremely low permeability of the model liner. As observed in the kaolin tests, the flow rate increases during deformation but approaches zero again soon after stopping the deformation (region B to C). This behavior is repeated until 9.5° of liner deformation is achieved (at D). At this point a permanent increase of flow rate is observed from which an average permeability of 1.89×10^{-10} m/sec has been calculated. On further deformation to 11.5°, the flow rate into vessel D increases slightly but then remains constant for the remainder of the deformation process. The final average permeability for the liner at the end of the test with a liner deformation of 15° was estimated to be 2.915

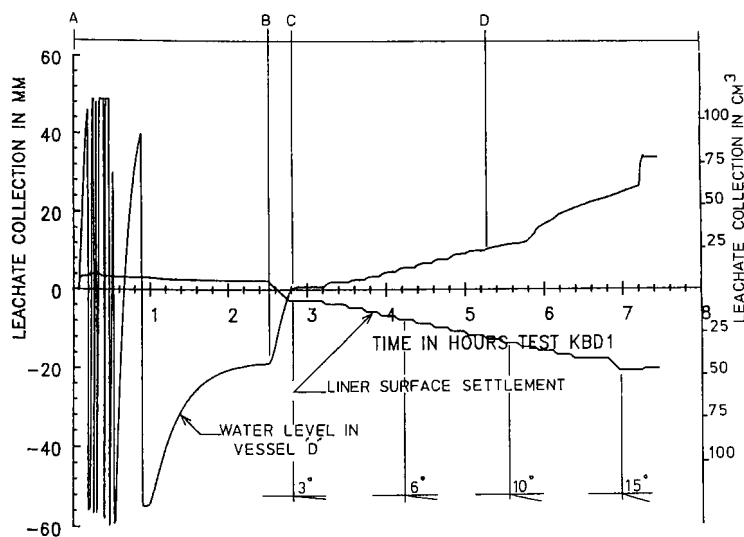


Figure 7
Selected Transducer Records For Test KBD1
(fine/coarse mixture material liner, zero overburden).

$\times 10^{-10}$ m/sec.

These increases in flow rate through the liner at high degrees of liner deformation are likely to be the result of local changes in permeability in regions of severe deformation; thus, the values of average permeability are somewhat misleading. It is not possible at this stage to make any statements about localized permeability changes, but clearly the severe liner failure observed for the kaoline test TD10 is not evident with this material. In fact, it could be argued that at such large deformations the assumption of a smooth profile of differential settlements at the base of the liner is no longer applicable, since deformations within the underlying sand will have localized into thin bands of intensely shearing material. The interaction of these shear planes with the base of the liner will generate local discontinuities of both slope and displacement.

DISCUSSION

The tests reported in this paper were performed to investigate the effect of overburden and choice of liner material on the response of a model liner to imposed deformations.

The liner response was significantly different in the presence of an overburden where no tension cracking was evident and the formation of multiple shear surfaces was observed. The suppression of tension cracking is explained by the increased lateral stresses generated within the liner. Greater deformation (straining) of the liner therefore is possible before tensile stresses necessary for cracking to occur are generated. However, before such stress levels are reached, localization of deformation occurs with the formation of multiple shear ruptures in regions of greatest liner deformation. Consequently, tensile stresses do not arise and no tension cracking is observed once rupturing has occurred. It is not possible at this stage to make any statements as to when shear rupture occurs and what combination of overburden and liner thickness is necessary to prevent tension cracking. The presence of shear ruptures did not affect the performance of the kaoline model liner as an effective hydraulic barrier. However, there is some evidence that in the presence of large hydraulic gradients this is not necessarily the case, and such ruptures could provide preferential flow paths^{8,9} reducing liner effectiveness.

Where no overburden was present, the growth of tension cracks in regions of large deformation resulted in failure of the pure kaolin model liners to function as effective hydraulic barriers. However, in liners of greater thickness, the larger lateral stresses present in the lower depths of the liner may also result in the onset of shear rupture rather than tension cracking—as argued above for the case of an overburden. In such instances, a liner 'failure' would arise from the creation of preferential flow paths consisting of a combination of shear rupture and tension cracking. This was thought to be the case in test TD8 (see Fig. 5a for interpretation).

Comparison of the fine/coarse mixture and pure kaolin model liners illustrates a much greater capacity of the fine/coarse mixture liner material to function effectively when subjected to even large deformations. The reasons for this response are not entirely clear, but the following interpretation is suggested. First, the absence of significant tension cracking suggests that the material possesses a very small cohesive strength and, hence, large unsupported tension cracks cannot appear, i.e., the response to deformation of the material is as might be expected for a sand. Second, the very low permeability of the material, which is derived from the nature and size distribution of the fine fraction filling the voids of the sand, is maintained under imposed deformation by the ability of this fine fraction—which would behave like a slurry of zero effective strength—to flow within the sand matrix. Hence, the material would exhibit an extremely quick and efficient self-healing property.

CONCLUSIONS

The ability of the centrifuge to induce prototype stress levels within a small scale model allows the stress dependent response of the model to be directly interpreted to the corresponding prototype situation. Thus, from the model tests presented in this paper, where model liners have

been subjected to deformations of a similar nature to those that might occur in the field, the following conclusions can be drawn:

- Tension cracking and rupture are likely responses for pure compacted clay liners. The dominant mode of liner response will be dependent on the lateral stress level. For example, small lateral stresses will favor the development of tension cracking, whereas larger lateral stresses will promote localization of deformation into shear ruptures.
- The development of severe tension cracks can lead to failure of the liner to function as an effective hydraulic barrier.
- The presence of ruptures alone is unlikely to affect the satisfactory performance of the liner in a prototype situation.
- Liners manufactured from fine/coarse (sand/clay) mixtures may provide hydraulic barriers virtually unaffected by likely prototype deformations. This design is thought to be due to a highly efficient self-healing system.

REFERENCES

1. Kleppe, J.H. and Olson, R.E., "Desiccation Cracking of Soil Barriers," in *Hydraulic Barriers in Soil and Rock*, ed. A.I. Johnson, R.K. Frobels, M.J. Cavalli, C.B. Peterson, ASTM STP 874, Philadelphia, PA, pp. 263-275, 1985.
2. Andersland, O.B. and Al-Moussawi, H.M., "Crack Formation in Soil Landfill Covers due to Thermal Contraction," *Waste Mana. Res.*, 5, pp. 445-452, 1987.
3. Sterling, M.J. and Ronayne, M.C., "Centrifugal Modelling of Subsidence of Landfill Covers," *Proc. Symp. on Recent Advances in Geotechnical Centrifuge Modelling*, University of California, Davis, CA, pp. 71-81, 1982.
4. Jessberger, H.L. and Thiel, G., Abschätzung des Setzungsverhaltens von Deponie-Basisabdichtungen—Berechnung und Modellversuch. In preparation.
5. Stone, K.J.L. and Wood, D.M., "Some Observations of Faulting in Soft Clays," *Centrifuge '88*, ed. J.F. Corte, Balkema Publ., Rotterdam, 1988.
6. Jessberger, H.L. and Guttler, U., Bochum Geotechnical Centrifuge, *Centrifuge '88*, ed. J.F. Corte, Balkema Publ., Rotterdam, 1988.
7. Arulanandon, K., Thompson, P.Y., Kutter, B.L., Meegoda, N.J., Muraloetharam, K.K. and Yogachandran, C., "Centrifuge Modelling of Transport Processes for Pollutants," *J. Geotech. Eng. ASCE*, 114 (2), pp. 185-205, 1988.
8. Jessberger, H.L., Guttler, U. and Stone, K.J.L., "Centrifuge Modelling of Subsidence Effects on Clay Barriers," paper submitted to Sardinia '89, *Second International Landfill Symposium*, 1989.
9. Gronow, J.R., "Migration Pathways in Seabed Sediments," in *Disposal of radioactive Wastes in Seabed Sediments*, ed. T.J. Freeman, publ. Graham and Trotman Ltd., London, pp. 179-199, 1988.

Composite Liner System to Retain Inorganic and Organic Contaminants

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ABSTRACT

Hazardous waste disposal facilities presently rely on RCRA-required liner systems, composed of two geomembrane liners overlying natural or compacted clay, to impede the migration of contaminants into the environment. Limitations to the present liner systems include the potential for construction defects, long-term changes in the properties of the membrane and diffusion of organic contaminants through the otherwise intact liners. The present design philosophy, simply stated, is to design a liner system that does not leak.

Since liner systems cannot be perfectly constructed and diffusion causes contaminant migration through liners, a composite liner system is proposed which would further reduce the rate of contaminant migration into the environment. The design philosophy of this composite liner approach is markedly different than the present design philosophy. While present designers strive to minimize the hydraulic conductivity of the system, it may be more prudent to acknowledge the potential for contaminant transport across the barrier layers and design the system to adsorb these contaminants.

The proposed composite liner starts with the same features as a conventional RCRA liner system including two geomembrane liners, two leachate collection systems and the appropriate drainage and filter layers. However, the proposed composite also includes components to sorb the contaminants in the leachate. A sequence in the liner system is also proposed but this can be left to the individual designer's preference. We propose that the liner include a layer of calcium bentonite and natural zeolite attached to the bottom of the uppermost geomembrane. Calcium bentonite and zeolite will preferentially adsorb and filter inorganic species which may penetrate this liner. We also propose that the liner include a layer of organically-modified clay attached to the lowermost geomembrane. This liner composite will adsorb organics which would otherwise migrate into the environment. Performance data are presented to support these concepts.

INTRODUCTION

The present philosophy for the design of liner systems is to reduce the hydraulic transport of contaminants through the system. The design strategy recognizes the potential for imperfections and accommodates these through redundancy and through quality control measures. The present design philosophy does not, however, explicitly acknowledge diffusion as a contaminant transport mechanism. Research has shown that contaminant transport in response to diffusion gradients may be significant. We propose that liner systems be designed as composites which include sorption layers as well as barriers to hydraulic transport. In this way, a mechanism is provided through which the liner system can minimize the rate of inorganic and organic contaminant transport into the environment in response to both hydraulic and diffusion

gradients.

Described in the following paper are several proposed materials that have demonstrated the capability to adsorb contaminants. Calcium bentonite and natural zeolite are suitable for inorganic constituents, and organically-modified clays are suitable for organic constituents. In addition, high carbon fly ash may be considered for both organics and inorganics.

PROPOSED COMPOSITE LINER

Liner systems presently employ two geomembrane barrier layers overlying natural or compacted clay as shown in Figure 1. This system is subject to constraints including:

- A clay source of adequate quality and quantity within an economic distance
- Compaction to remove natural defects (preferential contaminant migration pathways) such as root or desiccation cracks
- Quality control to prevent punctures in the synthetic liner not be during construction or during waste disposal
- No diffusion of contaminants occurs through the synthetic liner

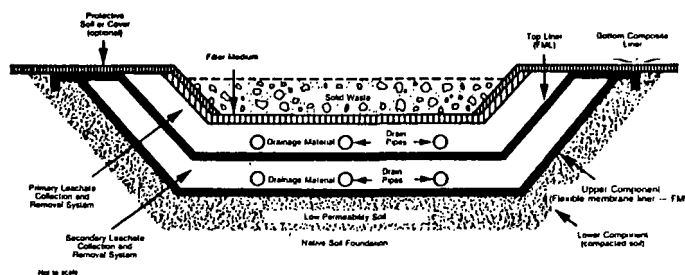


Figure 1
RCRA Liner System

Each of these constraints can be addressed with the present design approach to some extent. Clays of adequate quality and quantity are available, although costs may be quite high. Preferential contaminant migration pathways can be removed from the underlying clay layer, with difficulty, by mechanical means. Geomembrane liner's defects have been a problem commonly associated with synthetic liners. The final item presents the greatest difficulty for the present liner systems as diffusion through geomembranes does occur¹. It also has been shown that, as chemicals at the molecular level penetrate geomembranes, synthetic liners probably deteriorate². When geomembranes are exposed to chemicals over a long period of time, thickness, crystallinity and molecular structure are affected by chemical and thermal changes in the im-

mediate environment. A landfill is a chemical and biological environment in which chemical and biological degradation of the contents takes place over time. A composite liner system must be designed to accommodate these processes to achieve a maximum life span commensurate with the predicted time rate of chemical degradation.

A number of modifications to the conventional liner system are proposed in this paper to improve the performance of landfill liner systems for both inorganic and organic constituents (Fig. 2). The liner system performance can be enhanced using a series of natural and chemically-altered natural materials to create an improved composite liner system.

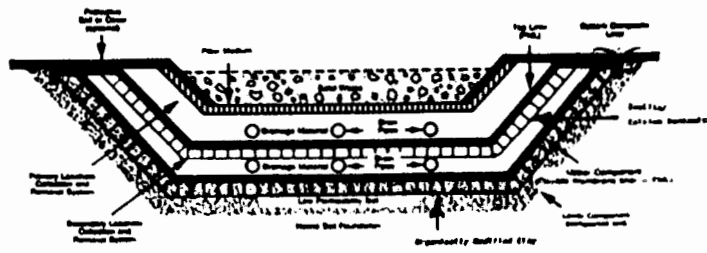


Figure 2
Proposed Composite Liner System

As shown in Figure 2, a layer of calcium bentonite and natural zeolite beneath the primary geomembrane liner is proposed. These two minerals effectively adsorb any heavy metals which have not been removed by the leachate collection system and have passed through the primary geomembrane barrier. The thickness of this natural material layer can be based on the required attenuation capacity. The layer may be relatively thin because the ion exchange capacity of both minerals is high (i.e., over 60 meq/100 g).

These materials underlie the primary geomembrane barrier and may be attached to the geomembrane consistent with presently available technology (the Paraseal System from Paramount Co., Spearfish, South Dakota). Alternatively, the added materials may be prepared as separate layers and serve as bedding for the primary geomembrane. In either instance, the sorptive layer will attenuate the rate of inorganic mass transport through the liner system.

The proposed composite liner is also equipped to attenuate the rate of mass transport of organic contaminants. This attenuation process is accomplished with the inclusion of a layer of organically-modified clay.

The organically-modified clay is designed to adsorb organic compounds that may have diffused through the liner. The organically modified clay may be attached on the bottom side of the secondary geomembrane. This liner may rest on a soft soil or clay to assure no damage to it. In this fashion, organics which may diffuse through the liner will be sorbed onto the organically-modified clays. Alternatively, the organically-modified clay may be attached to the upper side of the secondary geomembrane. In this fashion, the organically modified clay will protect the geomembrane from degradation as well as reduce contaminant transport across the layer.

The inclusion of a layer of carbon-rich fly ash also has been considered. Alkaline fly ash could increase the pH of the leachate, which would in turn cause precipitation of heavy metals. The layer also could contain an inexpensive reducing agent, such as reduced iron powder or graphite, to reduce hexavalent chromium to trivalent chromium to enhance precipitation. The fly ash should contain at least 10% carbon and be free of phenolics. This high carbon fly ash would then efficiently absorb low molecular weight organics¹.

This proposed system maximizes retention of contaminants through sorption processes. This new liner system contrasts to designs which focus on hydraulic transport mechanisms. The clays and zeolites will sorb metals and the environment is protected by the organically-modified clay against diffusing organic chemical transport. The remainder of this paper describes the individual components in detail and discusses some test results which support the composite liner concepts.

MATERIALS DESCRIPTION

Calcium Bentonite

Calcium bentonites are non-gelling bentonites containing montmorillonite as their major constituent. This montmorillonite has, as its primary exchangeable cation, calcium (typically from 35 to 99% of the exchangeable cations). Calcium bentonites, such as those from Mississippi and Alabama, have ion exchange capacities of more than 70 meq/100 g.

Calcium bentonites are in abundance worldwide⁴. These clays expand little upon wetting with water a desirable characteristic since their function is as an ion exchange barrier rather than as a water barrier. Calcium bentonite transmits water, where the secondary leachate collection system can collect it. The calcium ions on the surface of this clay exchange readily with heavy metals such as lead, copper, nickel and others, with strong preference for lead⁵.

Zeolite

A natural zeolite (of a 200 mesh grain size) can be blended with the calcium bentonite, or it can be placed as a separate layer to enhance the sorption of inorganic species. Placement of the zeolites as a separate layer would prevent possible exchange reactions of the calcium from the bentonite with the sodium from the zeolite. Natural zeolites are also hydrous aluminum silicates, like montmorillonite, but with an entirely different crystalline lattice arrangement. Zeolites are crystalline-hydrated, three-dimensional aluminosilicates with a cage structure, wherein the exchangeable ions are sorbed. Its exchange capacity is up to 250 meq/g. The major exchangeable ions are sodium and calcium. The zeolite acts like a sieve when permeated by water, trapping metals that pass through by ion exchange. The zeolite would complement the calcium bentonite to assure maximum adsorption of metals.

There are five major zeolite classes including: Analcime, Chabazite, Clinoptilolite, Erionite and Mordenite. Zeolites presently are used to purify water contaminated with radioactive cesium and other ions (e.g. Three Mile Island), remove ammonium from wastewater treatment plant effluent and fish tanks, control odor cat litter and adsorb metals from industrial wastewaters in columns.

Arsenic, lead and cadmium are preferentially adsorbed by zeolites. A study by the Montana College of Mineral Science and Technology⁶ showed that a chabazite from Bowie County, Arizona was an excellent adsorption media for metals in groundwater. The structure and behavior of zeolites have been studied extensively⁷ but further details are beyond the scope of this paper.

Organically-Modified Clays

Organically-modified clays were developed in the 1940s. Jordan^{8,9} published the first original work on the subject. Organoclays are further described by Alther, et al.¹⁰ and Evans, et al.¹¹ In summary, the inorganic cation on the surface of a clay such as a montmorillonite, is exchanged with a suitable organic cation, preferentially with an amine of a composed chain length of at least 12 carbons⁹. The important reactions that take place in this process are adsorption, ion exchange and intercalation.

According to Mortland¹², an organically-modified clay adsorbs organic molecules due to two controlling factors: (1) adsorbent-adsorbate interactions and (2) adsorbate-solvent interactions. The adsorption capacity of an organically-modified clay is thus dependent on the amine used to convert the clay and the properties of the medium, such as its temperature, pH and type of solvent. Additional insight into the behavior of organically-modified clays is provided by Boyd, et al.¹³, Mortland, et al.¹⁴, and Wolf, et al.¹⁵. These authors and others have designed organically-modified clays by exchanging onto them dioctadecyl dimethyl, hexadecyltrimethyl ammonium chloride (very hydrophobic in nature), the less hydrophobic tetramethyl ammonium chloride and hexadecyl pyridinium compounds. Boyd, et al.¹³, and Mortland, et al.¹⁴, have shown those clays (the ones modified with strongly hydrophobic organic molecules) to be excellent adsorbents of chlorophenols, while not suitable for straight phenols.

Wolfe, et al.¹⁴, tested the efficiency of three organically-modified clays as to their efficiency (versus activated carbon) in the removal of 11 organic compounds from water, with encouraging results. Boyd, et al.¹⁵, have shown that, as hydrophobicity of the sorbate increases, sorption by the organically-modified clay increases while the reaction of primary amines with other molecules is pH-dependent. This is not the case for quaternary amines, making them more suitable sorbents for water decontamination.

The entire process of sorption of organics onto organically-modified clays is described as a partitioning process^{15,16}. Boyd, et al.¹⁵, describe the process such that the quaternary ammonium ion attached to the clay surface acts as a solubilizing (partitioning) medium to remove organic molecules from water, being functionally and conceptually similar to a bulk organic solvent such as hexane or octanol¹⁵. They used the hexadecyl trimethyl ammonium chloride ion (16 carbons long) to remove non-ionic organic contaminants such as benzene, dichlorobenzene and perchloroethane from water, with good success. The evidence points to the effectiveness of organically-modified clays for the removal of such toxic compounds.

Fly Ash

A description of the type of fly ash properties best suited for landfill liners desired for this application is found in Mott and Weber¹³. The properties of the fly ash from Trenton, Michigan are shown on Table 1. These authors showed that molecular diffusion of organics through soil/bentonite backfills in slurry walls result in solute breakthrough within a relatively short time. The addition of high-carbon fly ash within the barrier caused a substantial delay in breakthrough.

Table 1
Fly Ash Properties

Density (g/cm ³)	2.29
Loss on Ignition (%)	9.14
Carbon ¹ (%)	6.14
Phenol ²	nd
Tannin ²	951
Specific Surface (m ² /g) ³	2.65

¹ Measured as CO₂ recovered during wet combustion

² Normalized to the carbon fraction of fly ash

³ Primary surface Area by B.E.T. nitrogen adsorption

LABORATORY TESTING

Laboratory studies were undertaken to further demonstrate the viability of the proposed composite liner concepts. Samples of sorptive media were compacted into cylindrical specimens for permeation in a triaxial cell permeameter. Samples were permeated with distilled water spiked with several inorganic and organic species including copper, lead and nickel at concentrations of 10 mg/L. Samples of the influent and effluent were taken throughout the permeation period and analyzed for the spiked constituents.

The results are shown in Figures 3 through 5. As shown, the calcium bentonite, chabazite (a natural zeolite) and a naturally occurring silty clay all attenuate the contaminant concentrations. In fact, breakthrough does not occur for the lead and nickel even after a pore volume displacement of 12.

This study also used a commercially available organoclay (PT-1, Bentec, Inc., Ferndale, Michigan) which is modified with dimethyl dihydrogenated tallow ammonium chloride, an 18-carbon alkyl ammonium molecule. As expected, the organically-modified clay had little effect upon the sorption of inorganic species. Analytical data on the concen-

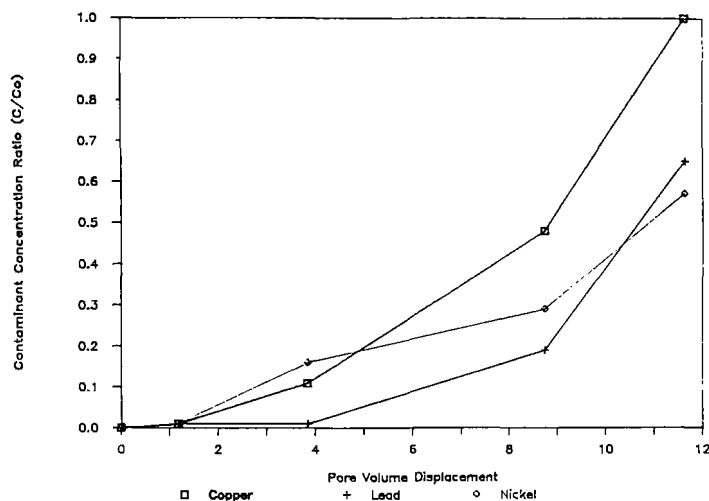


Figure 3
Permeation of Silty Clay

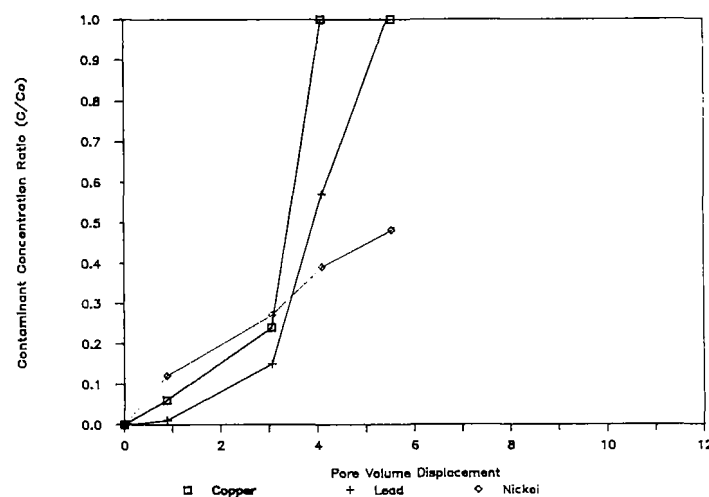


Figure 4
Permeation of Calcium Bentonite

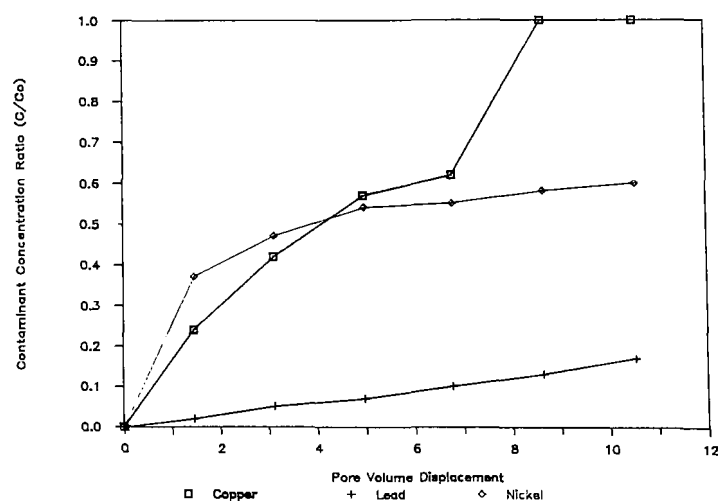


Figure 5
Permeation of Chabazite

trations of the organic species were not available at the time of publication but are expected to demonstrate the adsorption capacity of the organically-modified clay for organic species.

Results for the fly ash were less conclusive. Although some inorganic ions were adsorbed from the influent, copper concentrations significantly increased in the effluent. Further studies investigating alternative fly ash sources and types are needed to justify the use of a fly ash layer within the composite liner system.

CONCLUSIONS

An alternative philosophy for the design of secure landfill liner systems is proposed. Whereas designers presently focus on the need for low hydraulic conductivity, we propose that designers recognize that liners may leak and contaminants will migrate across the barrier layers due to the hydraulic imperfections and molecular diffusion. With this recognition of contaminant transport across the barriers, comes the need to include adsorptive layers in the liner system. Thus, a composite liner would use technologies presently employed to reduce the hydraulic conductivity (such as geomembranes) coupled with media to sorb contaminants. Adsorption media include calcium bentonites and natural zeolites for inorganic species and organically-modified clays for organic species.

REFERENCES

1. Haxo, H. E., Haxo, R. S., Nelson, N. A., Haxo, P. D., White, R. M., Dakessian, S. and Fong, M. A., *Liner Materials for Hazardous and Toxic Waste and Municipal Solid Waste Leachate*, Noyes Publications, Park Ridge, NJ, 1985.
2. Verschoor, K., Britton, L. and Thomas, R., "Chemical Compatibility Testing of Geosynthetics to be Used as Containment Barriers in Hazardous Waste Management," *Haz Waste/Haz Mat*, 5, pp. 205-209, 1988.
3. Mott, H. V. and Weber, W. J., "Diffusive Transport and Attenuation of Organic Leachates in Cut-Off Wall Backfill Mixes," Presented at the Twelfth Annual Madison Waste Conference, Department of Engineering Professional Development, University of Wisconsin, Madison, WI, Sept., 1989.
4. Grim, R. E. and Guven, N., *Bentonites, Developments in Sedimentology*, Elsevier Scientific, New York, NY, 978, 256 pp., 1978.
5. International Minerals and Chemical Corporation, Laboratory Report, 1986.
6. Montana College of Mineral Science and Technology, Open File Report, 1989.
7. Mumpton, F. A., *Mineralogy and Geology of Zeolites*, Mineralogical Society of America, Short Course Notes, Southern Printing Co., Blacksburg, Va., 4, 233 pp., 1977.
8. Jordan, J. W., "Alteration of the Properties of Bentonite by Reaction with Amines," *Mineralogical Magazine and J. of the Mineralogical Soc.*, 28, 205, pp. 598-605 June 1949.
9. Jordan, J. W., "Organophilic Bentonites. Swelling in Organic Liquids," *Phys. & Colloid Chem.*, 53, (2), pp. 294-306, 1949.
10. Alther, G.R., Evans, J.C. and Pancoski, S.E., "Organically-modified Clays for Stabilization of Organic Hazardous Wastes," Superfund '88, *Proceedings of the Ninth National Conference*, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 440-445, November 1988.
11. Evans, J.C., Pancoski, S.E. and Alther, G.R., "Organic Waste Treatment with Organically-modified Clays," Third International Conference on New Frontiers for Hazardous Waste Management, (Submitted May, 1989).
12. Mortland, M.M., Shaobai, S. and Boyd, S.A., "Clay-Organic Complexes as Adsorbents for Phenol and Chlorophenols," *Clays and Clay Minerals*, 34, (5), pp. 581-585, 1986.
13. Boyd, S. A., Lee, J-F and Mortland, M. M. "Attenuating Organic Contaminant Mobility by Soil Modification," *Nature*, 333, pp. 345-347, May, 1988.
14. Wolf, T.A., Demirel, T. and Bauman, R. E., "Adsorption of Organic Pollutants on Montmorillonite Treated with Amines," *JWPCF*, 58 (1), pp. 68-76, 1986.
15. Chiou, C. T., Porter, P. E. and Schmedding, D. W., "Partition equilibria of Nonionic Organic compounds between Soil Organic Matter and Water," *Envir. Sci. Technol.*, 17 (5), pp. 227-231, 1983.
16. Chiou, C. T., Peters, L. J. and Freed, V. H., "A Physical Concept of Soil-Water Equilibria for Nonionic Organic Compounds," *Science*, 213, pp. 684-685.

Recent Advances in Asbestos Assessment at Superfund Sites

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INTRODUCTION

As of August, 1989, asbestos has been identified as a chemical of concern at 22 Superfund sites. At many of these sites, it is the sole chemical of concern. The sources of the asbestos are quite variable. On one hand, the source may be mining and/or milling activities or emissions from natural deposits (Atlas/Coalinga, California, Globe, Arizona). Other sites consist primarily of material disposed improperly from secondary processing (Ambler, Pennsylvania). At still other sites, the source of the asbestos is tailings which have been put to a supposedly beneficial use (South Bay/Alviso, California). In addition to the sites where asbestos is the sole chemical of concern, there are numerous other sites where it occurs with other toxic chemicals. These sites containing mixed wastes range from abandoned hazardous waste disposal sites (Hardage, Oklahoma) to sites where asbestos was used as a structural or insulation material (Sharon Steel, Utah).

Due to its unique nature, asbestos presents some special problems in its analysis, remediation and risk assessment. Specialized analytical concerns regarding asbestos at Superfund sites have been dealt with in the literature for asbestos in air¹ and in soil². The U.S. EPA has produced a Health Effects Assessment³ and a review of the health effects of asbestos⁴ which incorporates risk-based information. Additionally, ATSDR is in the process of producing a toxicological profile for asbestos. However, a methodology has not been developed for asbestos risk assessments at hazardous waste sites which parallels the methods developed by the U.S. EPA for chemicals⁵. The development of this type of methodology has been hampered by many questions of scientific controversy which surround asbestos. These unanswered questions relate to the definition of biologically active fibers, the shape of the dose response curve, the relevance of analytical measurements to risk assessment techniques, the problem of route-specific carcinogenicity and the presence of ubiquitous background concentrations at levels associated with relatively high cancer risk.

The U.S. EPA has conducted considerable research under regulatory programs other than Superfund such as AHERA⁶ and the Phase-down rule⁷. Other regulatory agencies both within the United States⁸ and abroad⁹ also have developed programs for asbestos management. The purpose of this paper is to present a methodology for asbestos risk assessment which we have synthesized from our activities at three Superfund sites in addition to risk and exposure assessments performed under AHERA.

A RISK BASED DEFINITION OF ASBESTOS

Asbestos is a generic term referring to a family of naturally occurring silicates having a fibrous crystalline structure. There are six fibrous silicates defined as asbestos types: chrysotile, actinolite, amosite, anthophyllite, crocidolite and tremolite. Of these six silicates, only

chrysotile is typically detected at Superfund sites.

Deposition and absorption of asbestos fibers can be influenced by fiber characteristics such as fiber length, fiber diameter, aspect ratio (ratio of length to diameter), fiber number, stability of fibers in the body, surface chemistry of the fiber, interactions between fibers and other surfaces, fiber translocation and migration, overall fiber dose and fiber type¹⁰. Specific data relating individual asbestos type and physical characteristics of the fiber with biological activity via ingestion are lacking.

Following inhalation, there is some evidence to suggest a relationship between asbestos fiber dimension and carcinogenic potential. This relationship is known as the Stanton Hypothesis and is based on correlations between pleural sarcomas in rats and dimensions of fibers in addition to human epidemiologic data¹¹. Long, thin fibers ($> 5 \mu$ in length, aspect ratio > 3) appear to elicit the greatest biological response. However, a critical fiber length below which there would be no carcinogenic activity has not been demonstrated. Fibers less than 5μ in length appear to be capable of producing mesothelioma⁴, and the results of one analysis show that carcinogenicity appears to be a continuously increasing function of the aspect ratio¹².

A re-analysis of Stanton's original data¹³ concludes that factors other than size and shape may play a role in asbestos carcinogenicity. Therefore, for purposes of risk assessment, all asbestos fibers will be considered to be carcinogenic, although direct preparation total TEM fiber counts (where available) must be converted to PCM equivalents for purposes of using human health data derived from epidemiologic studies in which exposure was measured by PCM.

HAZARD IDENTIFICATION/ DOSE-RESPONSE QUANTIFICATION

The primary non-carcinogenic health effect of asbestos is asbestosis, a chronic lung disease associated with function disabilities and early mortality; however, development of asbestosis usually is associated only with high-level occupational exposure⁴. For low-level environmental exposure, cancer is considered a more appropriate endpoint for criteria development than asbestosis.

The carcinogenicity of asbestos following ingestion has not been conclusively demonstrated by direct studies. In a National Toxicology Program (NTP)¹⁴ bioassay in male rats, a significant increase in benign epithelial neoplasms in the large intestine was interpreted as limited evidence that orally ingested chrysotile fibers may be carcinogenic. Available data from occupational studies also suggest a link between inhalation and subsequent ingestion of asbestos and gastrointestinal cancer⁴.

The U.S. EPA¹⁵ developed an oral unit risk factor of 1.4×10^{-13} (fiber/liter)⁻¹ based on the NTP bioassay in which benign neoplasms

were observed in male rats exposed to asbestos ($>10 \mu$ in length) in drinking water; this cancer potency factor was used by the U.S. EPA as the basis for the drinking water maximum contaminant level goal. There are a number of uncertainties associated with this approach including the absence of adequate dose-response data from human populations exposed via ingestion, the induction of benign tumors only and the fact that the criterion is limited to fibers greater than 10μ in length.

Inhalation exposure in humans and experimental animals can result in both lung cancer and mesothelioma. The calculation of risk for inhalation exposure is based primarily on the methodology set forth in the U.S. EPA's Airborne Asbestos Health Effects Update⁴. This calculation relies on the use of risk tables which give maximum likelihood estimates for mesothelioma and lung cancer as a function of sex, age at onset of exposure, years of exposure and ambient atmospheric concentrations. Situations not exactly described by the risk tables are evaluated by linear interpolation among values on the tables.

Since the tabulated function is non-linear at high concentrations, for situations when concentrations are substantially higher than those shown on the tables, the resulting risks presented should not exceed the maximum risk shown in the health risk table (3×10^{-4}), but should rather be listed as " $>3 \times 10^{-4}$ ". For situations below the range of the tables (e.g., exposure periods of less than 1 yr., concentrations substantially lower than 10^{-4} to 10^{-6} fiber/cm³), the linearized unit risk of 2.3186×10^{-1} (fibers/cm³)⁻¹ developed by the U.S. EPA⁴ for a lifetime exposure may be used. The risk calculated by this method must be adjusted to compensate for less than lifetime exposure.

APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS

The U.S. EPA's interim guidance¹⁷ defines ARARs as follows.

Applicable requirements means those cleanup standards, standards of control or other environmental protection requirements, criteria or limitations which are promulgated under Federal or State law and specifically address a hazardous substance or other circumstance at a CERCLA site. On the other hand relevant and appropriate requirements address situations which are sufficiently similar to a CERCLA site that their use is well suited to the particular site or situation.

Federal regulatory action on asbestos has taken on a variety of forms. Regulations have been promulgated by numerous agencies including the U.S. EPA, the Consumer Product Safety Commission (CPSC), the Department of Transportation (DOT), the Food and Drug Administration (FDA), the Mine Safety and Health Administration (MSHA) and the Occupational Safety and Health Administration (OSHA). Although none of the promulgated regulations may be applicable to a specific asbestos site, they may be relevant and appropriate.

In 1980, the National Institute for Occupational Safety and Health (NIOSH) recommended to OSHA a maximum level for asbestos in the workplace in addition to several measures which would act to minimize exposure. Recently, OSHA issued a rule implementing many of these regulations and lowering the old workplace standard of 2 f/cm³ to 0.2 f/cm³ of air as an 8-hr time weighted average (51 FR 22612, 1986). Asbestos was first designated by the U.S. EPA as a hazardous air pollutant under the Clean Air Act in 1971. Since their initial promulgation in 1973, the National Emissions Standards for Hazardous Air Pollutants (NESHAP) for asbestos have been revised several times. As they currently read, the regulations call for no visible emissions from milling, manufacturing and asbestos waste disposal activities (43 FR 26372, 1977) and require that asbestos containing waste be kept thoroughly wet with water during handling. The standard of no visible emissions may be relevant and appropriate to the asbestos soils and wastes at hazardous waste sites.

Asbestos was first determined to be a hazardous water pollutant in 1973. Effluent limitation guidelines for asbestos manufacturing have been promulgated (40 FR 1874, 1975). Also under the Clean Water Act, the U.S. EPA published an Ambient Water Quality Criteria document for asbestos¹⁸. The document noted that data were inadequate to issue criteria for the protection of aquatic life. For protection of human health, the estimated levels of asbestos in water which would result in increased lifetime cancer risks of 10^{-5} , 10^{-6} and 10^{-7} are 300,000 total fibers/L,

30,000 total fibers/L, and 3,000 total fibers/liter, respectively. The U.S. EPA also has proposed an MCLG for asbestos in drinking water under the Safe Drinking Water Act which equated an excess cancer risk of 10^{-6} to an asbestos concentration of 7.1×10^{-6} fibers greater than 10μ in length/L¹⁹.

Another significant regulation is the Asbestos Hazard Emergency Response Act (AHERA) which enacted Title II of TCSA. Under this act, the U.S. EPA has published regulations related to inspection and management of friable asbestos in schools (52 FR 42826, 1987). The monitoring procedures specified in this regulation may be relevant to hazardous waste sites. In the rule, local agencies must consider an area to contain asbestos if asbestos fibers are found in any sample at greater than 1% as analyzed by PLM. Since 1% generally is accepted as the detection limit for asbestos in soil, it could be argued that this represents a standard for non-detectable asbestos, i.e., that any detectable asbestos in soil warrants action.

EXPOSURE ASSESSMENT

There are two general routes through which individuals may be exposed to asbestos at a Superfund site: inhalation and ingestion. Experimental and epidemiological studies indicate that inhalation exposures to asbestos are of greatest potential concern to human health. Exposure to asbestos via ingestion, although not considered to be as important toxicologically as inhalation, may also be associated with an increased risk of neoplasms. These ingestion exposures include direct ingestion of contaminated soil, direct ingestion of contaminated surface water and indirect ingestion of asbestos which has been inhaled. Dermal contact and subsequent absorption is not an exposure route of concern since asbestos is not likely to be absorbed through intact skin.

Although a thin crust usually forms on the asbestos material in mining tailings piles, mill tailings piles, soils, etc. after rainstorms, this crust is easily disturbed with the net result that the asbestos materials become friable and may be eroded by high winds. Persons in downwind off-site residential areas may be exposed to ambient airborne asbestos. In addition, individuals who trespass or engage in recreational activities in the vicinity of a site may inhale ambient air concentrations of asbestos on-site. Ambient concentrations of airborne asbestos are usually detected in various on-site and off-site areas by air monitoring conducted during an RI; therefore, this exposure pathway is considered complete.

Problems with sampling and analysis of airborne asbestos, however, often make airborne data difficult to use for risk assessment. At one site, for example, air samples were collected both in summer and winter and both during the day and at night in order to account for the complex, changing nature of meteorological conditions affecting air concentrations at different times of the year. A threshold wind velocity is necessary to cause soil entrainment of asbestos; however, air monitoring samples were collected during periods when this threshold velocity was exceeded. Therefore, using the available air monitoring data and the site-specific meteorological monitoring data collected during an RI, modeling was conducted to determine annual average air concentrations of asbestos at various locations. Annual average air concentrations of asbestos were determined for each sampling location based on the air monitoring concentrations and modeling which accounted for periods when the threshold velocity was exceeded.

A further limitation of air monitoring concerns the presence of more than one potential source of airborne contamination. If more than one site is contributing to airborne contaminant levels, ambient air monitoring data often do not allow determination of the fraction of measured concentrations associated with each source. The concentrations used to estimate exposures in a risk assessment should in theory reflect site-specific conditions, but a wide variety of potential off-site sources of asbestos can contribute to background asbestos concentrations in air. Air monitoring for asbestos often does not allow differentiation between these background ambient asbestos levels, whether naturally occurring or anthropogenic. It is also difficult to distinguish between primary sources of asbestos (e.g., the mining and mill tailings piles on the sites) and secondary sources of asbestos (e.g., sedimentary deposits of asbestos which have been transported downstream during rain storms and subsequently become dry and subject to wind erosion).

For many sites, it is necessary to conduct modeling which estimates the fractional contribution of the different sources to calculate annual average air concentrations of asbestos in various locations.

Although of short duration compared to inhalation of contaminated ambient air, asbestos air concentrations resulting from activities which disturb contaminated source materials may be elevated above ambient levels by several orders of magnitude¹⁹. Thus, in addition to chronic exposures to lower ambient asbestos levels, activity-related exposures of the individuals participating in the activity to airborne asbestos could potentially result in cumulative asbestos exposures of concern to human health if they occur with sufficient frequency.

For a typical non-residential mining or milling site, on-site activities which could potentially generate increased levels of airborne asbestos (i.e., above ambient) include off-road vehicle traffic (e.g., motorcycles, cars and trucks) on asbestos piles and on jeep trails, horseback riding, hiking, camping and hunting. Vehicle traffic and horseback riding are expected to stir up greater quantities of dust than are hiking, camping and hunting. In addition, hikers, campers and hunters are not expected to spend extensive periods of time on the asbestos piles present at the sites. Therefore, only inhalation exposures related to vehicle traffic and horseback riding activities usually need to be assessed for the activity-related air exposures.

For a typical site involving secondary contamination, activities which could potentially generate airborne asbestos include vehicle traffic on dirt roads and agricultural tilling of a contaminated area.

Air monitoring is not usually designed to measure exposure to point concentrations of airborne asbestos for on-site and off-site activities. These exposures are, instead, estimated using a combination of results from empirical experiments in addition to emission and air dispersion models. An emission model is required to predict the rate of release of the contaminant from the site into the air. The dispersion model uses the estimated emission rate to predict concentrations of a contaminant in air around the source.

Emissions of this type may be evaluated by using the results of the U.S. EPA's Environmental Asbestos Roads Study²¹. The results of some experiments performed by California Department of Health Services¹⁹ at the South Bay/Alviso Superfund Site may be used to evaluate individual exposures during some routine activities which involve soil disturbance on a small scale. Due to the lack of quality assurance for these activity studies, the experiments can be used only to yield an order-of-magnitude (or qualitative) estimate.

Efforts to correlate particulate matter emissions with asbestos emissions have been undertaken in hopes that fugitive dust emission models could be adapted for estimating ambient concentrations of asbestos. Addison, et al.,²² have shown, for instance, that trace amounts of asbestos in soils (e.g., 0.001%) may yield airborne asbestos concentrations greater than 0.001 fibers/mL, and that a 1% concentration in soil may yield up to 20 fibers/mL in air. In general, however, current efforts have shown that airborne concentrations of particulate matter do not correlate in a consistent manner with asbestos concentrations, and the U.S. EPA has not developed emission factors specifically for the release of asbestos from soil. The emission models mentioned above have, however, been developed to characterize releases of fugitive dust (soil) from exposed sites due to mechanical disturbances (e.g., vehicle traffic and agricultural tilling)²⁰. The U.S. EPA considers their air pollution manual, AP-42, emission factors for total suspended particulate matter to be a reasonable approach for risk assessments of activity-related exposures providing that the asbestos fibers are relatively short. The fact that TEM fiber counts are much greater than PLM counts at most chrysotile asbestos sites is an indication of short fiber lengths. The U.S. EPA also has provided precedent in using a box model for asbestos decision-making purposes.

It should be noted that for usual activity modeling, the units for the soil asbestos concentrations are expressed in PLM area percent, which were assumed to be equal to PLM weight percent. These soil concentrations are applied to the air emissions modeling, and air concentrations of asbestos in units of PLM ug/m³ were calculated. In order to assess the potential human health impact of inhaling airborne asbestos fibers, air concentration units must be PCM fibers/cm³. Therefore, the

mass of fibers reported as ug by PLM may be assumed to be equal to mass in units of ug by TEM analysis and a conversion factor of 30 TEM ug/m³ = 1 PCM fiber/cm³ may be applied to obtain air concentrations in PCM fiber/cm³.

As mentioned above, a few research efforts have been undertaken in an attempt to determine the impact of some routine activities (e.g., playing and gardening) which involve soil disturbance on a small scale. These studies have been conducted by the California Department of Health Services (DHS)¹⁹ at the South Bay/Alviso Superfund Site. Four general types of activities have been examined: (1) a worst-case scenario in which asbestos contaminated soil was thrown in front of a fan and air concentrations were measured 10 ft downwind at 30 in. above the ground¹⁹; (2) vehicle scenarios in which a truck or car was driven along an asbestos contaminated dirt road and samples were collected upwind and downwind^{19,21}; (3) a playing scenario in which a toy dump truck was filled and emptied for 15 min. and personal air samples were collected at 1 and 4 ft above ground¹⁹; and (4) a gardening scenario in which loose dirt containing asbestos was turned over with a shovel for 15 min. and personal air samples were collected again at 1 and 4 ft above surface level¹⁹.

The results of these activity-related experiments can provide an indication of the potential air concentrations and resulting exposures and risks that may be associated with similar activities conducted at the residential areas located in the vicinity of Superfund sites. The playing scenario was conducted in soil containing approximately 5% asbestos (approximately 13% by TEM); breathing zone air concentrations were estimated to be roughly 1.7 NIOSH fibers/cm³ (equivalent to PCM fibers/cm³). If activities similar to the simulated playing scenario were to occur repeatedly (e.g., every other weekend for several months of the year for a period of several years) among children playing in the residential areas, cumulative asbestos exposures could result in increased lifetime cancer risks exceeding one in one million.

The worst-case and vehicle scenarios for the California DHS experiments resulted in greater impacts on air concentrations than did the playing scenario. The worst-case scenario was conducted in soil containing less than 1% chrysotile based on PLM and roughly 30% asbestos based on TEM and resulted in air concentrations of approximately 200 f/cm³ by PCM. The most experimentally rigorous activity-related experiment was a vehicle scenario conducted by the U.S. EPA²¹. In this experiment, a car was driven back and forth along a 100-ft test section of dirt road in California containing approximately 0 to 4% asbestos, during which 1-hr and 8-hr air samples were taken. Two upwind and four downwind air samples were collected. One-hour median and maximum upwind air asbestos results were 0.01 and 0.09 PCM structure/cm³, respectively. One hour median downwind air asbestos sample concentrations varied from 0.08 to 0.21 PCM structures/cm³, depending on the distance of the sampling station from the experiment location. One-hour maximum downwind air asbestos concentrations varied from 0.23 to 0.9 PCM structures/cm³. Since the majority of soil sample results from the dirt road were less than 1% (by wt), ratios of air concentrations resulting from the vehicle movement to the soil concentrations cannot be calculated. From a qualitative standpoint, however, these results indicate that vehicle use on unpaved surfaces containing asbestos at elevated concentrations could result in elevated air concentrations of potential concern to nearby residents or on-site workers.

Individuals may directly contact and subsequently inadvertently ingest chemicals present in contaminated soil which may adhere to hands, toys, tools, etc. Inadvertent ingestion of chemicals present in soil is most likely to occur in young children, although exposures could possibly occur among adults who engage in activities involving soil contact such as farming or gardening. In asbestos risk assessment, two types of exposures via soil ingestion typically may be evaluated; one involving the lifetime exposure of local off-site residents and one involving the intermittent exposure of adult hikers, campers and hunters to on-site contaminated materials.

Estimating cancer risks for incidental ingestion of asbestos present in soil is complicated because the U.S. EPA¹⁵ has developed a unit risk factor for exposure to asbestos in surface water [1.4×10^{-13}

(fibers/L)⁻¹) only and not for exposure to asbestos from other environmental media where concentrations may be reported on a mass (not fiber) basis. This unit risk factor was used as the basis of the proposed Maximum Contaminant Level Goal (MCLG) for ingestion of water. There are several important uncertainties associated with even this unit risk factor, as discussed in the Hazard Identification section. In order to quantify risks associated with incidental ingestion of asbestos in soil, the U.S. EPA unit risk factor was converted into a mass-based potency factor (mg/kg/day)⁻¹.

This conversion was done only for the purposes of providing a rough indication of the potential excess lifetime cancer risks associated with direct contact with asbestos in soil and subsequent incidental ingestion at a site. The conversion factor from fibers to mass of asbestos was taken to be 0.129×10⁹ fiber per mg asbestos based on TEM drinking water measurements performed at the Illinois Institute of Technology Research¹⁴ in conjunction with development of the proposed MCLG. The converted asbestos potency factor can be multiplied by the CDI to derive an approximate estimate of the excess lifetime cancer risks associated with the specific exposure scenario.

RISK CHARACTERIZATION

Summaries of risks calculated by these methods are presented for two Superfund sites (Tables 1 and 2); background air (Table 3) and public buildings (Table 4). For site A, upperbound cancer risks associated with inhalation of ambient air on-site and downwind are less than an order of magnitude different than the upwind station. These risks are also similar to risks associated with inhalation of ambient air outdoors and in public buildings. Risks associated with specific activities are much higher, however and would be high enough to initiate remediation based on EPA's risk range of 10⁻⁷ to 10⁻⁴. For site B, on the other hand, risks associated with both inhalation by near site residents and casual recreational users exceed the U.S. EPA's risk range. Activity related risks are also high. The highest ingestion risk at either of the sites only slightly exceeds the U.S. EPA's risk range. It should be kept in mind, however, that this calculated value is derived from data on benign neoplasms rather than malignancies.

Table 1
Summary of Excess Individual Lifetime Cancer Risks for Exposure to Asbestos Superfund Site A

Exposure Pathway	Average Case	Maximum Case
Inhalation - Ambient Air		
Station 1 (off-site/upwind)		
- mesothelioma	1E-06 - 2E-05	6E-06 - 1E-05
- lung cancer	3E-07 - 1E-05	1E-06 - 7E-05
Stations 2-4 (on-site)		
- mesothelioma	6E-06 - 1E-04	5E-05 - 1E-04
- lung cancer	2E-06 - 9E-05	1E-05 - 7E-04
Station 5 (off-site/downwind)		
- mesothelioma	1E-06 - 3E-05	7E-06 - 2E-04
- lung cancer	4E-07 - 2E-05	2E-06 - 9E-05
Inhalation - Activity Generated Airborne Asbestos (a)		
Child Playing in:		
Residential Tailings Portions	2E-06 - 3E-05	5E-06 - 1E-03
Non-Residential Tailings Portions	1E-06 - 2E-05	5E-06 - 8E-05
Vacant Lots	NC	1E-06 - 2E-05
Trailer Park Yards	NC	2E-06 - 4E-04
Inhalation - Activity Generated Airborne Asbestos (a)		
Adult Gardening in:		
City Yards	NC	8E-06 - 1E-03
Trailer Park Yards	NC	1E-05 - 2E-03
Inhalation - Activity Generated Airborne Asbestos (a)		
Truck Traffic on Unpaved Surfaces		
Residents Inhaling:		
Dust from Truckyards	NC	>3E-03
Dust from Unpaved Roadways	NC	>3E-03
Street Dust from Paved Roadways	NC	>3E-03
Workers Inhaling:		
Dust from Truckyards	NC	>3E-03
Ingestion of Soil		
Children Playing on:		
Residential Portions of Tailings	7E-06	3E-04
Non-Residential Tailings Portions	2E-06	1E-04
All Other Areas	NC	3E-05

(a) Mesothelioma and lung cancer combined.

Table 2
Estimated Excess Lifetime Cancer Risks for Exposure to Asbestos Superfund Site B

Resident	Average	Maximum
Inhalation - Residential Air (a)	7E-04	1E-02
Inhalation - Recreational Users (a)	2E-04	1E-03
Inhalation - Off-Road Vehicles		
- mesothelioma	5E-06	1E-02
- lung cancer	4E-07	6E-04
Inhalation - Agricultural Tilling		
- mesothelioma	5E-04	3E-02
- lung cancer	9E-04	4E-02
Ingestion - Recreational	6E-07	5E-05
Ingestion - Residential	2E-06	9E-05

(a) Mesothelioma and lung cancer combined.

Table 3
Summary of Ambient Air Asbestos Concentrations and Associated Excess Lifetime Cancer Risks

Air Sample Set	Collection Period	Number of Samples	Arithmetic Average	
			ABA (a) Concentration (ng/m ³)	Total Excess Lifetime Cancer Risks
Quarterly composites of 5 to 7 24-hour U.S. samples (Nicholson 1971, Nicholson and Pundack 1973)	1968-70	187	3.3	3E-05
Quarterly composites of 5 to 7 24-hour U.S. samples (U.S. EPA 1974)	1968-70	127	3.4	3E-05
16-hour samples from 5 U.S. cities (U.S. EPA 1974)	1974	34	13	1E-04
5-day samples from Paris, France (Sebastien et al. 1980)	1974-75	181	0.96	7E-06
5-day, 7-hour control samples for U.S. school study (Constant et al. 1983)	1980-81	31	0.5	5E-05
12-hour samples from Toronto, Ontario (Chatfield 1983)	1980-81	24	0.83	6E-06
12-hour samples from Southern Ontario (Chatfield 1983)	1980-81	40	0.20	2E-06
U.K. urban and rural background (Lofgren et al. 1983)	1979-81	8	5.0	4E-05
Urban Switzerland (Littistorf et al. 1985)	1977	10	0.74	6E-06
Rural Switzerland (Littistorf et al. 1985)	1981-83	10	0.23	8E-06

(a) Sources: Nicholson (Ref 23); Ouellette et al. (Ref 24).

ABA = Airborne asbestos

REFERENCES

- Decker, J.A. and Suder, D., "Asbestos: Problems and Considerations Related to Airborne Asbestos Sampling in an Outdoor Environment," *Proc. Sixth Ann. Conf. Hazardous Wastes and Hazardous Materials*, HMCRI, Silver Spring, MD, pp. 505-508, 1989.
- Decker, J., Woo, N. and McDonald, A., "Environmental Asbestos: Problems Associated with PLM Soil Analysis," *Proc. 9th Nat. Conf. Superfund '88*, HMCRI, Silver Spring, MD, pp. 145-151, 1988.
- U.S. EPA, Health effects assessment for Asbestos. ECAO, Cincinnati, OH, 1984.
- U.S. EPA, Airborne Asbestos Health Assessment Update. Office of Research and Development, Research Triangle Park, North Carolina. EPA 600/8-84 003f, June 1986.
- U.S. EPA, *Superfund Public Health Evaluation Manual*. U.S. EPA Office of Emergency and Remedial Response. EPA 540/1-86-060, 1986.
- "Asbestos: Proposed Mining and Import Restrictions," *Fed. Reg.*, 51, p. 3738, Jan. 29, 1986.
- "Asbestos-Containing Materials in Schools," *Fed. Reg.*, 52, p. 41826, Oct. 30, 1987.
- Occupational Safety and Health Administration (OSHA), 20 CFR Parts 1910

Table 4
Indoor Asbestos Air Levels in Schools and
Associated Excess Lifetime Cancer Risks

Sample Set	Air (a) Concentration (ng/m ³)	Total Excess Lifetime Cancer Risk* for Teachers	Total Excess Lifetime Cancer Risk* for Students
Air in U.S. schoolrooms without asbestos	63	5E-05	1E-05
Air in Paris buildings with asbestos surfaces	35	3E-05	8E-06
Air in U.S. buildings with cementitious asbestos	15	1E-05	3E-06
Air in U.S. buildings with friable asbestos	48	4E-05	1E-05
Air in U.S. schoolrooms with asbestos surfaces	183	1E-04	3E-05
Air in U.S. schools with damaged asbestos	217	2E-04	5E-05
Air in U.S. schools with asbestos surfacing	61	5E-05	1E-05
Ontario buildings	2.1	3E-06 (b)	NA
U.K. buildings	1.5	1E-06 (b)	NA

* = Calculated using teacher exposure assumptions, converting ng/m³ - PCMe f/cm³, and summing lung cancer and mesothelioma.

(a) DATA SOURCE: Ouelette et al. (Ref 24); Nielsen (Ref 23).

(b) Calculated for an office worker.

and 1926. Occupational Exposure to Asbestos, Tremolite, Anthophyllite, and Actinolite. *Fed. Reg.*, 51, pp.22612-22790, June 20, 1986.

9. "Report of the Royal Commission on Matters of Health and Safety Arising from the Use of Asbestos in Ontario," J. Stefan Dupre, Chairman, Toronto, Ontario, 1984.

10. Schneiderman, M., Nisbet, I.C.T. and Brett, S.M., "Assessment of Risks Posed by Exposure to Low Levels of Asbestos in the General Environment," *Bga-Berichte*, 4, pp. 31-37, 1981.

11. Stanton, M.F., Layard, M., Tegriss, et al., "Relation of particle dimension to carcinogenicity in amphibole asbestos and other fibrous minerals," *J. Natl. Cancer Inst.*, 67, pp. 965-975, 1981.
12. Bertrand, R. and Pezerat, H., "Fibrous Glass: Carcinogenicity and dimensional characteristics," In Wagner, J.S. and Davis, W. eds. *Effets Biologiques des Fibres Minerales*, W.H.O., Lyons, France, pp.901-011, 1980.
13. Wylie, A.G., Virta, R.L. and Segreti, J.M., "Characterization of Mineral Population by Index Particle: Implication for the Stanton Hypothesis," *Environ. Res.*, 43, pp.427-439, 1988.
14. National Toxicology Program (NTP), "Broad draft. NTP Technical Report on the Toxicology and Carcinogenesis Studies of Chrysotile Asbestos in F344/N Rats," DHHS, Research Triangle Park, NC, NTP TR 295, 1984.
15. U.S. EPA, "Drinking Water Criteria Document for Asbestos," Environmental Criteria and Assessment Office, Cincinnati, OH, Mar. 1985.
16. U.S. EPA, "Memorandum from Brenda Riddle," Office of Air Quality Planning and Standards, Research Triangle Park, NC, Feb. 19, 1987.
17. U.S. EPA, "Interim Guidance on Compliance with Applicable or Relevant and Appropriate Requirements," *Fed. Reg.*, 52, pp. 32496-32499, Aug. 27, 1987.
18. U.S. EPA, "Ambient Water Quality Criteria for Asbestos," NTIS PB81-117335, 1980.
19. Aqua Terra Technologies, Interim Report South Bay Asbestos Area, 1, Pleasant Hill, CA, 1986.
20. U.S. EPA, "A method for estimating Fugitive Particulate emissions from hazardous waste sites," EPA 600/2-87-066, 1987.
21. U.S. EPA, "Environmental Asbestos Roads Study: Field Work Report," Emergency Response Section, San Francisco, CA, Jan. 1988.
22. Addison, J. Davies, L.S.T., Robertson, A. and Willey, R.J., "The Release of Dispersed Asbestos Fibres from Soil," *Institute of Occ. Med.*, Edinburgh, UK, 1988.
23. Nicholson, W.J., "Airborne levels of mineral fibers in the non-occupational environment," Mount Sinai School of Medicine of the City University of New York, NY, pp. 1-39, 1987.
24. Ouelette, R.P., Dilks, C.F., Thompson, W.C., Jr. and Cheremisnoff, P.N., *Asbestos hazard management*, Technomic Publishing Company, Lancaster, PA, 1987.

Alternatives to the Remedial Investigation/Feasibility Study Process

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INTRODUCTION

Since CERCLA was passed in 1980, the Superfund process at inactive hazardous waste sites has become more institutionalized and cumbersome as time progresses. Although sites are being cleaned up, the U.S. EPA has been severely criticized by environmentalists, industry and Congress alike for lack of progress in the program. A few statistics will enlighten this situation.

As of Mar. 31, 1989, the U.S. EPA¹ estimated that there was a total of 30,844 potentially hazardous sites in the United States. Removal activities had been completed at 1,121 sites; 642 sites were completed through removal action; and work at 41 NPL sites had been completed. Thus, it is apparent that a considerable amount of work still needs to be done. This work proceeds slowly.

For the program as a whole, only 680 RI/FS have been started. Some RI/FS can take many years to accomplish. For example, activity started at the Lowry Landfill in 1984, however the last feasibility study for an operable unit is not scheduled to be completed until 1994, fully 10 yr from initiation of work at the site.

The purpose of this paper is to suggest some alternatives to the traditional RI/FS process which could help to streamline the program with the net result that more sites would be cleaned up in a shorter time period and at less cost. We begin with a discussion of the Superfund process as it currently operates. This background material is followed by a discussion of the current status of the program, from the standpoint of numbers of sites at various stages of the process, types of sites and costs for performing various activities. Last, we make concrete recommendations in several areas which can be readily implemented to streamline the process. The reader should keep in mind that many of the comments in this paper also apply to corrective action under RCRA. In fact, one suggested goal is to merging of these two programs.

CURRENT SUPERFUND PROCESS

This discussion is intended to furnish a baseline which describes the Superfund process as it currently operates. It should be recognized that a Superfund cleanup is an extremely complex process and no two sites are treated in exactly the same way. Additionally, as this is being written (August, 1989), we are between two versions of the National Contingency Plan. Different elements of each version are being applied at different sites to varying degrees. Thus, the information in this section is intended as a paradigm and does not necessarily to represent any particular site.

The first step of the Superfund process is the identification of potentially hazardous sites which may require remedial action and their entry in a data base known as CERCLIS. At this point, or at any time thereafter, a removal action may be conducted at a site due to emergency conditions which may require rapid response or because the situation

at the site may worsen considerably before a full-scale remedial action can be implemented.

In the pre-remedial process, sites undergo a preliminary assessment (PA) and a site inspection (SI) which usually culminates in a scoring by the hazard ranking system (HRS). Currently, if a site scores over 28.5 on the HRS, it is placed on the NPL where it is eligible for investigative and possible remedial action. Approximately 10% of all sites which are initially identified are finally listed on the NPL. Concomitant with this, the Agency for Toxic Substances Disease Registry (ATSDR) conducts a health assessment to determine if an imminent health threat exists or if further community public health studies (e.g., epidemiology and biological monitoring) are necessary.

Once a site is listed on the NPL, it undergoes an RI/FS to determine the nature and extent of contamination and to evaluate alternatives for remedial action. The RI and FS usually overlap in time; for example, there can be initial scoping of alternatives while field data are being collected. The RI starts off with the preparation of a work plan. This process is an evaluation of all data previously collected (e.g., during the SI/PA or by other parties) and an in-depth cost and time proposal for the conduct of the RI/FS. A preliminary risk assessment, identification of applicable or relevant and appropriate requirements (ARARs), determination of data quality objectives (DQOs) and an initial screening of remedial alternatives often accompany the work plan is approved, actual investigative work commences at the site.

The majority of this work involves the collection of samples for chemical analysis with the results being used to determine the nature and extent of contamination. Samples are collected by site personnel and analyzed by the U.S. EPA's Contract Laboratory Program Regular Analytical Services (CLP-RAS). In cases where the RAS cannot meet the requirements of the RI/FS work plan, Special Analytical Services (SAS) are employed. During the time when field work is occurring, the FS engineers are screening initial alternatives.

After the data leave the CLP laboratory, they go through a process of validation which ensures that the data meet the U.S. EPA's QA/QC requirements. The data are then used in the RI report to describe the nature and extent of contamination.

Another use of analytical data from site samples is in the human health risk assessment or public health evaluation which is performed as part of the RI/FS. The objective of the risk assessment is to assist the U.S. EPA in decision making at the site, especially regarding remedial decisions which have a public health basis.

Additionally, during this time, the FS progresses through its final evaluation of alternatives, with the result that one alternative is recommended to the U.S. EPA. Two additional risk assessment activities accompany the FS. The first assessment is a determination of preliminary remediation goals (cleanup levels) for contaminants in various

media at the site; this determination takes health effects and ARARs into account. The second assessment is a health based screening of remedial alternatives which accompanies evaluations of long) and short-term effectiveness and reduction of toxicity as required by SARA.

Following the completion of the RI/FS, the U.S. EPA issues a ROD which states the chosen remedy, justifies its choice and responds to comments received from the public on the RI/FS. The ROD may decide on a no-action alternative. Additionally, a ROD may be issued for a portion or single operable unit at a site. In essence, the ROD is similar to a combination of a final environmental impact statement as used under the National Environmental Policy Act and a contract in which the government commits to ensuring that the site will not present a current or potential threat to public health, welfare or the environment.

After the issuance of a ROD, the site proceeds to the remedial design (RD) stage in which the details of construction for remediation are worked out. This step may be preceded by a conceptual design and also may require additional sampling and analysis over what was performed for the RI/FS. Once the RD is approved, the remedy is implemented as a remedial action (RA). When an effective cleanup has been accomplished, the site is removed from the NPL.

Most sites have ongoing operations and maintenance activities which typically last for 30 yr to cover post-closure monitoring requirements of RCRA. Additionally, if hazardous materials are left on-site in a form where they are still toxic and potentially mobile, the site may be revisited every 5 yr to ensure that the cleanup is still effective.

STATUS OF THE SUPERFUND PROGRAM

As mentioned previously, there are 30,844 potentially hazardous waste sites which have been entered into the CERCLIS inventory¹. There are numerous estimates of the total potential number of hazardous sites in the United States. The General Accounting Office² has analyzed this aspect of the program and determined that there are between 130,000 and 425,000 potentially eligible sites. Preliminary assessments have been completed at 28,101 sites and 9,902 sites have had site inspections performed¹. As time progresses and the worst and most obvious sites are remediated, it becomes more difficult to perform these pre-remedial activities. More sophisticated sampling techniques such as groundwater wells and air monitoring programs are required at sites where wastes are present, but not obvious. It is estimated that current costs for SI/PA activities may exceed \$100,000 and may be as high as \$200,000 per site.

Thus far, 2,053 sites have been scored by the HRS to date¹. In Dec., 1988, the U.S. EPA proposed a revision to the existing HRS which is more sophisticated and uses more principles from risk assessment than the current version. No further action is planned at 12,416 sites, while the U.S. EPA proposed to list 1,163 sites on the NPL. If we use the rule of thumb that 10% of all identified sites are finally added to the NPL, the number of NPL sites could ultimately exceed 40,000.

RI/FS activities have been started at a total of 845 sites, including Federal Facilities¹. Since an RI/FS is usually carried out for all sites listed on the NPL, up to 40,000 RI/FS studies ultimately will be performed. The U.S. EPA currently³ estimates that the cost of an RI/FS is \$1,100,000. Note that this cost has escalated rapidly. As recently as 1985, the comparable figure was \$800,000 per site. Remedial design activities have been performed for 300 sites¹. The costs associated with a remedial design are approximately \$750,000 per site³.

Remedial activities have been implemented or are in progress at a total of 204 sites¹. The U.S. EPA estimates the cost of an average remedial activity to be \$13,500,000³.

Taken as a whole, the costs for an average site, excluding pre-remedial activities, but including the RI/FS, remedial design, remedial action and O & M, are approximately \$19,000,000. If this cost factor were to be applied to the upper bound potential of 40,000 sites, the ultimate cost of the Superfund program would be over \$700 billion.

In addition to cost considerations, there are time considerations. A typical RI/FS requires approximately 1 yr to perform. The U.S. EPA would like to see this time reduced if possible. At some sites, however, this time is substantially prolonged. At the Lowry Landfill site, there are five operable units. One of these units involves an expedited removal action which will be completed by the middle of 1991. The remainder

of the activities leading up to the FS for the last operable unit, however, will not be completed until 1994. The RI/FS studies for the individual operable units will each require about 4 yr to complete.

ALTERNATIVES TO THE RI/FS PROCESS

The remainder of this paper is devoted to recommendations for streamlining the RI/FS process. It is recognized that some of these recommendations may be controversial and that all of them could not be implemented at once. The goal of making these recommendations is to achieve greater flexibility and less institutionalization in the Superfund process. Some of these recommendations could be implemented readily. However, some would require regulatory action such as a revision to the NCP.

Maintain Consistency in Contractors

The U.S. EPA uses numerous mechanisms to procure professional services at hazardous waste sites. These contracts include field investigation teams, technical assistance teams, laboratory management and remedial management.

Throughout the history of the program, various types of contracts have been in place. For example, the REM II contract covered the whole United States and involved a small group of contractors. The REM III and REM IV contracts divided the country in half and used a greater number of contractors. The ARCS contracts are regionalized and will use almost 50 contractors. PRPs and State governments also use a series of contractors.

Often no contractor continuity is maintained and inexperienced contractors are used to satisfy procurement rather than technical requirements. Additionally, artificially strict conflict of interest rules often make it difficult for the most experienced and qualified contractors to work on government contracts and they are relegated to the private sector. The bottom line is that one contracting team should be hired for all activities at a site from SI/PA through remedial design. Unless the contractor fails to perform, the firm should be kept at the site until all these activities have been completed.

Minimize Reliance on Contract Laboratory Program

One of the largest cost elements of an RI is chemical analysis. The stringent quality assurance and record-keeping requirements of the contract laboratory program can add as much as 50% to the cost of performing an analysis. Additionally, there seems to be a common perception that DQO Level IV analysis is required for risk assessment, evaluation of alternatives and engineering design⁴. In reality, the largest source of uncertainty in risk assessment lies in the quantitative toxicological parameters used to characterize risk and the mathematical fate and transport modeling used to calculate exposure point concentrations.

Since the risk assessment will only be as accurate and precise as its component parts, it does not seem reasonable to make the chemical analytical data more accurate than toxicological or modeling results. Evaluation of alternatives also is often carried out in a qualitative fashion with order of magnitude estimates of cost. As with risk assessment, this activity does not require rigorous QA/QC.

In addition to the problem associated with perceived data quality needs, there are some problems with the CLP itself. First, a large proportion of data received from the CLP are often "qualified" (this is the CLP term for data which do not meet the contract requirements). The net result is that decisions for risk assessment and engineering design often are made on the basis of estimated data. In one recent site, for example, fully 85% of the soil analytical data were estimated.

Last, there often is a time delay associated with obtaining CLP analyses due to the large number of samples in the program and the limited number of qualified laboratories. It is difficult to rationalize the additional incremental costs of CLP QA/QC with the large amount of qualified data and long time delays endemic to the program.

In lieu of sending large numbers of samples through the CLP with its attendant cost and time constraints, we propose maximizing reliance on field measurement techniques and on lower degrees of quality assurance (e.g., DQO Level III) for measurements actually performed

in the laboratory, the U.S. EPA¹ has developed an automated system for specifying a wide variety of field analytical methods ranging from atomic absorption and x-ray fluorescence for metals to mobile gas chromatographs for volatile organic compounds to on-site GC analysis for PCBs. Although not mentioned by the U.S. EPA, there are no technical or cost barriers to using on-site, mobile GC/MS.

Data collected by these field measurements could be used for risk assessments, engineering design and selection of alternatives. Only in cases where litigation was anticipated would the more rigorous CLP QA/QC program be used.

Perform the RI/FS Critical Path

At most sites, a complete RI/FS/RD may not be necessary. Evaluation of numerous completed RI/FS studies reveals that there are many redundant elements and that there often is a critical path through a RI/FS which would eliminate redundancy. Since SI/PA activities have expanded recently, for a number of sites, data from an SI/PA may be all that is required to go directly to remediation. An example of this type of site would be one where groundwater contamination from a known source was a problem. If sufficient samples are taken during pre-remedial activities, the identity and a rough idea of the concentration of the chemicals of concern will be known. The remedy is obvious: source control and pump-and-treat.

Groundwater cleanup technology has been studied extensively and the U.S. EPA has developed guidance on remedial actions for contaminated groundwater at Superfund sites². Most typical groundwater contaminants such as volatile organics and heavy metals have ARARs in the form of maximum contaminant levels; thus, the cleanup objective is already known. A remedial response would involve the following: (1) remove the source; (2) install one or more extraction wells in the zone of known contamination; (3) initiate pumping and treatment of contaminated water; (4) use well points (possibly in conjunction with geophysical techniques) to explore the extent of the problem, taking measurements with a portable GC as wells are drilled; and (5) install new extraction wells as necessary.

Similar scenarios could be envisioned for contaminated soils. Again, the U.S. EPA has produced guidance for treatment of CERCLA soils³. When contaminated soils are discovered as part of pre-remedial activities, field screening techniques may be rapidly deployed to determine the extent of the problem. Preliminary remedial objectives (numerical cleanup goals) may be calculated using the Preliminary Pollutant Limiting Value⁴ (PPLV) approach.

Excavation or in situ treatment could be preceded by field analysis. For example, at an inactive secondary lead refinery site, a portable x-ray fluorescence unit could be used to determine on a real-time basis those areas where lead concentrations exceed the cleanup goal calculated by the PPLV approach. The analytical unit could be followed by the construction unit which would excavate the lead-contaminated soils for subsequent treatment.

Information from other U.S. EPA programs could be used to identify treatment technologies. For example, if a listed RCRA waste was identified, then the best demonstrable available technology as identified in the land disposal restrictions could be used.

Combine all Public Health Related Activities

Currently three public health evaluation activities take place at all Superfund sites. These three separate evaluations include the HRS

scoring, the risk assessment performed by the U.S. EPA and the health assessment performed by ATSDR. Again, with increased SI/PA activities and HRS scoring taking on more of the attributes of risk assessment, it may be possible to eliminate the HRS entirely and go directly to the baseline risk assessment. Preferably, risk assessments would be performed in an iterative manner. The first risk assessment would be based on data from the SI/PA. If these data were adequate to demonstrate an actionable level of risk, no further work would be required. If the data were not adequate, exposure-based sampling plans could be designed to fill the data gaps. In no case would data which were extraneous to the risk assessment process be collected.

To eliminate the redundancy caused by the ATSDR Health Assessment, we suggest that ATSDR propose guidelines for conducting these activities. These guidelines could be provided to risk assessment contractors and integrated into the baseline risk assessment. For example, statistical analysis of cancer incidence in a given area to determine if the local observed incidence is greater than the norm observed for the state is an activity which is delegated to ATSDR, often is performed by state or local health departments and fails to be integrated into the Superfund process. This activity could be performed by qualified risk assessment contractors and become part of the baseline risk assessment.

Privatize the Superfund Process

Recently, a great deal of attention has been paid to the role which contractors are playing in Superfund. The U.S. EPA has been criticized, with allegations being made that contractors are writing Agency policy, for example. One solution to this problem would be to remove all U.S. EPA personnel from the Superfund management process and transfer them to policy formulation roles. Superfund management could be taken over by contractors. There are, indeed, many contractors with the requisite experience to manage large engineering projects which would be directly transferrable to Superfund management. Under this option, the Superfund staff would be located at U.S. EPA headquarters and be responsible for policy, enforcement and ensuring consistency among contractors.

REFERENCES

1. Memorandum from T. Juszczak, Director Resource Management Staff, OSWER, to J. Cannon and R. Duprey, dated May 16, 1989, entitled "Superfund Progress Report as of March 31, 1989."
2. General Accounting Office (GAO) 1987, Superfund: Extent of Nation's Potential Hazardous Waste Problem Still Unknown. GAO/RECD-88-44.
3. U.S. EPA National Priorities List for Uncontrolled Hazardous Waste Sites—Final Update No. 5, *Federal Register*, 54(61), pp. 13296-13317, Mar. 31, 1989.
4. U.S. EPA, *Data Quality Objectives for Remedial Response Activities*, EPA/540/G-87/003, Office of Emergency and Remedial Response, Washington, D.C., 1987.
5. U.S. EPA, *Field Screening Methods Catalog*, EPA/540/2-88/005, Office of Emergency and Remedial Response, Washington, D.C., 1988.
6. U.S. EPA, *Guidance on Remedial Actions for Contaminated Groundwater at Superfund Sites*, EPA/540/G-88/003, Office of Emergency and Remedial Response, Washington, D.C., 1988.
7. U.S. EPA, *Technology Screening Guide for Treatment of CERCLA Soils and Sludges*, EPA/540/2-88/004, Office of Solid Waste and Emergency Response, Washington, D.C., 1988.
8. Dacre, J.C., Rosenblatt, D.H. and Cogley, D.R., "Preliminary Pollutant Limit Values for Human Health Effects," *Environ. Sci. Technol.*, 14(7), pp. 778-784, 1980.

Optimizing the Use of Soil Gas Surveys

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ABSTRACT

Recently there has been a significant increase in the use of soil gas surveys as an assessment tool to investigate hazardous waste sites. The conventional soil gas survey technique was developed to investigate subsurface contamination from volatile organic compounds by measuring the concentration of their vapors in shallow soils. With benefits that include cost-effectiveness, thoroughness, safety and speed, soil gas investigations have become commonplace staple in the remedial investigation process.

Widespread acceptance and use of this technology has spawned numerous techniques and vendors with a wide array of sampling, analysis and interpretation services. Soil gas surveys range from simple, do-it-yourself techniques to in situ testing providing detailed, real-time analytical data.

This paper presents an overview of available techniques and methods to determine the level of survey sophistication required to meet specific remedial investigation objectives. Recent studies conducted by Earth Technology are discussed to illustrate the implementation of site-specific soil gas surveys.

INTRODUCTION

Volatile organic compounds establish a vapor phase plume in the intra-granular space in the vadose zone above contaminated areas. Soil gas survey techniques allow one to exploit this transport process specific to volatiles in order to build a two-dimensional picture of soil and/or groundwater contamination. This information can be utilized in both contaminant source detection and plume delineation. The key characteristics which make the soil gas survey an effective component of field investigations are:

- Rapid acquisition and turn-around time of data
- Ability to use soil gas data to focus or redirect project resources
- Capability to thoroughly screen large areas at a relatively low cost

The foundation for successful application of soil gas techniques lies in clearly identifying remedial investigation objectives and designing a survey to support these goals. Figure 1 presents the life-cycle of a typical phased remedial investigation along with the stages where soil gas surveys may be appropriate.

Available Survey Techniques

A broad assortment of methods exists for soil gas sample acquisition, analysis and interpretation which provide a range of qualitative/quantitative results. Each method has its appropriate application—from site screening to plume boundary delineation for recovery well placement, etc. Selecting the optimal approach requires examining the site and contaminant characteristics, determining analytical needs and determining the level of interpretation required.

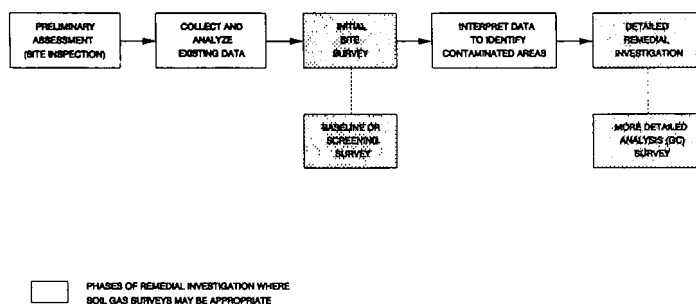


Figure 1
Appropriate Phases of Remedial Investigation
For Soil Gas Survey

Economic and scheduling constraints must also be incorporated into this analysis. Figure 2 presents a step-by-step approach designed to identify the degree of survey sophistication necessary for project success. The following sections address these key elements and present pertinent technical data essential to proper survey scoping.

Sampling

Sampling for soil gas can be done at any depth above the groundwater table due to the existence of a vapor concentration gradient from the contaminant source/plume to the surface. Standard practices involve sample collection in the vadose zone at depths where surface/atmosphere effects are minimal. Soil gas collection depths typically range in the 3- to 5-ft depth level. Compounds which are amenable to soil gas detection at this depth can be characterized as those which possess high vapor pressures under ambient conditions, low aqueous solubilities and degrade slowly in the environment. For compounds which degrade quickly, a depth of 10 ft is preferable to reduce the effects of oxidation/microbial breakdown. Other factors which influence sampling depth include the subsurface conditions such as perched aquifers or groundwater at great depth.

Soil gas samples are obtained through headspace volatilization of a containerized soil sample or through in situ extraction of gas using shallow probes. Soil samples can be obtained using a hand auger, while in situ gas samples require more sophisticated equipment. In situ sampling can be performed with specialized equipment such as small-volume, slide hammer driven probes or hydraulically driven cone penetrometer units mounted on a vehicle. Once a representative sample has been obtained, on-site or remote analytical qualitative or quantitative work can be completed.

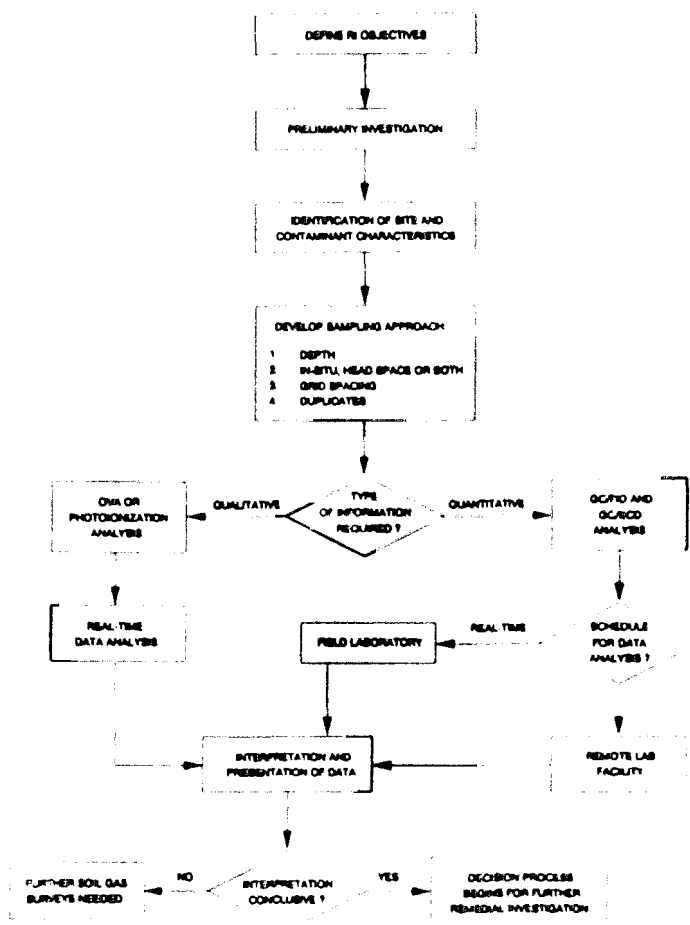


Figure 2
Decision Tree for Optimization of Soil Gas Survey

Analysis

At this point in the survey, there is little variation in the costs (sample acquisition); it is the analytical techniques which generally drive project costs and the quality/detail of the results. Techniques employed in the characterization of soil gas samples are shown in Table 1 and range from qualitative measures of total volatile organic compounds to a quantitative compound by compound analysis. Qualitative results require ionization and detection of volatile sample components, while quantitative data require chromatographic separation of the volatile components followed by ionization and detection using electron capture methods.

Table 1
Soil Gas Analysis Techniques

Analytical Technique	Quality of Results	Application (sensitivity)
Organic Vapor Analyzer (OVA)	Qualitative	Real-time analysis, Flame Ionization Detection for Total Organics (ppm)
Photoionization Detector	Qualitative	Real-time analysis, Ionization of volatile organic compounds limited by lamp photoionization energy (ppm)
GC/FID GC/ECD	Quantitative	Full range of EPA volatile priority pollutants

All these analytical methods can be used on-site as samples are acquired or remotely at a full-service laboratory. Key factors which should be considered when selecting the optimal analytical strategy include:

- Required turn-around time
- Value of qualitative vs. quantitative results
- Number of compounds to be analyzed
- QA/QC requirements

Costs and quality/detail need to be balanced at this point for the most useful results. Typical unit costs for the acquisition, analysis and interpretation of soil gas samples are provided in Table 2.

Table 2
Soil Gas Analysis Unit Costs

Analytical Technique	Analysis Location/ Sample Collection Rate	Unit Costs
Qualitative: Total Volatile Organics		
Organic Vapor Analyzer (OVA) Photoionization Detector	Real-time (3 samples per hour)	\$ 17.50
Quantitative: 8-10 compounds		
GC/FID GC/ECD	Real-time (2 samples per hour)	\$ 180
GC/FID GC/ECD	Remote Lab (3 samples per hour)	\$ 195

INTERPRETATION

Data presentation and subsequent interpretation is best done by developing isoconcentration maps of the soil gas survey results. Software is available which can quickly contour results for real-time use. Qualitative/quantitative data can be superimposed on a site map which contains all essential features such as the survey grid, existing boring and well locations and related data, groundwater flow direction, etc. Once all pertinent site-specific data have been collected, the soil gas data can yield:

- Relative location of subsurface contaminant sources
- Boundary of contaminant plumes
- The existence of preferential groundwater flow patterns

High quality data can provide information about the physical state of contaminants (i.e., dissolved species or free product), and the condition of the contaminant (weathered or degraded).

APPLICATION OF SOIL GAS SURVEY TECHNIQUES

Recent soil gas studies conducted by Earth Technology have ranged from qualitative measures of total volatile organic compounds to quantitative, compound-specific surveys, based on project needs. The following discussions present information about two site-specific surveys along with relevant details to illustrate the range of soil gas uses.

Abandoned Fuel Line Investigation

A preliminary screening soil gas survey was recently completed on a 1.5-mi long abandoned jet fuel line. Remedial investigation tasks included locating the 6-in. fuel line using geophysical techniques followed by a soil gas survey designed to delineate segments of the line where subsurface contamination had occurred.

Sampling involved probe penetrations at approximately 100-ft intervals, 2-ft off the center of the fuel line. A total of 55 samples was collected over the entire length of the line. Head-space analyses were conducted using a hand-held OVA. Sampling points, along with survey results, are presented in Figure 3.

This survey very clearly delineated segments of the line where volatile organic contamination existed due to jet propulsion fuel (JP-4) leaks. Based on these results, several soil borings were completed along the line to further delineate vertical and lateral contaminant migration.

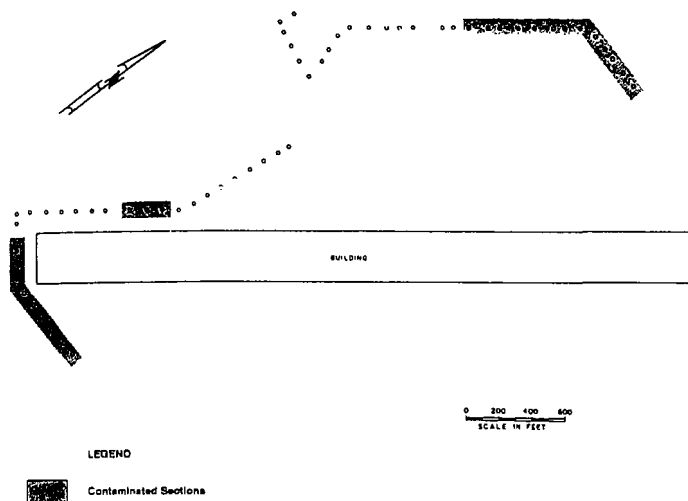


Figure 3
Abandoned Fuel Line Qualitative Soil Gas Survey

Plume Delineation to Support Remedial Action

A quantitative soil gas survey is currently underway to support placement of groundwater monitoring wells and a subsurface groundwater collection system. Contaminants have been thoroughly characterized through previous work at the site; however, the leading edge of the contaminant plume has not been defined. Figure 4 shows the soil gas survey area located downgradient of existing groundwater monitoring wells. Groundwater contaminants at this site include trichloroethene (TCE) and its degradation products. The survey incorporates GC/FID/ECD analysis of the samples to build a detailed picture of contaminant migration.

CONCLUSIONS

Soil gas survey techniques are powerful, cost-effective tools to survey and delineate volatile organic contaminant sources and migration. Several techniques exist which provide a wide range of qualitative and quantitative information. Careful review of investigation objectives to identify data quality needs results in the selection of the appropriate method to support future remedial efforts.

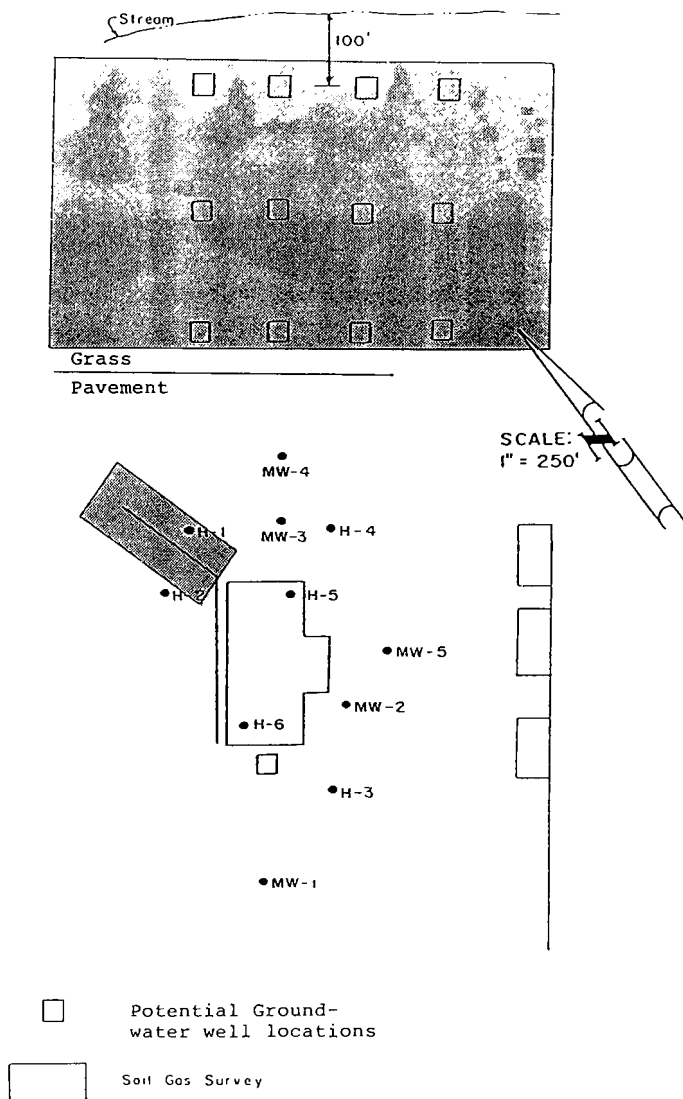


Figure 4
Plume Delineation to Support Remedial Action Development

Comparison of Air Stripping Versus Steam Stripping for Treatment of Volatile Organic Compounds in Contaminated Groundwater

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ABSTRACT

In many cases, steam stripping can be a viable alternative to air stripping for removal of VOC contaminants from groundwater. Each method is applicable to a broad range of VOC compounds normally found in contaminated groundwater, but each situation should be thoroughly researched or pilot-tested prior to design. When compared to air stripping systems requiring vapor recovery, steam stripping offers many advantages including greater environmental protection, better operating performance, less operating attention and lower capital cost.

Pre-assembled air strippers and vapor recovery units, including instrumentation and internals, are readily available from vendors. Although packaged steam stripping units are not as readily available, they can be designed using basic process engineering principles and a relatively simple process flow train. While design of air strippers requires mass transfer data or pilot testing, steam strippers often can be designed from boiling point data readily available in the literature thereby eliminating the need for expensive pilot testing.

INTRODUCTION

While a great deal of information has been published regarding air stripping of groundwaters contaminated with volatile organic compounds (VOCs), relatively little has been published regarding steam stripping. Although steam stripping has not been as widely used for groundwater treatment as air stripping, it has been used extensively in the chemical process industry for many years for solvent recovery and is a well-demonstrated technology. Air stripping probably is used more frequently because most cases involve low groundwater solvent concentrations (in the ug/L range) and many are in remote locations. These conditions favor air stripping since VOC-laden exhaust air often can be released uncontrolled to the atmosphere without significant impacts on ambient air quality.

However, for facilities treating relatively high concentrations of VOCs and/or large flow rates, air emissions can be significant and therefore subject to control prior to release. Increasingly more facilities are being required to control VOC emissions from air stripping facilities. Typically, air purification is accomplished with vapor recovery systems using activated carbon as a VOC-adsorption medium. Some special circumstances (high toxicity) may justify exhaust air incineration as a method of VOC control. However, these systems add significantly to the project cost and operating complexity.

For cases in which treatment of the exhaust air for VOC removal is required, steam stripping should be considered as an alternative for treatment of contaminated groundwater. In appropriate situations, it may offer a number of advantages over air stripping with vapor recovery, such as:

- Greater environmental protection

- Simplicity of operational control
- Better operational efficiency
- Lower capital costs
- Smaller equipment space requirements

The purpose of this paper is to provide information regarding the applicability of air and steam stripping, and factors to be considered in the evaluation of each method, for treatment of VOC-contaminated groundwaters. Information provided in this report is based on a study and a preliminary design evaluating air stripping versus steam stripping for an industrial facility required to treat 25 gpm of groundwater containing an average trichloroethylene (TCE) concentration of 300 mg/L and a maximum concentration of 1200 mg/L.

AIR STRIPPING

Air stripping is a well-documented method for the removal of small amounts of volatile organic chemicals from water. The potential effectiveness of air stripping can be evaluated using Henry's law, which provides a measure of the relative volatility of the VOC. According to Henry's law, the relative concentrations of VOC in the water and air will be functions of the VOC vapor pressure. Values for Henry's law constants can be calculated, determined from pilot studies or obtained from the published literature. Table 1 presents information published for five chlorinated solvents commonly found in contaminated groundwater¹.

Compounds with relatively large Henry's law constants are more easily stripped than compounds with lower values. As can be seen in Table 1, the value of Henry's law constant is very much temperature dependent. While many VOCs can be air stripped at ambient temperatures, those with low volatilities at ambient temperatures, those with low volatilities at ambient temperatures may require preheating of the groundwater entering the stripper². Preheating of the stripper feed also might be required during winter operations in extremely cold climates.

A schematic diagram of a typical packed tower air stripper with vapor recovery is shown in Figure 1. Contaminated groundwater is sprayed on the top of the tower and allowed to flow by gravity down through the packing. Air is blown upward through the packing and then passed through a vapor recovery unit. In the tower, VOCs are transferred from the water phase to the air phase. The water exiting the tower normally is acceptable for discharge.

To size a stripping tower, mass transfer coefficients are required to determine how much VOC contaminant is transported from the water into the air per unit volume of packing per unit time. Appropriate mass transfer coefficients are difficult to obtain because their values are dependent upon air loading, water loading, VOC concentrations, operating temperatures, packing type, packing size and properties of

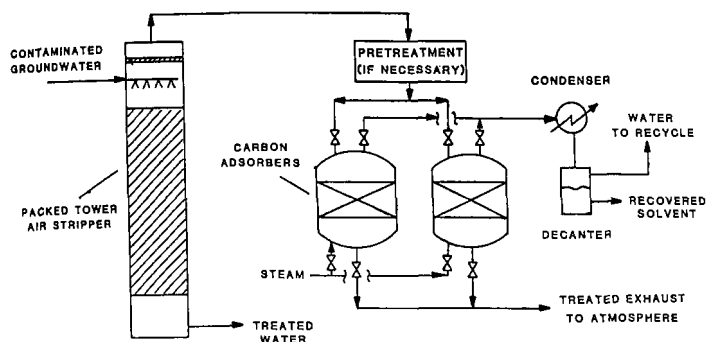


Figure 1

the fluids and solutes to be removed. However, because of the large number of interdependent factors, the overall efficacy of air stripping is sensitive to temperature, influent VOC concentrations and the air/water ratio, even for a well-designed tower. To assure consistent operational results in an air stripping system, the design must make provisions to accommodate possible variations in such conditions as air and water temperature and VOC concentrations in the groundwater.

Vapor recovery systems used with air stripping usually consist of two or more carbon adsorption vessels connected in parallel. The use of multiple vessels allows for on-site regeneration of one vessel while the other is on-stream. While various regeneration systems are available using hot inert gas, steam is used most often since it is economical and normally is readily available. Flow between the vessels can be controlled automatically by a timer or via an in-stack monitor. Following the desorption step, the steam is condensed and the VOCs are separated in a decanter. The condensed water layer is returned to the stripping tower inlet system.

STEAM STRIPPING

Table 2 lists the organic solvents most frequently found in remedial action projects at NPL sites³. Most of the solvents on the list (13 out of 14) are readily amenable to steam stripping.

Steam stripping is technically feasible when the following conditions are present:

- The VOC will form an azeotrope with water which has a boiling point less than that of water
- The condensed overhead azeotropic product separates into an organic layer and a water layer

Table 1
Henry's Constant for Five
Chlorinated Solvents¹

Compound	Henry's Constant (m ³ -atm/mol @ 20°C)	Temperature dependence equation (°K)
1,1,1-trichloroethane 4262/T)	0.0132	Hc = exp(10.21-
tetrachloroethylene 5119/T)	0.0130	Hc = exp(13.12-
trichloroethylene 4929/T)	0.00764	Hc = exp(11.94-
chloroform 4180/T)	0.00333	Hc = exp(8.553-
methylene chloride 4191/T)	0.00225	Hc = exp(8.200-

Except for phenol, all of the VOCs listed in Table 2 form azeotropes with water, separate into distinct layers upon condensation and thus are amenable to steam stripping. Data regarding azeotropic compositions and boiling points for most of these VOC compounds are presented in Table 3. All of these materials form low boiling azeotropes, i.e.,

Table 2
Most Frequently Reported Organic Solvents³

Rank	Substance	Percent of Sites
1	Trichloroethylene	33
2	Toluene	28
3	Benzene	26
4	Chloroform	20
5	Tetrachloroethylene ¹⁶	
6	Phenol	15
7	1,1,1-Trichloroethane	14
8	Ethylbenzene	13
9	Xylene	13
10	Methylene chloride	12
11	Trans-1,2-Dichloroethylene	11
12	1,2-Dichloroethane	8
13	Chlorobenzene	8
14	1,1-Dichloroethane	8
15	Carbon tetrachloride	7

the boiling point of the solution is less than the boiling point of either pure constituent. Also, all of the azeotropic compositions shown in Table 3 are substantially higher in VOC content than in water content. Both of these conditions are favorable factors for steam stripping. Additionally, all of the VOCs have limited solubility in water, thereby yielding a two-phase system upon condensation.

Table 3
VOCs Commonly Found in Contaminated Groundwater
Which can be Steam Stripped³.

Substance	Azeotropic Boiling Point (°C @760 mm)	Azeotropic Composition (Weight % water / solvent)
Trichloroethylene	73.1	6.3 / 93.7
Toluene	85.0	20.2 / 79.8
Benzene	69.4	8.9 / 91.1
Chloroform	56.3	3 / 97
Tetrachloroethylene	88.5	17.2 / 82.8
1,1,1-Trichloroethane	86.0	16.4 / 83.6
Ethylbenzene	92.0	33.3 / 66.7
Xylene	94.5	40 / 60
Trans-1,2-Dichloroethylene	71.0	8.2 / 91.8
Chlorobenzene	90.2	28.4 / 71.6
Carbon tetrachloride	66.8	4.1 / 95.9

It should be noted that for cases in which several different VOCs are present, ternary or complex azeotropes may be formed; however, these also may boil below the boiling point of water.

A block flow diagram of a steam stripping system that can be used for removal of VOC from groundwater is shown in Figure 2. Contaminated groundwater is recirculated through a steam reboiler,

which provides heat for vaporization of the azeotrope. Instead of the indirect heating method using a reboiler, live steam can be added directly into the column. Direct overhead vapor, consisting of the VOC azeotrope and some excess water, is condensed and collected in a decanter vessel. In the decanter, the VOC and water separate; the water layer flows by gravity or is pumped via a reflux line back to the stripper column. The VOC layer can be controlled by an interface controller which can sense either specific gravity or conductivity. Steam-stripped groundwater from the column is passed through a feed preheater to cool the effluent and to heat the feed entering the column. The water is then discharged.

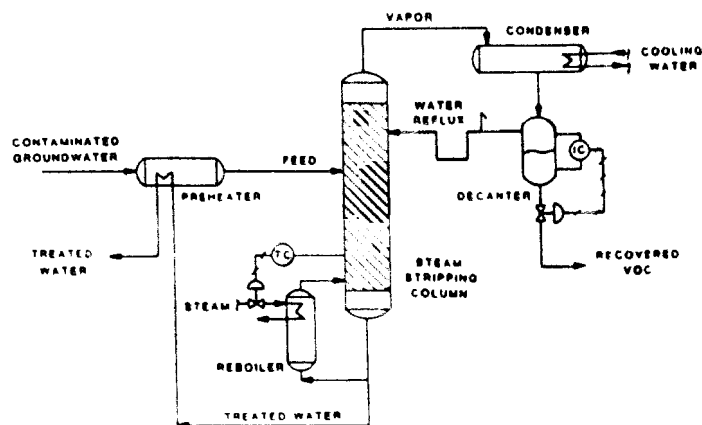


Figure 2

Unlike air stripping which is sensitive to many variables, steam stripping is dependent only upon the operator maintaining the temperature at the column bottom above the boiling point of the azeotrope. This temperature level ensures that the VOC cannot exist in liquid form within the column. In practice, the temperature in the column can be maintained at or near the boiling point of water to ensure proper VOC removal.

A temperature control loop regulates the steam supply so that the column temperature remains above the azeotrope boiling point or the boiling point of water. Because the system is totally enclosed, there is no contaminated off-gas requiring treatment. Sizing of the steam control system is dependent only upon the flow rate of the feed and is insensitive to the VOC concentration as long as there is an excess of water present and the column bottom temperature is maintained above the boiling point of the azeotrope.

CONSIDERATIONS IN THE SELECTION OF AIR OR STEAM STRIPPING

Items to be considered in selecting an air or steam stripping system include design and operating simplicity, capital and operating costs, environmental impacts and requirements for pretreatment.

Design and Operating Simplicity

Design and operating simplicity are important factors to be considered in the evaluation since they affect capital and operating costs, operating performance and operating and maintenance labor requirements.

While both air and steam stripping systems can be fully automated, a steam stripper requires less operator attention and less instrumentation than an air stripper since the only critical operating variable is the temperature in the stripper column bottom. On the other hand, air stripping systems are sensitive to a number of variables including:

- Air and water temperatures
- Air and water flows
- Air humidity
- Contaminant concentration variability
- Contaminant composition
- Air/water ratio
- Tower pressure drop

Additionally, air stripping systems may require VOC recovery units which add significantly to operating complexity and cost. Such recovery units are not usually required with steam stripping where efficient condensers are installed. These vapor recovery units often are required to have a high capture efficiency (95 to 98%), which approaches state-of-the-art performance for such equipment. For these applications, there are a number of design and operating factors which can affect system performance.

Vapor recovery for air stripping is comprised of three closely related process operations: adsorption, desorption and cooling/drying. After carbon regeneration with steam, a hot, wet carbon bed will not remove organics from air effectively since high temperature and humidity do not favor complete adsorption. Therefore, it is important to allow an adequate cycle time to completely dry and cool the beds with air. It may be necessary to add an air preheater to dehumidify such air entering the adsorbers. In hot humid climates it may be necessary to precede the air preheater with an air cooler to condense moisture, since only preheating may increase the temperature of the beds to such an extent that adsorption efficiency will be reduced.

Proper construction materials are critical to the design life of the adsorber vessels due to the moisture present during regeneration cycles. Stainless steel may not be acceptable for chlorinated solvents because of the possibility of chloride stress attack. Therefore, exotic material such as Hastelloy may be necessary.

In order to achieve consistently high removal efficiencies of 95 to 98% in the vapor recovery unit, careful operating and maintenance attention is required. Minor failures of the many vapor recovery system components (such as small leaks in valves, piping or adsorber vessels) can affect operating performance. Valve selection is especially important because valves isolate the air outlet from the air inlet stream. Thus, a small valve leak may result in unacceptable outlet VOC concentrations even when adsorption is accomplished in the operating adsorber vessel.

Also, while sequencing between the adsorber vessels may be automatically controlled, periodic operator surveillance is required due to the potential for release of VOC air pollutants. In summary, air strippers with vapor recovery units are more complex systems to design and operate than steam stripping systems.

Capital and Operating Costs

The choice of materials of construction has a great influence on capital costs. While fiberglass-reinforced plastic is usually a cost-effective choice for air strippers, steam stripping towers and vapor recovery adsorber vessels may require more exotic materials. However, since equipment used with steam stripping systems is relatively small-scale, the use of expensive materials such as glass-lined vessels and titanium heat exchangers may not be cost-prohibitive. In a 1986 industrial case study of the treatment of 25 gpm, we found that a glass-lined vessel could be purchased for \$22,000 and a titanium heat exchanger could be purchased for \$10,000.

Typically, the purchased costs of vapor recovery units are significantly higher than the air stripping towers. In the study described in this paper, the bare equipment cost for the vapor recovery unit was \$83,000 (for lined, steel adsorber vessels) compared to the equipment cost of \$30,000 for the air stripper. Using Hastelloy adsorber vessels would have increased the equipment cost of the vapor recovery unit to \$140,000. Also, associated costs such as foundations, piping, installation costs and instrumentation can significantly add to the cost of vapor recovery units.

Table 4 shows an annual operating cost analysis for a packed tower air stripper versus steam stripper for the treatment of 25 gpm of TCE-contaminated groundwater. As shown in Table 4, the annual costs are slightly lower for the steam system. The comparison is based on installation cost of the stripping equipment and associated ductwork, piping and instrumentation. The costs do not reflect water handling equipment to and from the strippers such as pumps, storage tanks and other ancillary equipment that would be common to both systems. Also, the capital cost analysis does not include the cost of foundations, which can be expected to be higher for the air stripping/vapor recovery system due to its greater space requirements.

Table 4
Annual Cost Comparison of Air versus Steam Stripping

Cost Item	Air Stripper/ Vapor Recovery	Steam Stripper
Capital Charges*	60,000	26,000
Utilities		
Electricity (\$0.05/KWH)	3,500	
Steam (\$6/1000 lb)	3,600	38,000
Carbon Replacement	2,000	
Total	<u>\$69,100</u>	<u>\$64,000</u>

(1) Annual capital charges @24% of installed cost including: depreciation and interest @15%; taxes, insurance, and administrative charges @4%; maintenance and materials @5%.

The installed cost of the air stripper/vapor recovery system is \$250,000 versus \$108,000 for the steam stripping system. The steam stripper cost includes a glass-lined column and two titanium heat exchangers required by the high chloride content and low pH of the water entering the column. Use of such exotic materials is probably not necessary in most cases. Use of carbon steel equipment would lower the installed equipment cost by about 25%. The use of carbon steel may be acceptable if sufficient corrosion allowance is provided to achieve the equipment design life expectancy.

Since operating labor requirements are very site-specific, estimation of labor costs associated with each system is difficult. For simplification, the cost analysis assumes labor and maintenance costs are a fixed percentage of the overall capital cost. However, the air stripping system is likely to require more operating attention since it is more complex.

For this example, treating 25 gpm of groundwater contaminated with 300 mg/L of TCE, the capital cost of an air stripper/vapor recovery system is greater than the steam system but utility costs are lower. While this cost picture will generally be the case in comparing these two types of systems, the more concentrated the groundwater stream, the more the economics will favor steam stripping. Since the temperature of the entire waste stream must be raised to approximately the boiling point of water in steam stripping applications, the utility cost associated with steam stripping is proportional to the volume of water treated and independent of the concentration of the contaminant.

For air stripping with vapor recovery, the amount of steam required for regeneration of the carbon bed is proportional to the amount of carbon present (which is proportional to the amount of VOC in the groundwater), since the steam is used to increase the temperature of the entire bed for desorption. Therefore, using our example of a more concentrated stream (> 300 mg/L), steam stripping would offer greater annual savings per pound of VOC removed, while at some concentration below 300 mg/L, the air stripper would begin to offer more cost savings. Of course, if waste stream is available, the utility cost of the steam would

be insignificant and steam stripping most likely would have lower operating and capital costs.

System Performance and Environmental Protection

Emission control requirements for stripping units often are in the range of 98% removal of VOC emissions, which approaches state-of-the-art performance for such systems. Because of the difficulties that can be encountered with the vapor recovery units associated with air strippers, steam stripping can offer greater environmental protection. Since steam stripping is a totally enclosed system, there are no air contaminants released to the atmosphere. Also, steam stripping is not prone to an air emission release as can occur in the event of an upset in the vapor recovery system used for air stripping. Furthermore, the additional emission source presented by an air stripping/vapor recovery system will increase the environmental regulatory burden of the operator since it may involve stack emission testing, permit modification and associated paperwork burdens. In addition to the cost savings involved, the elimination of an air emission source with potential to emit hazardous pollutants offers significant non-economic rewards.

Other Considerations

Some groundwaters have a high degree of hardness which can cause scaling problems in both the air and steam stripping equipment. While the hardness can be a problem for both systems, steam stripping systems usually are more susceptible to scaling since they operate at higher temperatures. Also, heat exchangers in steam stripping systems are added potential problem areas for scaling. To strip groundwater with high hardness, the water may need some type of pretreatment such as pH adjustment or water softening.

Packed tower air strippers often plug due to biological growth accumulation on the packing, a phenomenon that does not occur in steam stripping. Biological fouling requires periodic shutdown of the air stripping system to wash the internals with a hypochlorite solution or some other chemical. This maintenance process adds to the operating cost and requires periodic system shutdown for cleaning.

CONCLUSIONS

The preceding paper has demonstrated that, in many cases (especially those cases of highly contaminated groundwater), steam stripping offers many advantages over air stripping for cleanup. These advantages include: cost savings, better controllability, easier recovery of the contaminants and fewer operating problems. Moreover, data for design of steam strippers are readily available from the literature, while design of air stripping systems often requires pilot testing.

REFERENCES

1. J.M. Gosset, et al., Mass Transfer Coefficients and Henry's Law Constants for Packed-Tower Air Stripping of Volatile Organics: Measurements and Correlations, prepared by Air Force Engineering and Services Laboratory at Tyndall Air Force Base, FL, June, 1985.
2. K. Sullivan, et al., Pilot Testing and Design of a Modular High-Temperature Air Stripping System for Waste Cleanup, presented at Annual Technical Meeting of the Water Pollution Control Federation, New Orleans, LA, Sept., 1984.
3. U.S. EPA, CERCLA 301 "C" Study, Dec., 1984.
4. C.S. Parmele, O'Connell, W.L. and Basdekis, H.S., "Vapor-phase adsorption cuts pollution, recovers solvents," Chem. Eng. 86(58), 1979.

In Situ Vapor Stripping: Preliminary Results Of A Field-Scale U.S. EPA/Industry Funded Research Project

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INTRODUCTION

A 2-yr. long in situ vapor stripping research program is being conducted at the CIBA-GEIGY Plant in Toms River, New Jersey. The research is being conducted by ECKENFELDER INC. and is co-funded by the U.S. EPA Small Business Innovative Research Program and CIBA-GEIGY Corporation. The research project, which began in August of 1988, involves the closely monitored installation of in situ vapor stripping technology. The research program calls for the vapor stripping facilities to operate for a period of 1 yr. This paper reports on findings through the first 10 mo. of operation.

The general objectives of the research program are: (1) to improve the scientific foundation for this remedial technology; (2) to better define its technical limitations; and (3) to further refine the mathematical model of the stripping process developed in an earlier phase of the research program. Further objectives of the research are: (4) to study this technology at the lower concentrations of volatile organic constituents as experienced near the end of remedial actions, and (5) to evaluate the performance of granulated activated carbon as a treatment agent for the extracted vapors at these low levels.

Site Geology

The CIBA-GEIGY Toms River Plant lies in the Atlantic Coastal Plain Physiographic Province in Toms River, New Jersey. The site is underlain by the Cohansey Sand, a geologic formation consisting predominantly of moderate to high permeability sand, interbedded with finer-grained, often lenticular, strata of silt and clay. The site chosen for the research program lies within the central production area of the 1200 ac. plant site at the location of several recently demolished chemical process buildings. Soil contamination was detected in the razing of the buildings, presumably resulting from underground storage tank leaks and process pipeline leaks.

INITIAL CHARACTERIZATION OF THE RESEARCH SITE

A drilling program was undertaken in order to characterize initial levels of soil contamination within the study area. The program consisted of 26 exploratory borings and collection and analysis of 40 soil samples representing horizontal and vertical locations. The complete menu of organic priority pollutant analyses was run. Table 1 lists the specific chemicals detected and their respective concentration ranges (including limits of detection). Not all chemicals were identified as present at all probe locations or at all depths at a given location. No acid extractable compounds were detected at a limit of detection of 2.0 ppm (mg/kg) with the exception of one sample which exhibited a phenol value of 3.0 ppm. The most prevalent soil contaminants in the study area are 1,1-dichlorobenzene, 1,3-dichlorobenzene, 1,4-dichlorobenzene and 1,2,4-trichlorobenzene.

Table 1
Summary of Chemicals Identified in the Soil
At The Study Site

Family	Chemical (limit of detection)	Range of Concentration
Volatile	(ppb)	(ppb)
	Trichloroethylene (10)	ND-21
	1,2-dichlorobenzene (10)	ND-3,000,000
	1,1,2,2-tetrachloroethane (10)	ND-23
	Tetrachloroethylene (10)	ND-11
	1,1,1-trichloroethane (10)	ND-36.5
	Chloroethane (50)	ND-257
	Methylchloride (50)	ND-34
Base Neutral	(ppm)	(ppm)
	Benzidine (3)	ND-5.2
	Di-n-butylphthalate (1)	ND-3.4
	Fluoranthene (1)	ND-13
	Phenanthrene (1)	ND-15
	Pyrene (1)	ND-11
	1,2,4-trichlorobenzene (1)	ND-294
	Bis(2-ethylhexyl) phthalate (1)	ND-10
	Fluorene (1)	ND-1.4
	Indeno (1,2,3-cd) pyrene (1)	ND-2.2
	Anthracene (1)	ND-3.1
	Benzo(a) anthracene (1)	ND-5.3
	Benzo(a) pyrene (1)	ND-4.3
	Benzo(ghi) perylene (1)	ND-1.1
	Benzo(h) fluoranthene (1)	ND-4.2
	Chrysene (1)	ND-5.0
	1,3-dichlorobenzene (1)	ND-100
	1,4-dichlorobenzene (1)	ND-161
	Naphthalene (1)	ND-2.4
	Nitrobenzene (1)	ND-1.4

Characterization of soils in the areas including and adjacent to the proposed study area was performed prior to the initial site characterization. An area of high organic (semi-volatile) constituent content was identified approximately 35 ft from the location where the extraction well was emplaced. This area of high organic concentration was designated "Test Pit 9". The chemical constituents present in the soil taken from approximately 5 ft below the surface at Test Pit 9 are listed in Table 2. Approximately 1,600 ppm additional semi-volatile constituents were estimated in a non-target library search.

RESEARCH PROGRAM FACILITIES AND EQUIPMENT

One of the initial tasks was the installation of an extraction well in the approximate center of the area of contamination. The well consisted of a 4-in. diameter, 5-ft long, factory-slotted PVC screen which was set slightly above the water table on a 4-in. diameter PVC casing. In the area of the project, the water table is at a depth of approximately 20 ft.

Table 2
Chemical Constituents Identified In Soils From Test Pit 9

Constituent	Concentration (ppm)
1,4 dichlorobenzene	31
1,2 dichlorobenzene	300
nitro benzene	21
1,2,4 trichlorobenzene	200
naphthalene	55
2-chloro naphthalene	27

A series of 38 soil gas probes was installed at radial distances of approximately 20, 40, 60 and 80 ft from the extraction well. A number of the probes were constructed as clusters with individual probes at depths of 5, 10 and 15 ft below ground surface. A sketch of a typical soil gas probe is shown in Figure 1.

The probes were constructed of Teflon tubing and were installed by a truck-mounted hollow steam auger rig. The screened section of the probe was sand-packed and the remaining annular space was sealed by bentonite pellets and grout. The probes allow for measurement of in situ soil vacuum and also permit sampling of soil gas quality. Twelve of the probes were fitted with thermistors to permit measurement of the soil temperature.

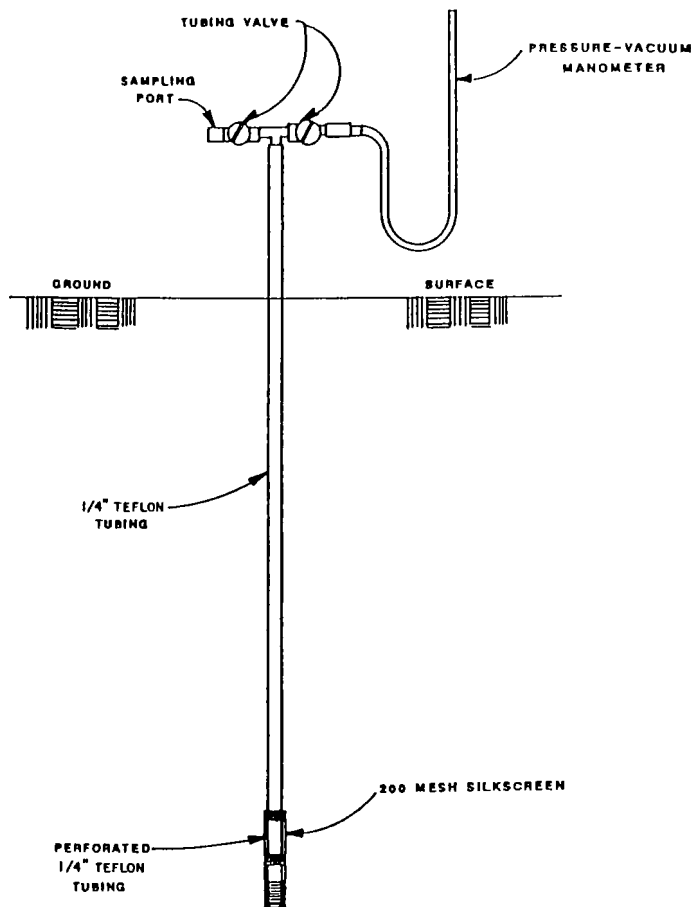


Figure 1
Sketch Of Typical Soil Gas Probe

Extraction of the soil gas vapors and much of the monitoring is performed by ECKENFELDER INC.'s In Situ Vapor Stripping Pilot Unit. The 8-ft by 12-ft long pilot unit trailer houses two New York Blower Model 2606-A pressure blowers. Each blower utilizes a 26-in. aluminum compression fan blade encased in a steel-frame housing and is powered by a 7-12 hp, 460 v, 3-phase motor. At the rated 3500 rpm fan speed, the two blowers produce 50.5 in. water column pressure on the outlet at a flow rate of 400 scfm. The blowers and associated ducts are configured for individual, series or parallel operation, depending upon flow rate and pressure requirements.

The pilot unit trailer also contains a baffled demister to remove water droplets from the air stream and instrumentation and controls for operation of the system and the monitoring of system performance. A layout of the pilot unit trailer is illustrated in Figure 2.

There are five sampling ports in the duct work to allow sampling of extracted gas quality at various points in the system. Measurements of temperature and pressure can be taken remotely at each sampling port.

Treatment of the extracted gas is accomplished by use of granular activated carbon. A carbon canister is set up outside the trailer as indicated in Figure 2.

An HNU Model PI-201 photoionization monitor with an Esterline Augus Model 410 chart recorder is utilized to continuously record gas quality. An electronic control panel, in conjunction with a Masterflex pump, automatically samples each of the five gas monitoring probes and a calibration gas cylinder once every hour. The automatic sequencing can be overridden if manual readings are desired. The HNU photoionization-detected output data are stored on the chart recorded for manual interpretation. The flow rate of the system is monitored by means of a Dwyer pilot tube and micromanometer.

An air permit was obtained from the New Jersey Department of Environmental Protection in order to operate the vapor stirring system. The permit established a maximum discharge concentration of 50 ppm total volatile organic compounds.

PRELIMINARY FINDINGS

The preliminary findings of the research project center upon the measured zone of influence of the extraction well, the change in the quality of the extracted soil gas with time, the treatability of the extracted gas by means of the granulated activated carbon system, temperature variations occurring in the system and the observed rate of the groundwater table induced by the vacuum extraction.

The preliminary findings in each of these areas are briefly discussed below.

Zone of Influence

Mathematical modeling of the in situ vapor stripping process indicates that in an isotropic soil the zone of influence of an extraction well screened near the base of the unsaturated zone should produce a zone of influence with a radius approximately equal to the depth of the well (i.e., unsaturated zone depth). In a soil with vertical anisotropy, the radius of the zone of influence is proportional to the degree of anisotropy. Because the Cohansey Sand was expected to have a vertical anisotropy of two to three, the in situ soil gas monitoring probes were set out at radial distances of 1D, 2D, 3D and 4D, where "D" equals the depth to the water table (or well depth).

Soil gas extraction was commenced on Sept. 6, 1988, at a rate of 180 cfm. In situ soil gas vacuum levels were observed almost immediately throughout the study area and reached a steady-state condition in less than 15 min. The in situ vacuum levels have remained essentially constant throughout the course of the research program. Contours of in situ vacuum levels are depicted in plan view and in cross-section in Figures 3 and 4, respectively. As indicated in these figures, a wider zone of influence was established than anticipated, even considering the vertical anisotropy of the Cohansey Sand. It can be extrapolated from the measured in situ vacuum levels to be approximately 150 ft. This distance is more than twice the anticipated radius of influence.

In order to determine the causative factor behind this observed phenomenon, an attempt was made to calibrate Wilson's two-

dimensional, axial-symmetric, ISVS numerical model to the measured in situ vacuum levels¹. A finite difference grid which was 165 ft. wide along the r axis and 23 ft. deep along the z axis was set up. A uniform grid spacing of 3.3 ft. was used along both axes, producing a total of 350 nodes. Because the model currently simulates an extraction well as a sphere, the 5-ft long, 4-in. wide well screen and surrounding gravel pack were represented as a sphere with a radius of 1.2 ft. The following parameters were also held constant during the modeling:

Extraction rate = 180 scfm
 Depth of extraction well intake = 22 ft.
 Soil porosity = 0.25
 Temperature = 63°F
 Extraction well vacuum = 0.94 atm

It was quickly discovered in the modeling process that no combination of soil permeability and vertical anisotropy would permit the model to adequately reproduce the observed in situ vacuum levels. The modeling results and field data suggested that observed in situ vacuum levels were attributable to more complex hydrogeologic conditions than simple vertical anisotropy.

The numerical model was therefore revised to permit modeling of dual layer stratigraphy with varying anisotropies in each layer. The

calibration was then continued. An excellent match to the field data was obtained when two soil layers were employed in the model: an upper, 3.3-ft. thick layer with an air permeability of 6.5×10^{-11} m²/atm-sec. and a lower, 20-ft. thick layer with an air permeability of 0.1×10^{-11} m²/atm-sec. A comparison of predicted and measured data is presented in Figure 5.

Because the upper layer is 191.5 times less permeable than the lower layer, vertical anisotropies within the individual layers are not pertinent to the results of the modeling. Air flow is nearly vertical in the upper layer, thereby negating the importance of lateral permeability in this stratum. Similarly, air flow is nearly horizontal in the lower layer, correspondingly diminishing the importance of vertical permeability in this layer.

The apparent reasons for this phenomenon can be tied to the site conditions. As mentioned earlier, the research project is located at the site of previous production buildings. Approximately 10 ft. below the surface of the study area is comprised of 10-ft.², 5-ft. thick concrete footings. Moreover, the intervening soil around the footings to a large extent is filled with a finer-grained character than the underlying native soils of the Cohansey Sand. Consequently, the few feet of soil impede the influx of atmospheric air from the surface, causing the zone of influence to spread laterally beneath this soil layer.

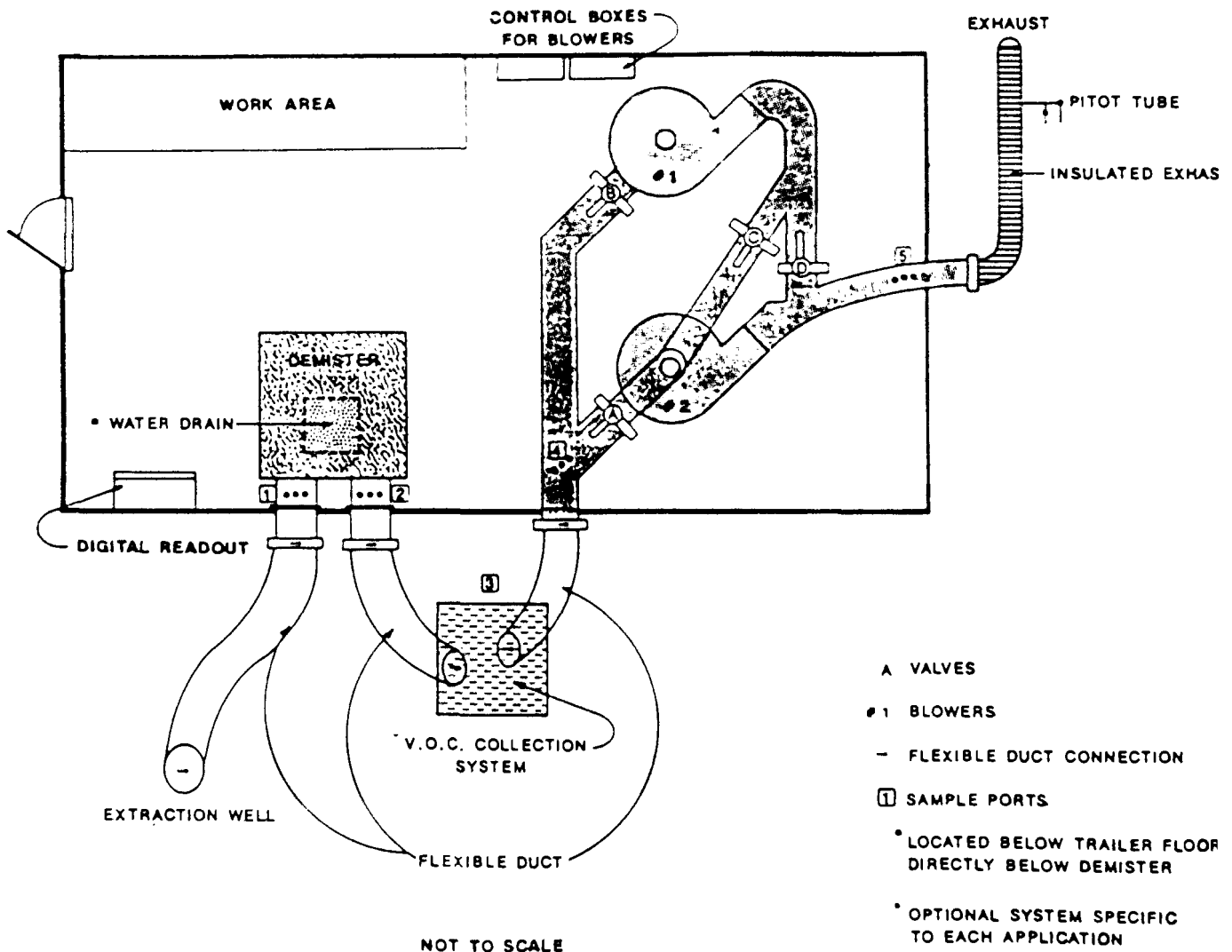


Figure 2
 Layout Of In Situ Vapors Stripping Pilot Scale Research Trailer

Extracted Soil Gas Quality

The quality of soil gas extracted during the first 10 mo. of the research program is presented in Figure 6. The soil gas concentrations are reported as a function of the days of system operation. Days of system shut-down for maintenance and installation of additional granulated activated carbon canisters are omitted from the graph.

Extracted soil gas concentrations initially were in the range of 100 to 140 ppm and have fairly steadily declined to current levels of approximately 60 to 70 ppm. Chemical analysis of the extracted soil gas reveals that the principal gas contaminants are: 1,1-dichloroethane, 1,1,2,2-tetrachloroethane, 1,1,1-trichloroethane, trichloroethylene, 1,2-dichlorobenzene and 1,3-dichlorobenzene. Upon completion of the testing, only 1,1,1-trichloroethane (TCA) and toluene were present in measurable quantity in the vapor from the extraction port. Below method detection limit quantities of TCA were noted in probe IID.

Figure 7 presents a graph of discharge gas quality after granulated activated carbon treatment. The five peaks in the graph represent progressive exhaustion of the granulated activated carbon canisters. These peaks represent exhaustion of the typical 1,200 lb of granulated activated carbon used in the project. The peaks represent a more rapid exhaustion of a standby granulated activated carbon system consisting of two parallel 55-gal drum carbon canisters.

The treatment efficiency of the granular activated carbon has been significantly diminished by sorption of water vapor in the carbon. The

demister has removed relatively little water since the water occurs in the form of water vapor rather than as a mist.

Temperature Variations

The temperature of the extracted gas, ambient air and the soil have been measured throughout the course of the study. Figure 8 depicts the variations in extracted soil gas temperature and ambient temperature. The temperature of the extracted soil gas was initially approximately 64°F (18°C) and has steadily declined during the fall and beginning of winter to temperatures of between 52°F (11°C) and 54°F (12°C). December through March exhibited the lowest gas and ambient air temperatures recorded. There was a steady increase exhibited throughout the spring as anticipated. June, 1989 temperatures were about 9° below last August, 1988 readings.

Figure 9 is a graph of in situ soil temperature variations occurring within the study area. The graph illustrates that, initially, soil gas temperatures were in the range 64°F (18°C) to 72°F (22°C). Also, the deeper soil probe (ID) exhibited a consistently lower temperature than the intermediate (II) and shallow (IS) probes. This result is not surprising considering the time of year. With the onset of fall and winter, in situ temperatures declined and reversed their relative positions. The deeper probe, probe ID, exhibited the highest temperature and the shallow probe, probe IS, the coolest temperature. Upon the arrival of spring, the relative relationships were again reversed.

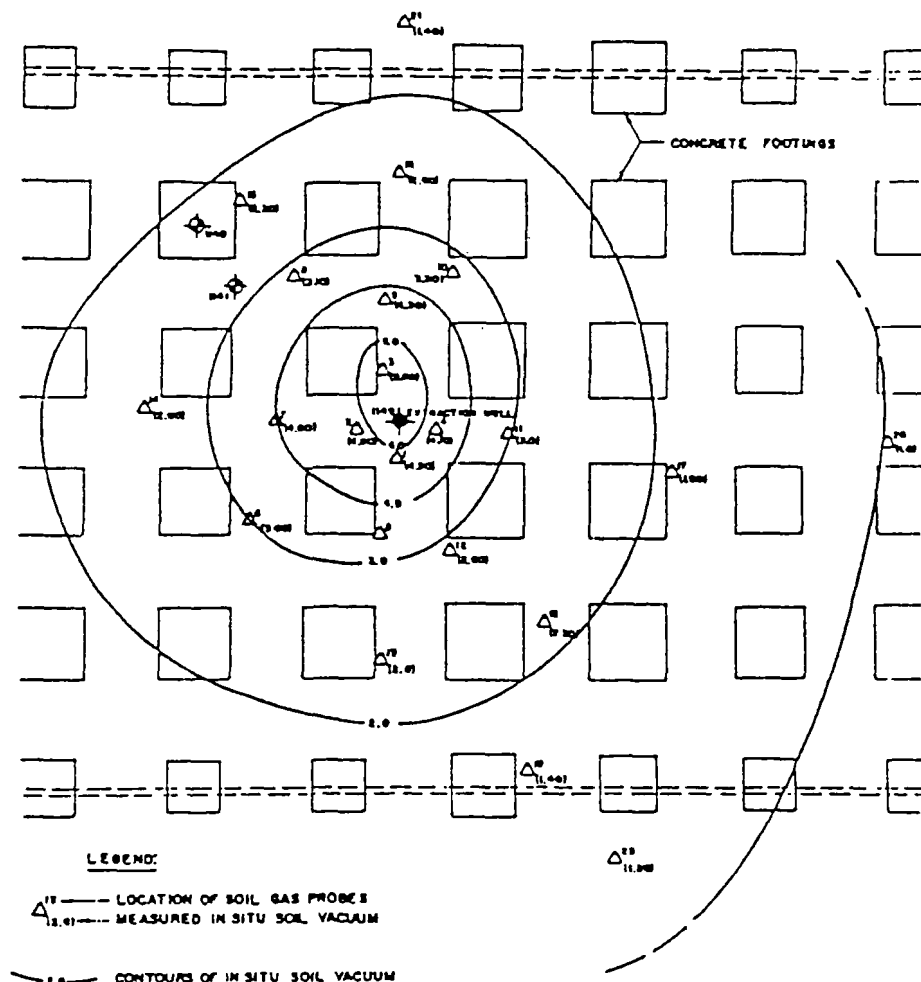


Figure 3
Contours Of In Situ Soil Vacuum

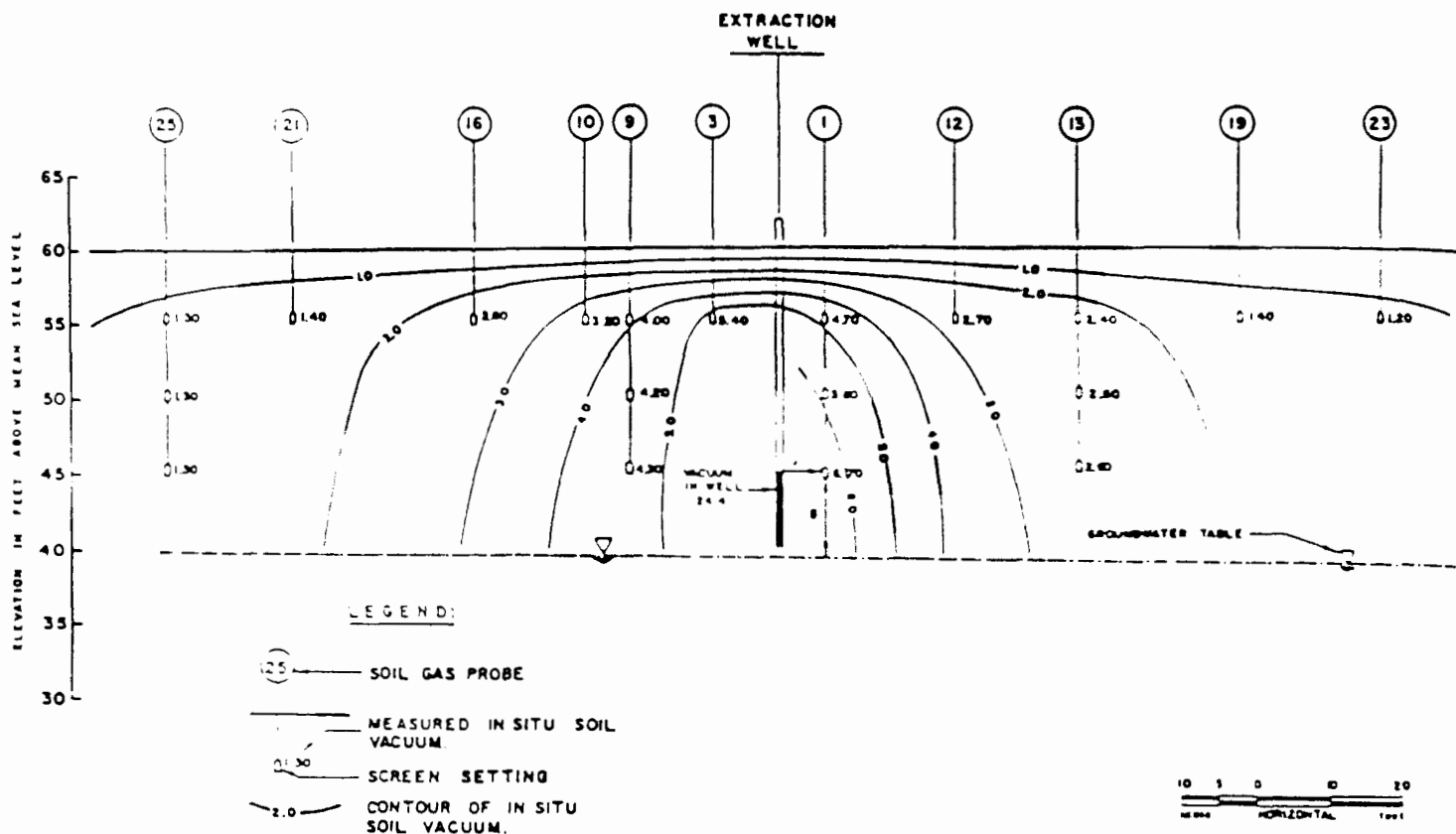


Figure 4
Cross-Sectional In Situ Soil Vacuum Contour Map

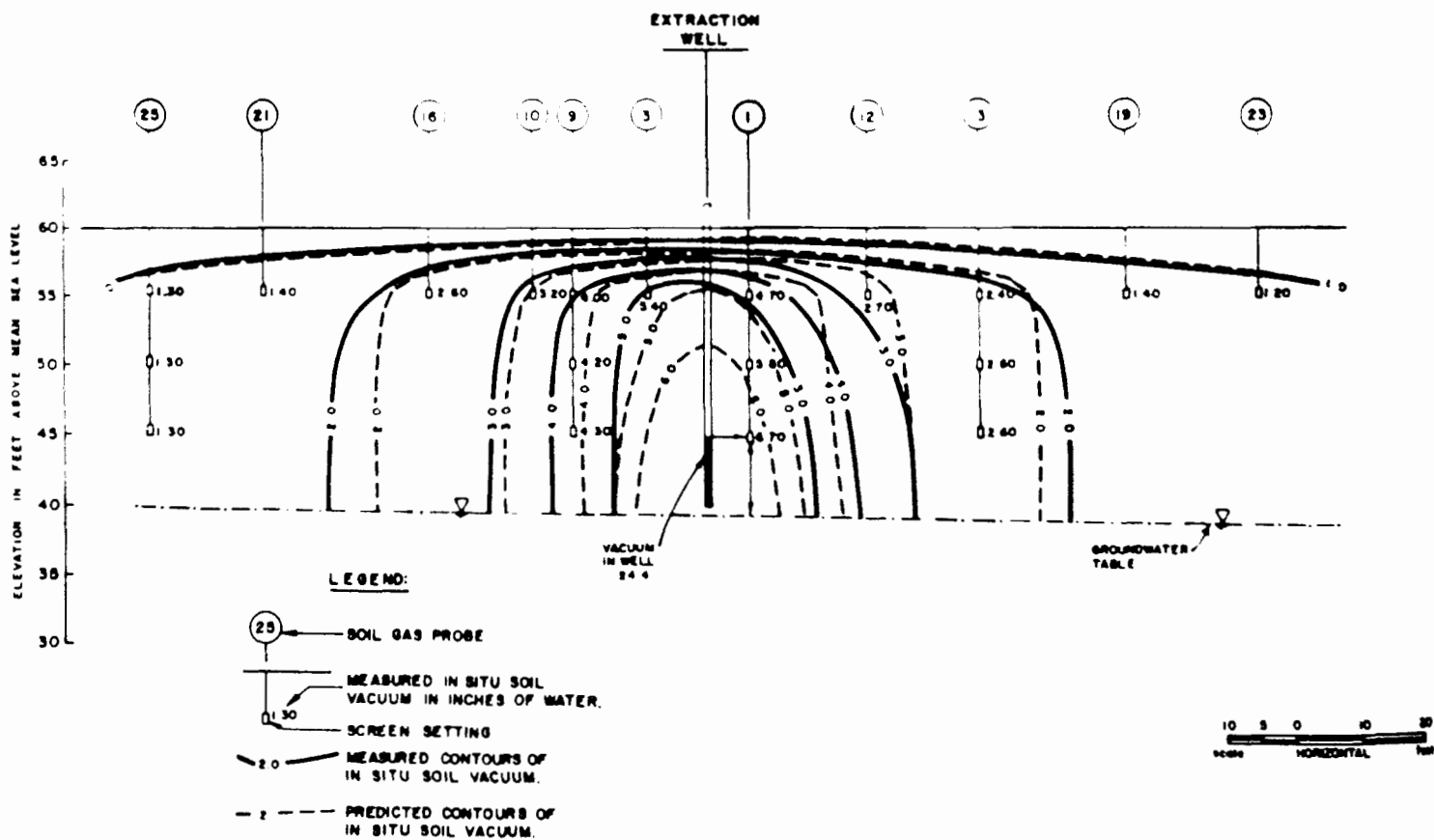


Figure 5
Comparison Of Measured And Predicted In Situ Soil Vacuum Levels

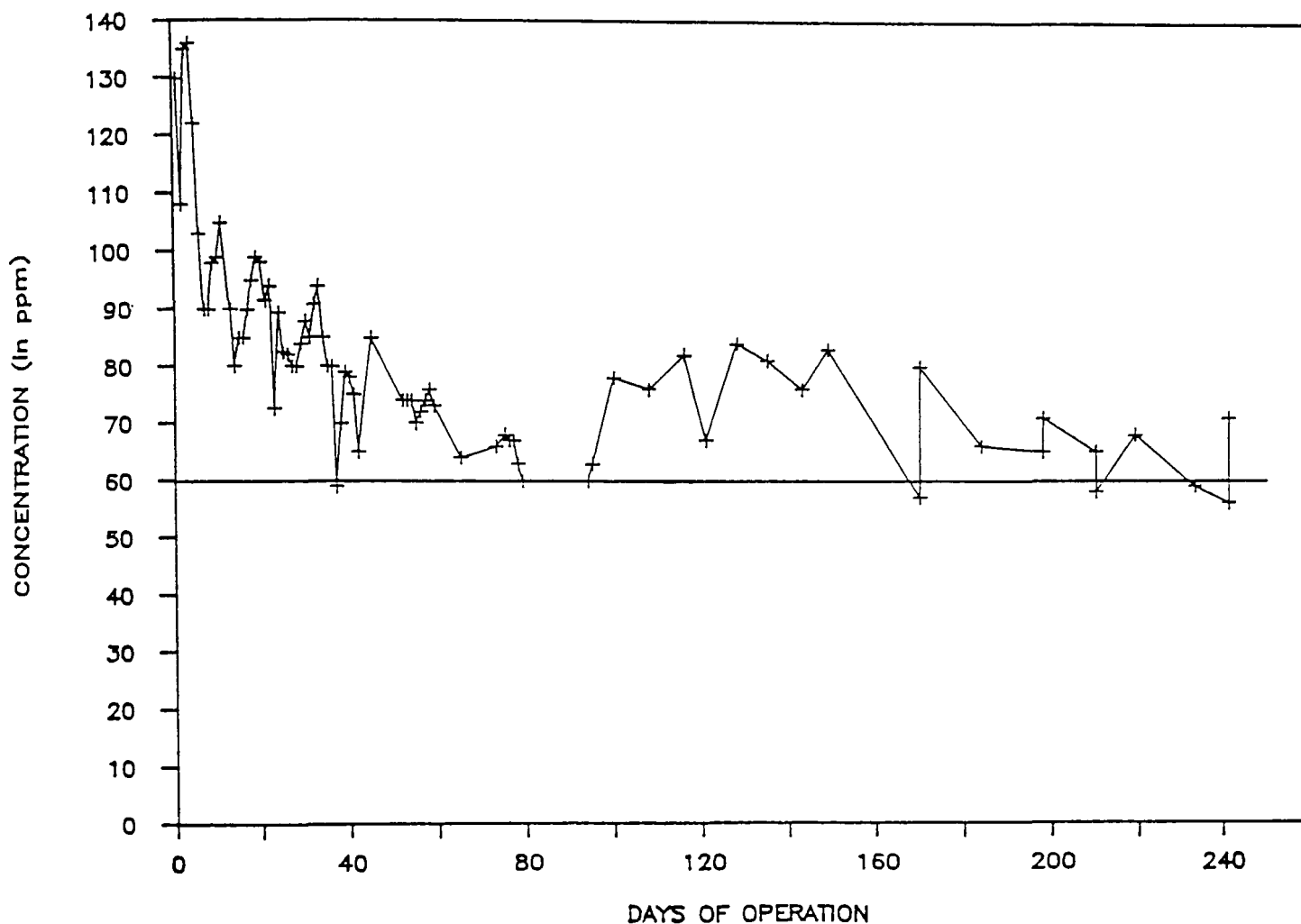


Figure 6
Extracted Gas Quality

Groundwater Levels

A rise in groundwater levels beneath in situ vapor stripping facilities has been both predicted and observed. The phenomenon results from the fact that the groundwater table represents the point in the subsurface where the voids in the soil or rock are not only fully saturated, but also at equilibrium with atmospheric pressure. Consequently, if soil gas pressures are reduced to below atmospheric pressure, a corresponding rise in the groundwater table should result. The magnitude of groundwater table rise (in inches) should coincide with magnitude of the pressure drop below atmospheric occurring at any point in the system (in inches). Monitoring of groundwater levels during the course of the research study confirms that the water table does indeed rise a level commensurate with the soil vacuum levels produced by the extraction well. The maximum rise in the water table of nearly 2.5 ft occurred immediately beneath the extraction well.

MATHEMATICAL MODELING

A mathematical model has been developed for predicting various aspects of a full-scale in situ vapor stripping system.¹ This model has been calibrated to the conditions of the Toms River field site. The model was originally calibrated using laboratory data generated from specially designed equipment which simulated actual field parameters and operating conditions². A model parameter critical to the estimation of chemical mobilities is the determination of a lumped partitioning coefficient for each chemical constituent of interest. This coefficient addresses the constituent's interaction with water, soil and other chemicals present and dictates the constituent's strippability.

The model can be used to generate important design criteria and optimize operating parameters from pilot-scale studies for use in full-scale remediations. The model can be run on a PC. A list of the model capabilities is provided in Table 3.

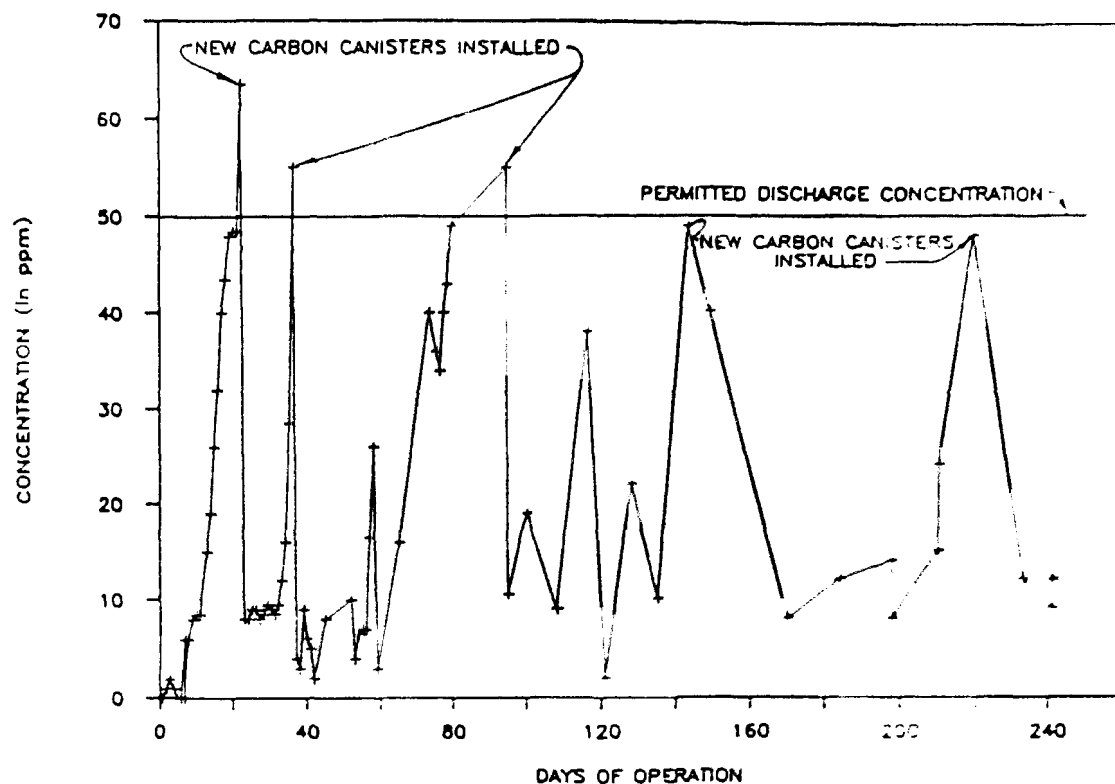


Figure 7
Discharge Gas Quality

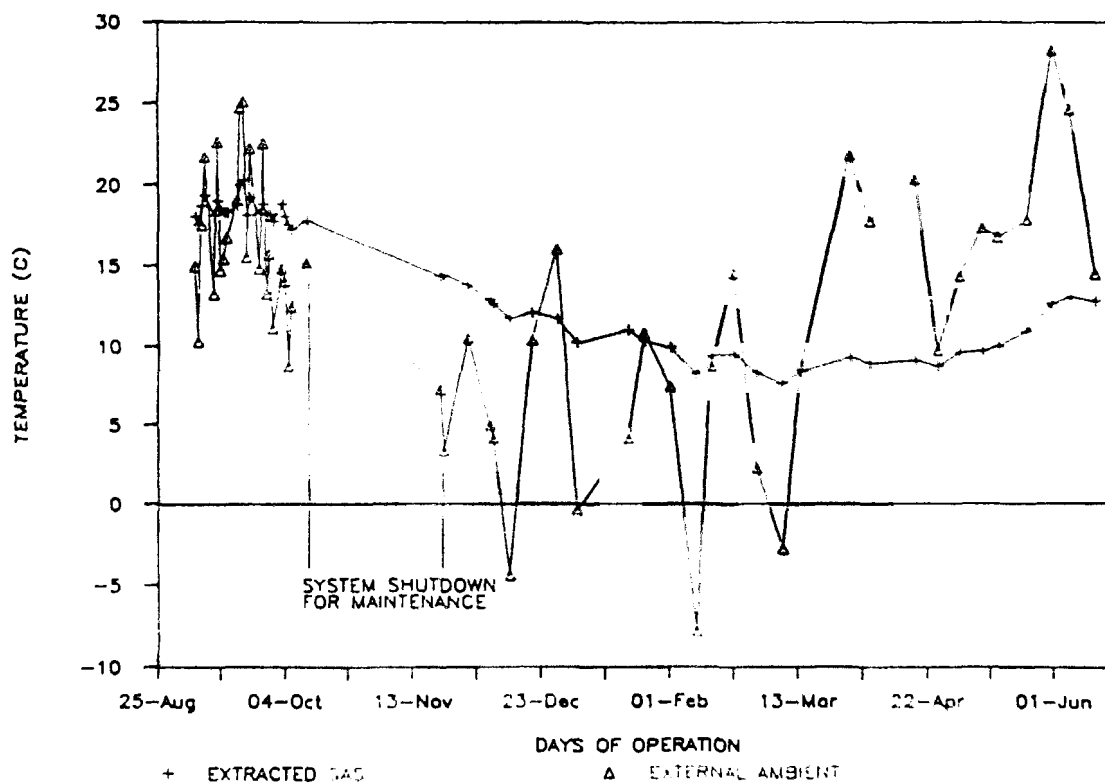


Figure 8
Extracted Gas and Ambient Temperatures

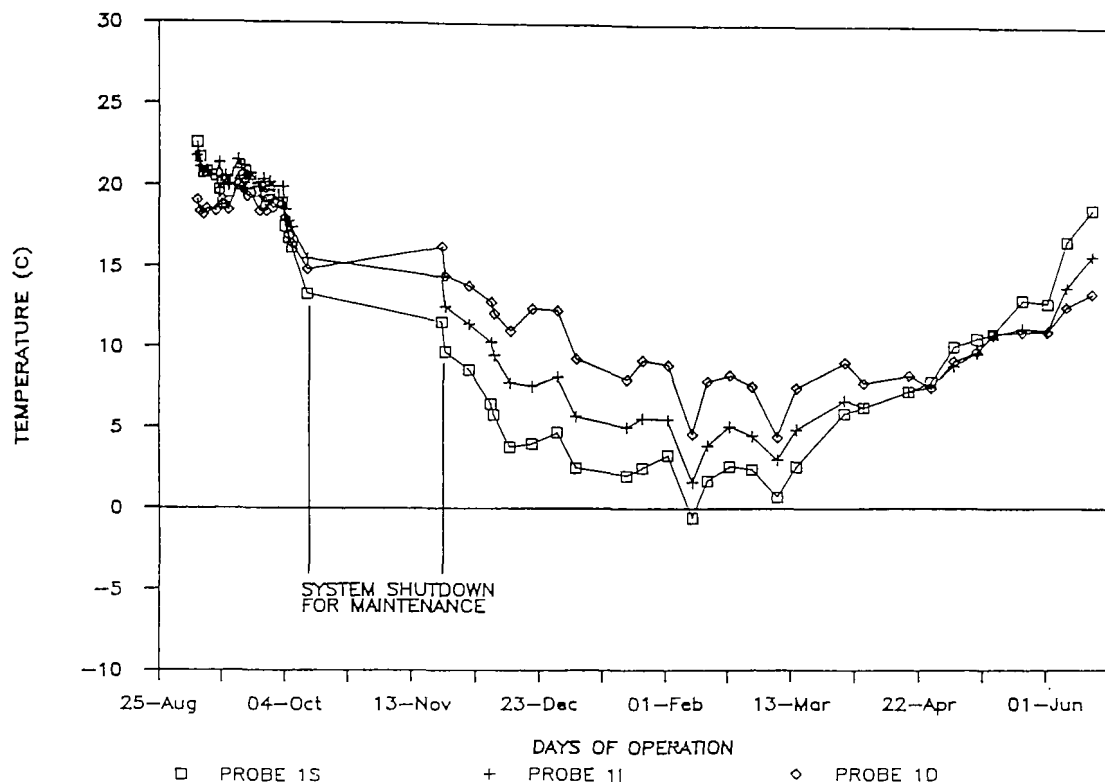


Figure 9
Soil and Ambient Temperatures

Table 3
List Of Model Capabilities For The Prediction Of Design And
Operating Parameters For Full-Scale In Situ Vapor Stripping^{1,3,6}

1. Predict clean-up time to reach a target level of residual contamination.
2. Predict residual contamination levels after a given period of operation.
3. Predict location of hot spots through diagrams of contaminant distribution.
4. Develop system design:
 - horizontal well placement
 - vertical well placement
 - screen placement
5. Predict impact of impermeable cap placement
6. Predict impacts of passive wells
7. Predict vapor stripping from fractured bed rock.
8. Predict clean-up levels around buried debris from various system designs.
9. Predict impact of ambient air temperature on removal.
10. Calculate the anisotropy of the soil or rock.
11. Predict recontamination time of the remediated vadose zone from slow moving contaminated groundwater.
12. Predict the rate of remediation of floating pools of LNAPLs.

FURTHER RESEARCH OBJECTIVES

While our findings to date have answered a number of questions concerning the behavior of in situ vapor stripping systems, several of the

research objectives remain to be accomplished. These unfulfilled objectives include the following:

- Description of the temporal variations in overall gas quality, as well as the relative proportions of individual constituents within the gas stream
- Determination residual levels of various contaminants in the soil at the conclusion of the project
- Description of the relationship between extracted gas flow and the resultant zone of influence and impact upon cleanup times

REFERENCES

1. Wilson, D.J., Clarke, A.N. and Clarke, J.H., "Soil Clean Up by In Situ Aeration. I. Mathematical Modeling", *Sep. Sci. Technol.*, 23, pp 991-1,037, 1988.
2. AWARE Incorporated, Phase I, *Zone I Soil Decontamination through In Situ Vapor Stripping Processess*, U.S. EPA, SBIR, Contract No. 68-024446, Apr. 1987.
3. Wilson, D.J., Gannon, K., Clarke, A.N., Mutch, Jr., R.D. and Clarke, J.H., "Soil Clean-up by In Situ Aeration. II. Effects of Impermeable Caps, Soil Permeability, and Evaporative Cooling", (*Sep. Sci. Technol.*)
4. Wilson, D.J., Clarke, A.N. and Mutch, Jr., R.D., "Soil Cleanup by In Situ Aeration. III Passive Vent Wells, Recontamination, and Removal of Underlying NAPL", (*Sep. Sci. Technol.*)
5. Mutch, Jr., R.D. and Wilson, D.J., "Soil Clean-up by In Situ Aeration. IV. Anisotropic Permeabilities", (*Sep. Sci. Technol.*)
6. Wilson, D.J., "Soil Clean-Up by In Situ Aeration, V. Vapor Stripping from Fractured Bedrock", (*Sep. Sci. Technol.*)

Mathematical Evaluation of Volatile Organic Compound Transport Via Pore-Space Dispersion Versus Advection

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ABSTRACT

The environmental behavior and fate of hazardous organic waste constituents in an unlined landfill was modeled in order to determine the speed and effectiveness of dispersion in the unsaturated pore space of soil as a contaminant transport mechanism. In addition to the well-known effects of downward advection (leaching) of contaminants in the water phase and upward air dispersion into the atmosphere, the results show the potential of downward dispersion of hazardous chemicals in unsaturated pore space as an important contamination pathway. This is due to the speed at which these constituents are transported by this mechanism.

The Vadose Zone Interactive Processes (VIP) computer model was used to simulate the migration and decay of several hazardous waste constituents in a variety of soil types based on physical and chemical properties of the constituents and local conditions (climate, soil properties, etc.). The model used partition coefficients to distribute the hazardous constituents into four "phases;" the soil, the waste, the water and the air phase.

The constituents were shown to move rapidly through the air phase, even if the leaching of the hazardous constituent was retarded by adsorption onto the soil. The constituents repartition into the water phase at detectable concentrations several meters below the lowest extent of the contamination by leachate advection. This effect is more pronounced in dryer soil, because the dispersion of organic constituents in the soil is a strong function of air porosity.

If this transport mechanism is neglected in a system where it is important, numerous misinterpretations are possible. For example, the high rate of transport could cause the misidentification of fractures. Groundwater monitoring data can underestimate the eventual concentration of constituents by orders of magnitude or give misleading clues as to the size of the mother lode because the transport was caused by a rapid but less efficient mechanism than leaching. The rate of transport can be underestimated by orders of magnitude if unsaturated flow equations are considered alone. Remedies could be chosen that limit liquid phase flow when the air phase is the key transport route.

This study shows that it is not sufficient to consider the extent or rate of transport of liquids in the soil in order to characterize soil or groundwater pollution at a Superfund site. Motion in the unsaturated pore space in the soil also must be taken into account.

INTRODUCTION

There are several contaminant transport mechanisms for volatile organic compounds in unsaturated zone soils: advection in the pore water, non-aqueous phase advection, dispersion in the pore water and dispersion in the unsaturated pore space. Nevertheless, it is common practice to consider migration only in terms of advection in the soil pore water or as a distinct organic phase.

In this study, a comprehensive computer model was used to simulate the fate and transport of two common volatile constituents of hazardous wastes in a variety of soil types and conditions. The objective was to quantitatively evaluate the transport mechanisms in terms of speed and effectiveness.

HYPOTHETICAL CASE

A hypothetical case was devised for the purpose of this investigation. Figure 1 illustrates an unlined landfill with barrels of hazardous waste, not atypical of many sites that are on or may be added to the NPL. The barrels are buried at a depth of approximately 5 m below the surface, and the water table is located at a depth of 10 m below the surface, only 5 m from the waste. In this hypothetical case, most of the barrels have leaked, and the soil is heavily contaminated from a depth of 4.5 m to 5.5 m. Soil cores from this depth contain 100 mg/kg of benzene and chlorobenzene in addition to other hazardous organic constituents.

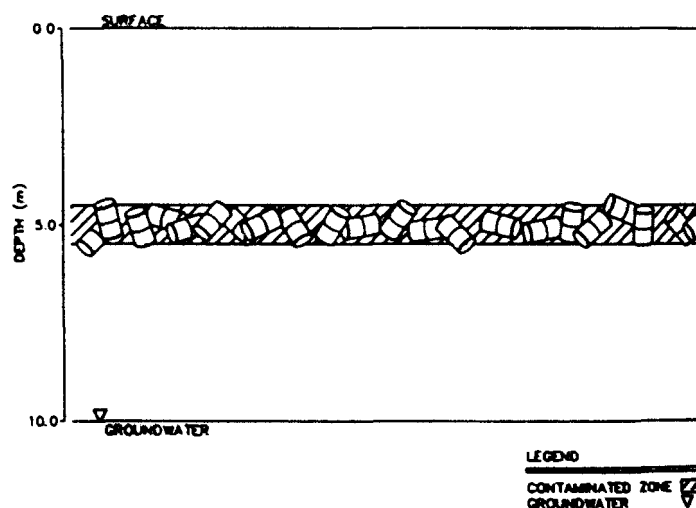


Figure 1
Unlined, Unregulated Landfill, 5 m Deep

The spread of chlorobenzene and benzene from the contaminated soil layer (Fig. 2) was computed for four soil types and three different water budgets. The soil types chosen were sand, sandy loam, loam and clay. Table 1 lists typical properties for these soil types¹. The three water budgets, representing low, high and excessive recharge rates, yielded deep percolations of 10^{-4} , 10^{-3} , and 10^{-2} m/day, respectively (1.43, 14.3 and 143 in./yr).

MATHEMATICAL METHOD

Organic molecules in the unsaturated soil can adsorb onto the organic matrix on soil grains. They also can reside in soil pore water, the unsaturated pore space or in any free organic or oil phase that often can be found in contaminated soils at CERCLA sites. For this reason, in evaluating the fate of organic contaminants (especially the more volatile compounds), it is necessary to quantify the behavior of the hazardous constituents for each of these four phases. In this study, the phases will be referred to as the soil, water, air and oil phases, respectively.

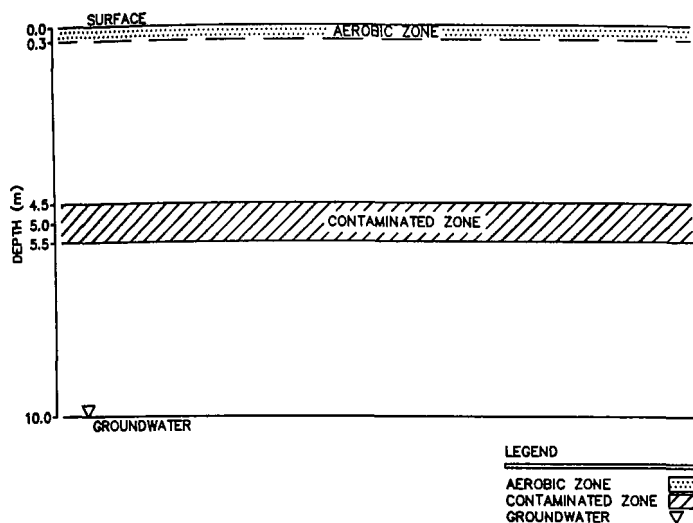


Figure 2
Initial Condition

Table 1
Properties of the Hypothetical Soils Used in this Study

Soil Type	Empirical Constant	Porosity (percent)	Dry Bulk Density (gr./cc.)	Sat. Hydraulic Conductivity (cm./sec.)
Sand	4.05	39.5	1.61	1.76×10^{-2}
Sandy Loam	4.90	43.5	1.50	3.95×10^{-3}
Loam	5.39	45.1	1.45	6.95×10^{-4}
Clay	11.40	48.2	1.37	1.28×10^{-4}

To quantify the fate and transport of volatile organic constituents, it is necessary to solve a suite of four partial differential equations. These equations would express the change in the concentration of a contaminant in each phase over time as the sum of advection, dispersion, adsorption/desorption and degradation. The solutions of these equations will be four functions of time and space, each representing the concentration of the contaminant in one of the phases.

Clearly, it would be very difficult to solve such a suite of partial differential equations analytically. Therefore, it was necessary to find a computer model that solved these equations numerically. The model would have to account for advection, dispersion, degradation, the partitioning between the phases and allow the input of initial conditions as well. The Vadose Zone Interactive Processes (VIP) model has all of these characteristics.

The VIP model has been described in detail in the literature^{2,3}. It has been tested mathematically⁴, experimentally⁵ and with field data⁶. VIP treats the soil system as a four-phase system. The four equations are coupled by the adsorption/desorption terms, which contain the partition coefficients. Model inputs include the soil-water partition coefficient K_{sw} (often referred to as K_d in the literature), the air-water partition coefficient K_{aw} , and the oil-water partition coefficient K_{ow} . Because partition coefficients in the literature almost always include water as a partition phase, the authors of the VIP model chose to assume that molecules migrating from one phase to another must pass through the water phase (Fig. 3).

In addition to adsorption and desorption, the model allows for degradation in each of the four phases. Migration is carried out mainly by advection in the water phase and dispersion in the air phase. Dispersion in the water equation was set equal to zero because all interphase constituent motion in the model must pass through the water phase, and the adsorption/desorption process provides dispersive phenomena sufficient to simulate the data observed by the modelers². Advection in the air phase was set equal to zero by the author since it is responsive to large barometric pressure changes that are not expected in the general case.

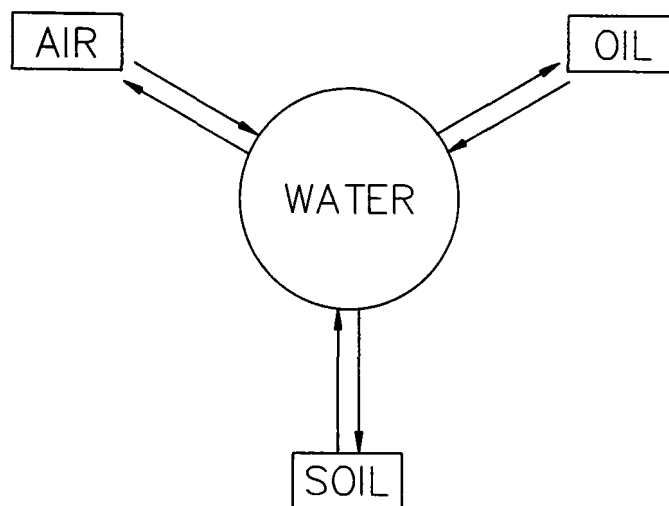


Figure 3
Partitioning Between Phases in Unsaturated Soil

MODEL INPUTS

The inputs into the VIP model include soil properties (Table 1), climatic data (Table 2) and chemical properties (Table 3). The soil-water partition coefficients presented in Table 3 were based on literature values for organic carbon-water partition coefficients^{9,10} and a fraction organic carbon of 1%¹¹. The soil-water partition coefficients for soil below a depth of 0.3 m are a factor of 10 lower, because the fraction organic carbon at this depth is assumed to decrease to 0.1%.

Table 2
Soil Temperature

Month	Temperature 0.0-0.3 meters (Deg. F) [*]	Temperature 0.0-0.3 meters (Deg. C)	Temperature 0.3-10.0 meters (Deg. C) [†]
January	53.6	12.0	23.5
February	55.8	13.2	22.5
March	61.3	16.3	21.5
April	68.5	20.3	20.5
May	76.0	24.4	21.5
June	81.6	27.6	22.5
July	83.0	28.3	23.5
August	83.2	28.4	24.5
September	79.2	26.2	25.5
October	71.4	21.9	26.5
November	60.8	16.0	25.5
December	55.7	13.2	24.5

^{*} Average monthly temperatures for Houston, Texas (7).

[†] Based on the Fluker model for a depth of ten feet (8).

Table 3
Chemical Properties

Property	Chlorobenzene	Benzene
Decay Rate (1/day)	2×10^{-4}	1×10^{-2}
Octanol-water Partition Coefficient	512.9	129
Air-water Partition Coefficient	.146	.224
Soil-water Partition Coefficient	3.89	0.89

The oil-water partition coefficients were octanol-water partition coefficients⁹⁻¹¹. Air-water partition coefficients were computed using Henry's law. Degradation rates obtained from the literature^{12,13} were reduced by an order of magnitude in Table 3 because biodegradation is primarily anaerobic at depths greater than 0.3 m¹⁴.

Air dispersion coefficients were obtained from the literature⁷ for chlorobenzene and benzene and were corrected for site temperature. The soil correction term for the air dispersion coefficient¹⁵ differed for

each of the 12 cases modeled (four soil types and three water budgets). Therefore, it had to be computed for each case based on the varying total porosity and air porosity in each soil (Table 4).

Table 4
The Size of the Phases in Each Soil Computed by the Model

Case	Soil (percent)	Water (percent)	Oil* (percent)	Air (percent)
Excessive recharge:				
Sand	60.5	20.4	0.1	19.0
Sandy loam	56.5	27.6	0.1	15.8
Loam	54.9	33.5	0.1	11.5
Clay	51.8	43.9	0.1	4.2
High recharge:				
Sand	60.5	16.6	0.1	22.8
Sandy loam	56.5	23.0	0.1	20.4
Loam	54.9	28.3	0.1	16.7
Clay	51.8	40.2	0.1	7.9
Low recharge:				
Sand	60.5	13.5	0.1	25.9
Sandy loam	56.5	19.2	0.1	24.2
Loam	54.9	24.0	0.1	21.0
Clay	51.8	36.7	0.1	11.4

*The oil phase was included to stabilize the model at the boundaries.

MODEL RESULTS

A total of 48 simulations was conducted, half for benzene and half for chlorobenzene. For each constituent, four different soil types were used in the model and three different water budgets. The 12 simulations were run with and without air dispersion to determine the consequences of neglecting this transport mechanism.

The simulations were for a period of 1 yr. The chlorobenzene results are presented in Tables 5 and 6. The benzene results are presented in Tables 7 and 8. By comparing the results of the VIP simulations, with and without air dispersion, it is immediately clear that the air dispersion transport mechanism is far more rapid than advection in moving volatile organic constituents in the water phase.

Table 5
VIP Results for Chlorobenzene with Air Dispersion

Simulation	Percent Degraded	Depth Reached (meters)	Release to Air (percent)	Release to Groundwater (percent)	Concentration in Groundwater (ug/l)
Excessive recharge:					
Sand	5.12	Release	4.54×10^{-3}	1.28×10^{-4}	14.8
Sandy loam	5.20	Release	4.87×10^{-5}	3.01×10^{-4}	0.7
Loam	5.31	Release	5.62×10^{-7}	4.02×10^{-6}	BDL*
Clay	5.49	7.6	0.0	0.0	0.0
High recharge:					
Sand	4.99	Release	1.47×10^{-1}	1.52×10^{-1}	35.9
Sandy loam	5.06	Release	2.32×10^{-2}	2.46×10^{-2}	8.9
Loam	5.16	Release	8.10×10^{-4}	8.86×10^{-6}	BDL
Clay	5.39	8.8	0.0	0.0	0.0
Low recharge:					
Sand	4.89	Release	4.82×10^{-1}	4.86×10^{-1}	64.1
Sandy loam	4.74	Release	1.67×10^{-1}	1.68×10^{-1}	30.0
Loam	5.06	Release	2.78×10^{-2}	2.82×10^{-2}	8.1
Clay	5.31	Release	2.16×10^{-6}	2.67×10^{-6}	BDL

*BDL indicates that the chemical is present, but below analytical detection limits.

Air dispersion becomes more important in coarser soils and at lower recharge rates (Fig. 4). For chlorobenzene, including this mechanism makes the difference between predicting a release to groundwater and not predicting a release within the 1-yr time-frame of the simulation. This is true in all but two cases, both involving clay at high and excessive recharge rates. A similar result can be observed in the benzene data. A benzene release was predicted in all of the cases in which air dispersion was included except for clay at the higher recharge rates.

Table 6
VIP Results for Chlorobenzene Without Air Dispersion

Simulation	Percent Degraded	Depth Reached (meters)	Release to Air (percent)	Release to Groundwater (percent)	Concentration in Groundwater (ug/l)
Excessive recharge:					
Sand	5.12	7.00	0.0	0.0	0.0
Sandy loam		7.10	0.0	0.0	0.0
Loam		7.10	0.0	0.0	0.0
Clay		7.10	0.0	0.0	0.0
High recharge:					
Sand	5.00	5.60	0.0	0.0	0.0
Sandy loam	5.06	5.60	0.0	0.0	0.0
Loam	5.16	5.60	0.0	0.0	0.0
Clay		5.60	0.0	0.0	0.0
Low recharge:					
Sand	4.90	5.50	0.0	0.0	0.0
Sandy loam	4.95	5.50	0.0	0.0	0.0
Loam	5.04	5.50	0.0	0.0	0.0
Clay		5.50	0.0	0.0	0.0

Table 7
VIP Results for Benzene with Air Dispersion

Simulation	Percent Degraded	Depth Reached (meters)	Release to Air (percent)	Release to Groundwater (percent)	Concentration in Groundwater (ug/l)
Excessive recharge:					
Sand	94.15	Release	4.53×10^{-6}	2.59×10^{-1}	579.4
Sandy loam	95.23	Release	8.25×10^{-7}	2.83×10^{-2}	150.2
Loam	95.93	Release	0.0	3.53×10^{-4}	5.1
Clay	96.75	9.70	0.0	0.0	0.0
High recharge:					
Sand	91.80	Release	4.47×10^{-1}	5.33×10^{-1}	71.2
Sandy loam	93.69	Release	7.06×10^{-2}	9.11×10^{-2}	20.9
Loam	94.70	Release	3.13×10^{-3}	4.58×10^{-3}	1.8
Clay	96.16	9.10	0.0	0.0	0.0
Low recharge:					
Sand	88.79	Release	1.63	1.63	76.8
Sandy loam	91.77	Release	5.64×10^{-1}	5.74×10^{-1}	35.4
Loam	93.55	Release	1.05×10^{-1}	1.07×10^{-1}	11.0
Clay	95.68	Release	8.78×10^{-7}	1.64×10^{-6}	BDL

Table 8
VIP Results for Benzene Without Air Dispersion

Simulation	Percent Degraded	Depth Reached (meters)	Release to Air (percent)	Release to Groundwater (percent)	Concentration in Groundwater (ug/l)
Excessive recharge:					
Sand	94.26	Release	0.0	4.45×10^{-10}	BDL
Sandy loam	95.24	Release	0.0	1.08×10^{-9}	BDL
Loam	95.93	Release	0.0	9.09×10^{-11}	BDL
Clay	96.75	9.70	0.0	0.0	0.0
High recharge:					
Sand	92.48	6.10	0.0	0.0	0.0
Sandy loam	93.80	6.10	0.0	0.0	0.0
Loam	94.72	6.10	0.0	0.0	0.0
Clay	96.16	6.00	0.0	0.0	0.0
Low recharge:					
Sand	91.04	5.50	0.0	0.0	0.0
Sandy loam	92.57	5.50	0.0	0.0	0.0
Loam	93.69	5.50	0.0	0.0	0.0
Clay	95.68	5.50	0.0	0.0	0.0

In the case of the excessive recharge rate, where it is possible to have a release in loam, sandy loam and sand without air dispersion, the air transport mechanism greatly enhanced the magnitude of the predicted release.

These results can be explained by studying the output of any case where air dispersion was included in the model. In the output from these cases, the contaminant reaches the groundwater through the air phase within a few days to a month at a concentration of pg/L. The

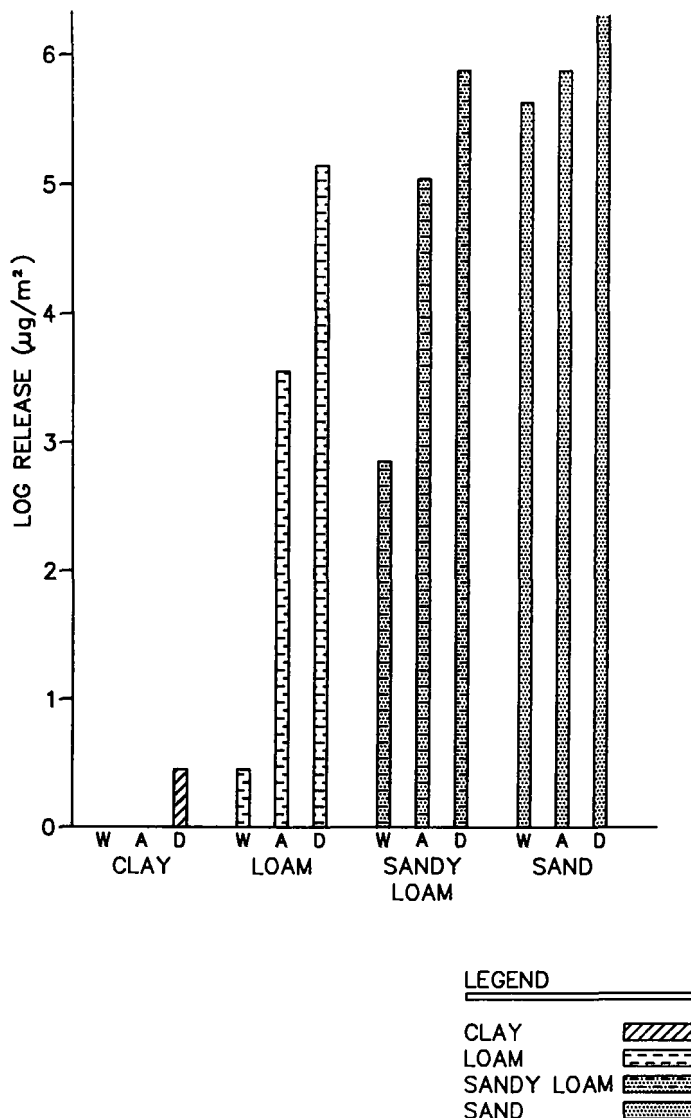


Figure 4
Release vs. Soil Type

concentration of the contaminant increases by orders of magnitude as one approaches the source from the water table. At every level, the contaminant in the air phases partitions with the other phases, contaminating the soil and the soil pore water (Fig. 5). Thus, the phases besides the air are also contaminated outside of the soil that had been in contact with primary leachate. Contaminants delivered to soil and soil pore water by the air phase are free to advect and disperse. Thus, the air dispersion mechanism not only moves contaminants, but also augments other transport mechanisms.

A clear illustration of this augmentation can be seen with benzene under excessive recharge. For the sand, the sandy loam and the loam, release would have occurred without air dispersion because of water advection. In Table 8, the size of the release is small in each case, because the concentrations represent the fringe of the downward-moving contaminant plume (given a few more months, the release would have been much greater as the bulk of the plume crossed the 10 m datum). Yet in Table 7, the predicted releases for these three cases are large, with concentrations in the groundwater in the mg/L. This is due to the advection of benzene in the water phase that had been carried to lower strata by dispersion in the air phase.

Air dispersion also is active in the upward direction. In drier soils, in which dispersion is more rapid, there is a symmetry in the concentration of contaminants in each phase, above and below the contaminant source (Fig. 6). This symmetry results from simultaneous upward and

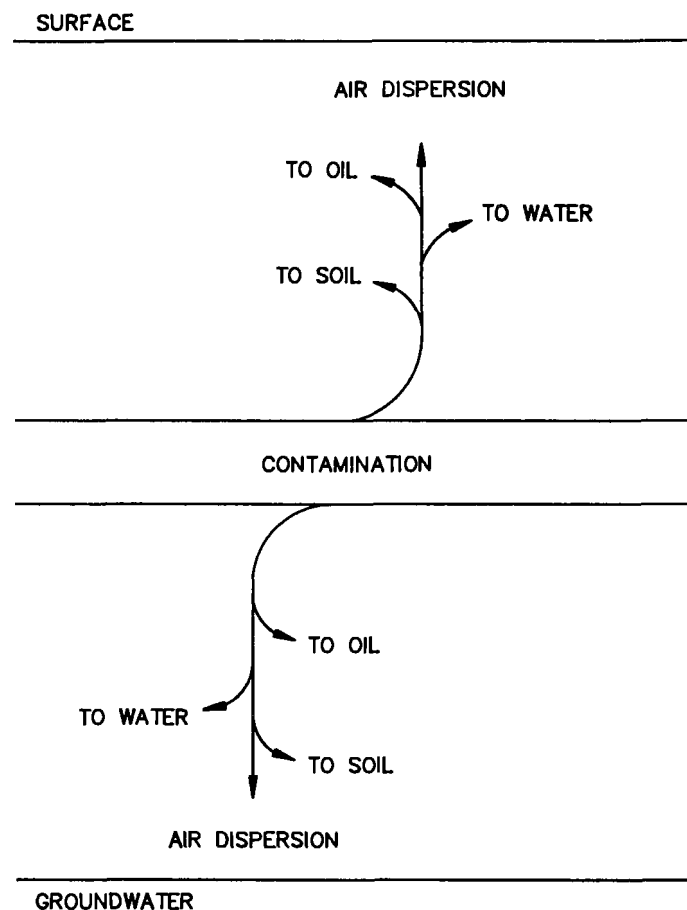


Figure 5
The Contamination of All Fourphases of the Soil by Air Dispersion

downward dispersion. Rapid advection (as in the case of higher recharge rates) and faster degradation (as in the case of benzene) decrease the amount of symmetry.

Hazardous constituents can be released to the atmosphere by upward dispersion in the air phase. But this mechanism also can contaminate soil and soil pore water above the contaminant source. Thus, if the barrels were covered with clean soil during the operation of this landfill, the soil above the barrels could be quite contaminated. For example, one year into a simulation involving loam with a recharge rate of 1.43 in./yr, soil can be contaminated in the mg/L range with chlorobenzene as much as 2 m above the barrels (Fig. 6).

DISCUSSION

One may underestimate the importance of the effect of dispersion of volatile organic contaminants in the air phase by reasoning that the mechanism, although much more rapid than advection, is much less effective than advection because it transports smaller masses. It could be argued that the hazardous waste constituents released by dispersion eventually would have been released by advection in the water phase anyway. Although such a view might be justifiable in the sense of long-term damage to the aquifer, it fails to address several key issues from the standpoint of Superfund.

First, in the negotiations between PRPs and the Agencies, it is in the interest of both sides to have an accurate understanding of the site soil system in order to implement an effective remedy. An overly optimistic view of the situation can lead to an ineffective cleanup. Remedies could be chosen that limit liquid phase migration when the air phase is an important transport route.

For example, neglecting air dispersion could cause an engineer to conclude that benzene would degrade before it could be released. Neglecting this mechanism can lead to overestimates in the time avail-

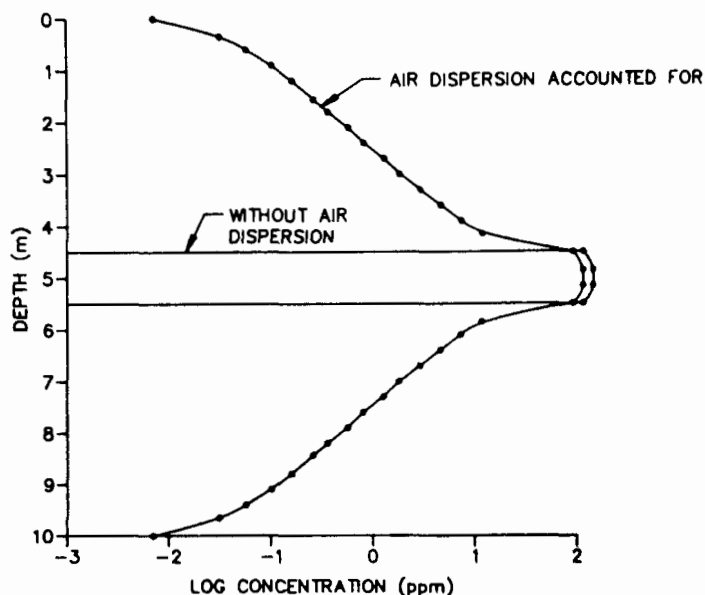


Figure 6
Chlorobenzene in Dry Loam After One Year

able to consider options before a release to groundwater. One could conclude from testimony that a site rich in volatiles could be capped with clean soil, neglecting the potential for contamination of that soil from below. Testimony by site personnel that they used clean soil to cover the barrels could lead to lax application of safety rules on-site in dealing with shallow soil.

Errors on the side of optimism can lead to errors that impact the environment as well as humans. Highly dispersive constituents with lower octanol-water partition coefficients such as xylene may be assumed to decay in place. Yet relatively low concentrations initially reaching an aquifer directly below a site could become substantial over time, especially if the landfill is large in area. It also should be remembered that VIP is only one-dimensional. It may be accurate in the middle of such a hypothetical landfill, but at the edges there will be lateral dispersive transport of volatile organic compounds as well as vertical transport. If advection is the only transport mechanism considered in a site rich in volatiles in a densely populated area, it would be easy to consider only downward transport, completely missing the peril to homeowners from horizontal motion of the constituents.

Another serious error of interpretation could occur if detections in monitoring wells were assumed to be caused solely by advection. The magnitude of the detections could be orders of magnitude lower than they will be when the advective plume finally reaches the monitoring well network. After a few well sampling events, the size of the mobile contaminant mass or of the source load could be grossly underestimated. A risk assessment based on such monitoring well data clearly would be misleading.

A pessimistic view can cause errors in selecting a remedy. It can discourage the use of an effective remedy in favor of a lesser one more suited to the pessimistic view of site conditions. For example, a site characterization could yield parameters for an unsaturated flow model that would erroneously predict the time that organic contaminants would reach an aquifer by advection. A suite of water samples taken from the aquifer could then show contaminants in places where they should not be. This finding could lead the investigators to assume fracture flow where it is not taking place, or conclude the presence of a highly transmissive zone. The presence of such fractures could have an adverse influence on the Agency or the PRPs in selecting a remedy.

It should be pointed out that some of the assumptions in this study were conservative. For example, the concentration of the contaminants in the source area in this simulation was only 100 mg/L. Data for clays in this study did not take into account the effect that organic constituents have on clays^{16,17}. Organic constituents can desiccate clays and create

fracture systems in the clay. Thus, results for the clays presented in the tables and figures may be optimistic.

Furthermore, if the VIP model is used to conduct site-specific simulations with actual soil parameters, it should be pointed out that degradation is not the end of concern for halogenated hydrocarbons. The daughter products of halogenated hydrocarbons are often also halogenated hydrocarbons¹⁸. Unlike the hazardous constituents found in petroleum refinery wastes, the daughter products of chlorinated hydrocarbons may be more hazardous than their parent compounds.

Finally, Figure 7 shows the concentration of chlorobenzene released in one year versus the dispersion coefficient of chlorobenzene in the soil. Rather, the size of the release differs from soil to soil. Therefore, no formula can be derived to present release strictly as a function of dispersion coefficient. The time and magnitude of the release can only be obtained by actually conducting a model run. It should be remembered that all predicted releases are functions of time. In Tables 5 through 8, values are presented for a time 1 yr after the start of the simulation. When the center of the advection plume reaches the water table, the bulk of the release will take place. For chlorinated hydrocarbons such as chlorobenzene, a release is an eventuality in spite of biodegradation, because the daughter products of chlorobenzene decay are also chlorinated hydrocarbons.

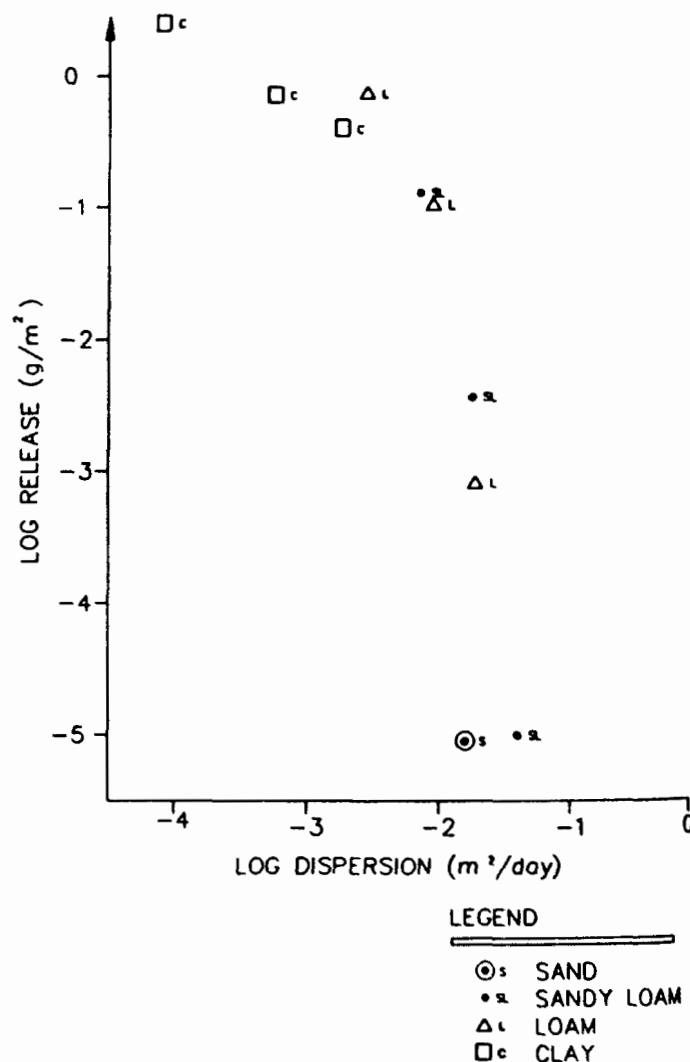


Figure 7
Chlorobenzene, Log Dispersion vs. Log Release

CONCLUSIONS

The release of two selected volatile organic compounds from a hypothetical unlined hazardous waste landfill was modeled using a

detailed unsaturated zone model. It was found that dispersion of the constituents in the air phase was rapid, and the size of the release was significant in some cases. Coarse soils with lower recharge rates (i.e., greater unsaturated pore space) allowed the greatest transport by this mechanism. In clays or wetter soils, advection in the air phase was less effective.

The model results show that at a Superfund site, it is not sufficient to consider contaminant transport mechanisms of liquids alone. Failure to take motion (both vertical and horizontal) in the unsaturated pore space into account can lead to errors, both in site assessment and in remedy selection.

ACKNOWLEDGMENT

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REFERENCES

1. Clapp, R. B. and Hornberger, G. M., "Empirical equations for some soil hydraulic properties," *Water Resources Research*, 14, pp. 601-604, 1978.
2. Caupp, C. L., Grenney, W. J. and Ludvigsen, P. J., *A Model for the Evaluation of Hazardous Substances in the Soil, Version 2*, Civil & Environmental Engineering, Utah State University, Logan, UT, 1987.
3. Grenney, W. J., Caupp, C. L., Sims, R. C. and Short, T. E., "A mathematical model for the fate of hazardous substances in soil: Model description and experimental results," *Hazardous Waste and Hazardous Materials*, in press, 1987.
4. Yan, Z., *Evaluation of the Vadose Zone Interactive Processes (VIP) Model Using Nonequilibrium Adsorption Kinetics and Modification of VIP Model*, Thesis, Department of Civil and Environmental Engineering, UT State University, Logan, UT, 1988.
5. Symons, B. D., Sims, R. C. and Grenney, W. J., "Fate and transport of organics in soil: model predictions and experimental results," *JWPCF*, 60(9), pp. 1684-1693, 1988.
6. Stevens, D. K., Grenney, W. J., Yan, Z. and Sims, R. C., *Sensitive Parameter Evaluation for a Vadose Zone Fate and Transport Model*, U.S. EPA Rept. No. EPA 600/2-89/039, U.S. EPA, Ada, OK, 1989.
7. Thibodeaux, L. J., *Chemodynamics: Environmental Movement of Chemicals in Air, Water and Soil*, John Wiley and Sons, New York, NY, 1979.
8. Fluker, B. J., "Soil temperatures," *Soil Science*, 86, pp. 35-46, 1958.
9. Karickhoff, S. W., Brown, D. S. and Scott, T. A., "Sorption of hydrophobic pollutants on natural sediments," *Water Resources*, 13, pp. 241-248, 1979.
10. Roberts, P. V., McCarty, P. L., Reinhard, M. and Schreiner, J., "Organic contaminant behaviour during groundwater recharge," *JWPCF*, 52, pp. 161-172, 1980.
11. Schwarzenbach, R. P. and Giger, W., "Behavior and Fate of Halogenated Hydrocarbons in Ground Water," in *Ground Water Quality*, ed. C. H. Ward, W. Giger, and P. L. McCarty, pp. 446-471, John Wiley and Sons, New York, NY, 1985.
12. Environmental Research and Technology, Inc., *The Land Treatability of Appendix VIII Constituents Present in Petroleum Industry Wastes*, Document-B-974-220, 1984.
13. Office of Air Quality Planning and Standards, *Air Release Screening Assessment Methodology*, U.S. EPA Draft, 1987.
14. Brown, K. W., and Donnelly, K. C., "Influence of the soil environment on biodegradation of a refinery and a petrochemical sludge," *Environ. Poll. (Series B)*, 6(2), pp. 119-132, 1983.
15. Farmer, W. J., Igue, K. and Spencer, W. F., "Effects of bulk density on the diffusion and volatilization of dieldrin from soil," *Journal of Environmental Quality*, 2, pp. 107-109, 1973.
16. Anderson, D. C., Brown, K. W. and Thomas, J. C., "Conductivity of compacted clay soils and organic liquids," *Waste Management and Research*, 3, pp. 339-349, 1985.
17. Brown, K. W., "Use of Soils to Retain Waste in Landfills and Surface Impoundments," in *Utilization, Treatment, and Disposal of Waste on Land*, ed. K. W. Brown, B. L. Carlile, R. H. Miller, E. M. Rutledge, and E. C. A. Runge, pp. 279-300, Soil Science Society of America, Inc., Madison, WI, 1986.
18. Wood, P. R., Lang, R. F. and Payan, I. L., "Anaerobic Transformation, Transport, and Removal of Volatile Chlorinated Organics in Ground Water," in *Ground Water Quality*, ed. C. H. Ward, W. Giger, and P. L. McCarty, pp. 493-511, John Wiley and Sons, New York, NY, 1985.

Radiological Monitoring of Select Faunal Species Indigenous to Environs of the Maxey Flats Shallow Land Burial Facility

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ABSTRACT

This study examines the radionuclide concentrations of four faunal species indigenous to the environs of the Maxey Flats Shallow Land Burial Facility located in northeastern Kentucky. The sample species were limited to the smokey shrew (*Sorex fumeus*), short-tailed shrew (*Blarina brevicauda*), white-footed mouse (*Peromyscus leucopus*) and the eastern box turtle (*Terrapene c. carolina*). Body fluids were analyzed for tritium by liquid scintillation. Whole body samples were ashed and analyzed for gamma-emitting radionuclides.

The most abundant gamma-emitting radionuclide encountered was potassium-40. The smokey shrew exhibited the greatest concentration of gamma-emitting radionuclides. The smokey shrew also exhibited the greatest tritium concentration.

With the exception of cesium-137, the gamma-emitting radionuclides identified in this study were endogenous. The cesium-137 concentration may be attributed to global fallout from nuclear bomb testing. The disposal facility did not seem to have influenced the concentrations of gamma-emitting radionuclides assimilated by the faunal species sampled. The concentrations of tritium measured indicate that tritium from the disposal facility has entered the biological systems of faunal species in the immediate area of the waste disposal facility.

INTRODUCTION

Information concerning the concentration of radionuclides assimilated by wildlife is essential in determining the environmental impact of waste disposal facilities. The purpose of this study was to determine

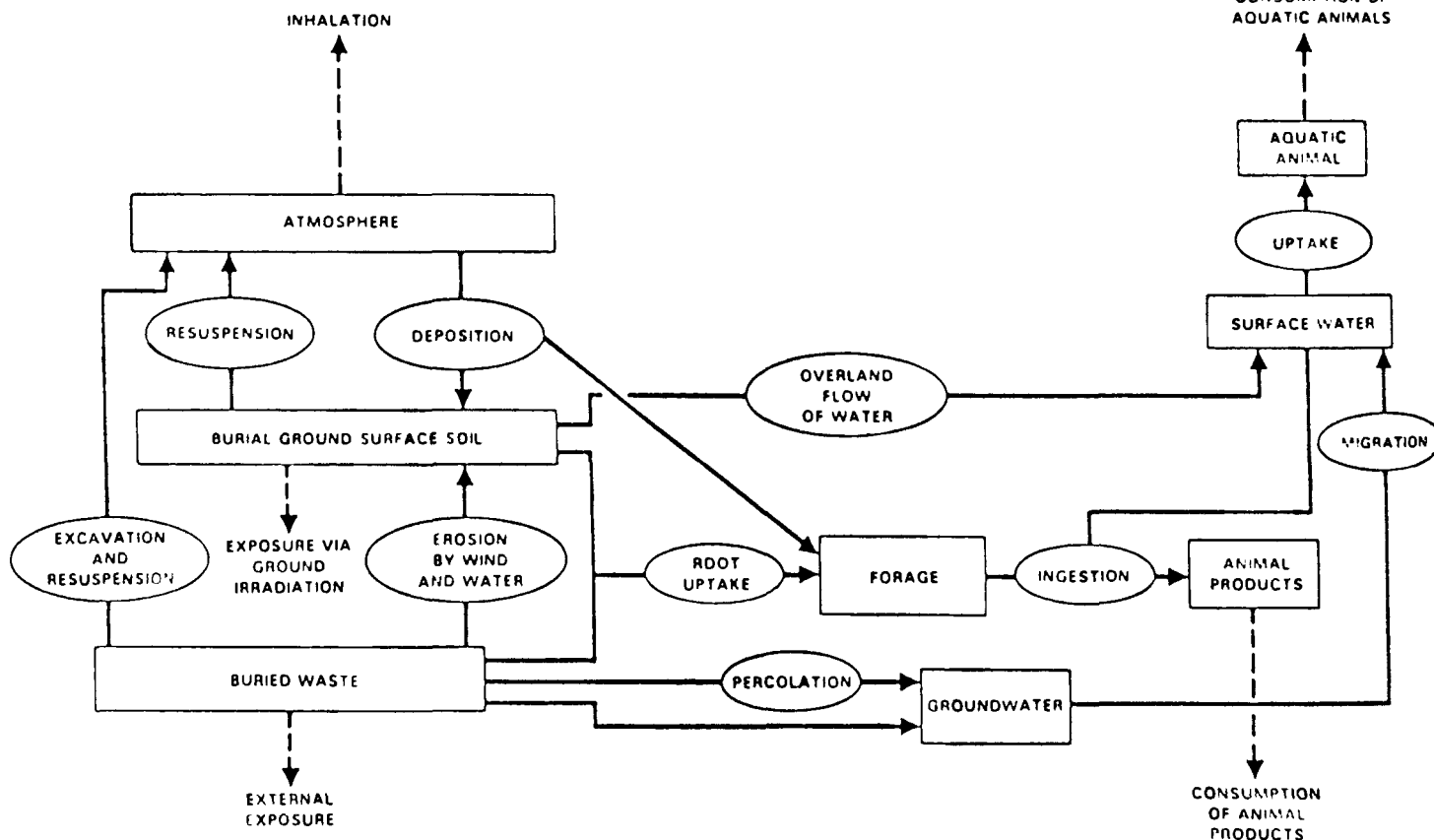


Figure 1
Potential Environmental Exposure Pathways at a
Low-Level Waste Burial Ground¹

the concentrations of radionuclides assimilated by four faunal species indigenous to environments surrounding the Maxey Flats Shallow Land Burial Facility located in northeastern Kentucky. This research was the first wildlife study conducted at the facility and was compared with other Maxey Flats studies to determine the environmental impact of the facility.

The sample species used in this study were the smokey shrew (*Sorex fumeus*); the short-tailed shrew (*Blarina brevicauda*); the white-footed mouse (*Peromyscus leucopus*); and the eastern box turtle (*Terrapene c. carolina*). These species were chosen for the following reasons: (1) the availability of indigenous species; (2) the opportunity to sample large numbers without causing a great impact on population numbers; (3) the burrowing habits of these animals; (4) food sources include ground dwelling animal matter.

It has been suggested that the species most exposed to radionuclides are the detritivores, the arthropods and earthworms living in the forest floor litter. It also has been suggested that the species that consume arthropods and earthworms are the most probable radionuclide vectors¹. A diagram of the potential environmental exposure pathways is shown in Figure 1.

Tritium was chosen as an indicator in this study for the following reasons: (1) its abundance in the burial facility³; (2) its abundance in the off-site environment⁴; (3) the ready uptake by the animals; and (4) its mobility in the environment.

The gamma-emitters were chosen for: (1) their abundance in the burial site⁵; (2) their presence in the off-site environment⁶ and (3) their excellent data base in the environment. The majority of nuclides in wastes from power plants, with physical half-lives of greater than 5 yr, are gamma-emitters⁷.

SITE DESCRIPTION

In January, 1963, the Nuclear Engineering Company was issued a license to operate the disposal facility and in May, 1963, the first radioactive material was buried at Maxey Flats. The major users of the facility included hospitals, power plants and various industries. Solid wastes were buried in large rectangular trenches that ranged from 5 to 20 m in length, 3 to 22 m in width and 3 to 10 m in depth. Liquid wastes were solidified, on-site, by mixing them with cement and paper. This mixture was then poured into polyethylene-lined trenches⁸.

From 1963 through site closure in 1977, 135,000 m³ of wastes were buried at Maxey Flats. The volume of wastes buried at Maxey Flats has been estimated to contain over 2.4 million curies of by-product materials and 64 kg of plutonium⁹.

The burial trenches geologically lie within the Nancy Member of the Borden Formations (Fig. 2). The Nancy Member consists of shale and sandstone interbeds. Water is discharged from the facility by three routes: (1) surface run-off, (2) interflow through the shallow soil zones and (3) subsurface bedrock flow (Fig. 2). These routes form potential water pathways for the migration of radionuclides from the facility. Due to the extensive grading and earthmoving and a natural dip in the strata, the land surface slopes southeasterly, channeling most surface run-off into a main east drainage channel¹⁰.

In December, 1974, the Kentucky Department for Human Resources released a report entitled "A History and Preliminary Inventory Report on the Kentucky Radioactive Waste Disposal Site." The report stated that radioactivity had been detected in the unrestricted environment of the disposal facility. The conclusions and recommendations of this study were:

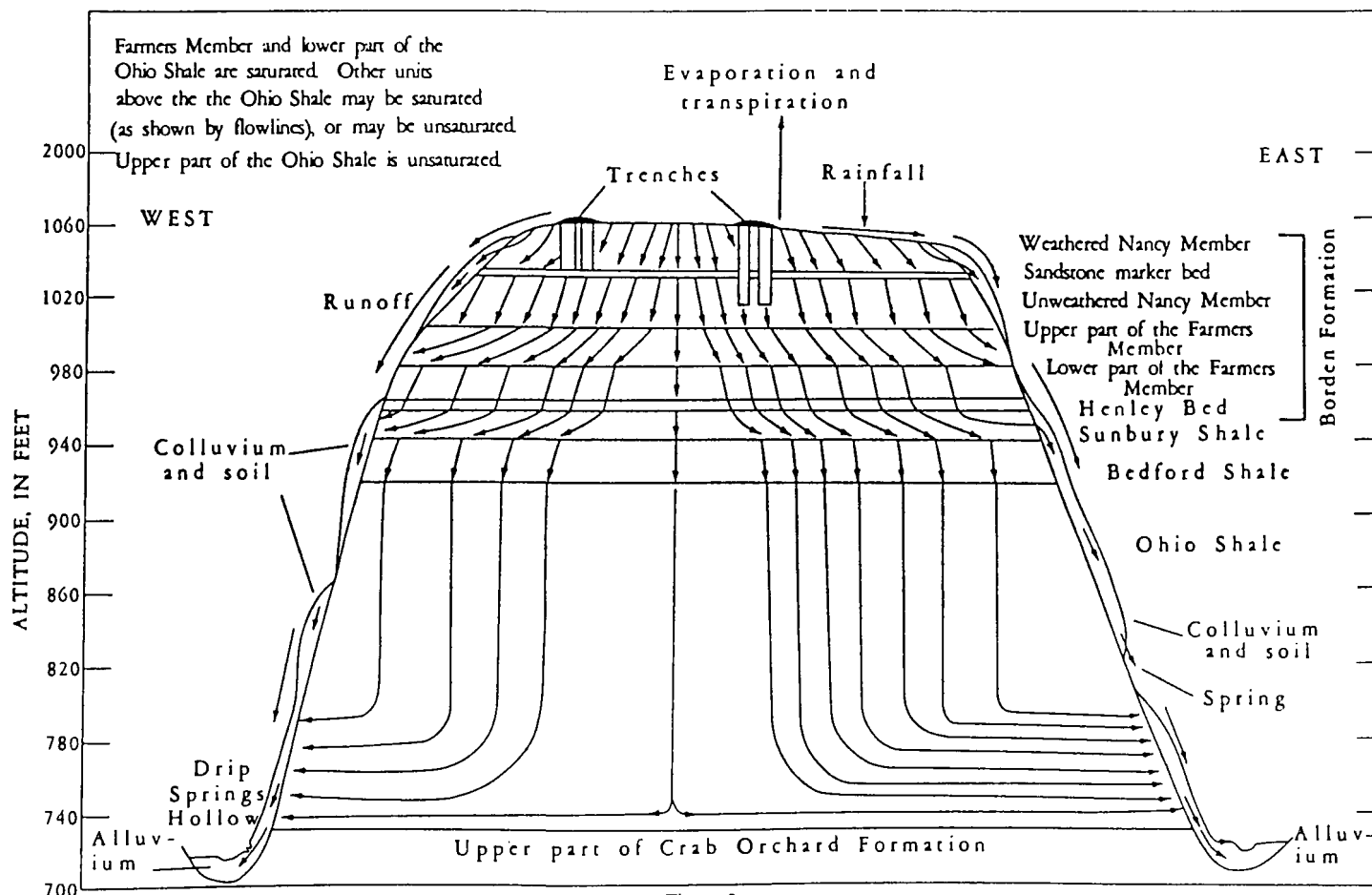


Figure 2
Hydrogeological Position of the Maxey Flats
Shallow Land Burial Facility¹⁰

- The facility was contributing radioactivity to the area environment, but the activity was not creating a public health hazard.
- Some samples collected showed the presence of man-made radionuclides in the unrestricted environment.
- Further geological, hydrogeological, and climatological studies should be conducted to determine a profile for the site¹²

A followup report providing additional data on the status of the disposal facility was released by the Department in December, 1976. The followup report concluded that the disposal facility was still contributing small amounts of radioactivity into the immediate environment, but it did not post a public health hazard. The report also concluded that the major mode of environmental contamination was surface run-off. It was suggested that other modes, such as subsurface movement also contribute to environmental contamination. The report recommended that routine analysis of water and sediment from specific sampling stations be performed by the Radiation Control Branch of the Department for Human Resources and by the licensee¹³.

METHODS AND MATERIALS

Trapping sites were established in the vicinity of the three major channels that drain the disposal facility (Fig. 3). These areas are covered by deciduous forest consisting mainly of oak, hickory and maple trees. Mouse-sized snap traps were randomly placed in areas that appeared to offer suitable habitat for the species being sought. The traps were checked and rebaited with peanut butter daily. Traps were discharged over the weekends due to the dehydration of the small mammals after death. When a sample was recovered, it was weighed, placed in a zip-top bag and labeled with the species name, collection locality and date of capture. The sample was then frozen until prepared for analysis.

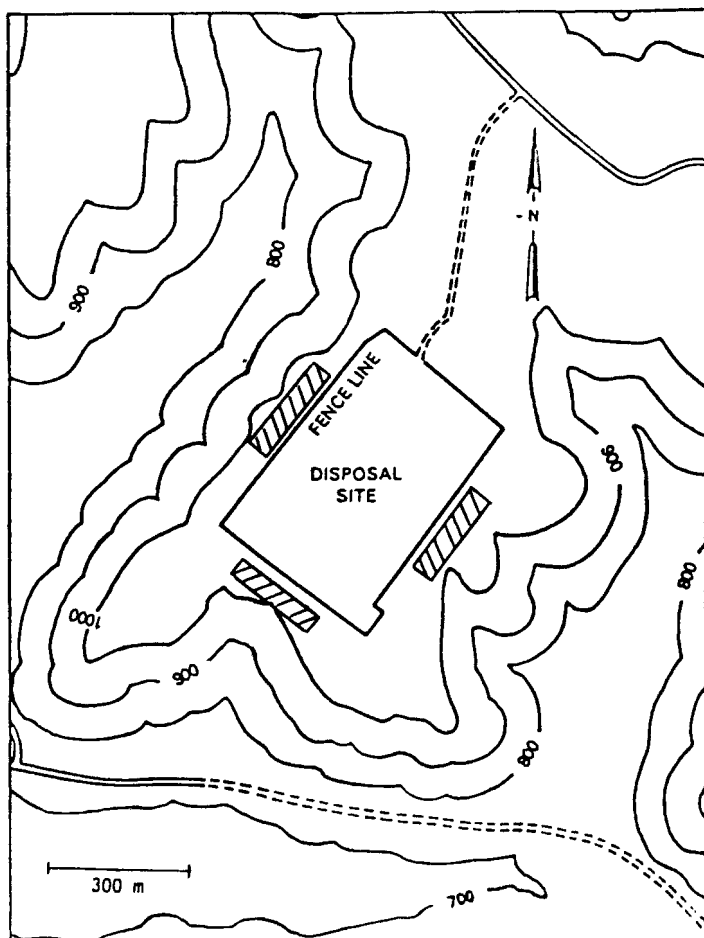


Figure 3
Approximate Trapping Locations

The capture of *Terrapene c. carolina* was performed by searching the forest surrounding the facility. These samples were documented and stored in the same manner as the mammals.

Mammalian body fluids were obtained by making an incision from the xiphisternum to the anus and folding the skin laterally. Internal organs were removed and fluids extracted with a vacuum funnel. Tritium is not selective for any one organ, and the quantity of body fluids was small; therefore no effort was made to distinguish between fluids from different tissue components. Any fluids remaining in the body cavity were collected with a syringe. The fluid was centrifuged at 1500 rpm until separation of liquid from solid constituents was evident. Only the liquid portion was transferred into vials and used for tritium analysis¹⁴.

Body fluids from *Terrapene c. carolina* were obtained by separating the carapace from the plastron and removing the internal organs. Fluids were removed with a vacuum funnel. The fluids that remained in the carapace were collected with a syringe. Attempts to separate the solid constituents from the liquid by centrifugation were ineffective. Therefore, to obtain a homogenous sample necessary for scintillation analysis, azeotropic distillation was performed using benzene. The sample and solvent were placed in a flask and allowed to reflux. Benzene was distilled and collected in a Barrett water/oil collecting tube. As the body fluids condensed and collected in the tube, they separated from the benzene which formed the top layer. The benzene layer was pipetted and discarded. The body fluid layer was pipetted into scintillation vials. A new pipette tip was used for each sample to prevent the possibility of cross-contamination.

"Insta-gel," used as the scintillator, was added to each sample. Samples were analyzed for tritium in a Hewlett-Packard Tri-Carb Liquid Scintillation Counter for 300 min.

To prepare collected faunal species for gamma ray spectroscopy, whole body samples were placed in evaporating dishes and ashed in a Form-8 oven at 300°C for 12 to 16 hr. The charred samples were ground with a mortar and pestle and transferred to petri dishes for analysis. Evaporating dishes and the mortar and pestle were thoroughly cleansed with nitric acid before each preparation to prevent the possibility of cross-

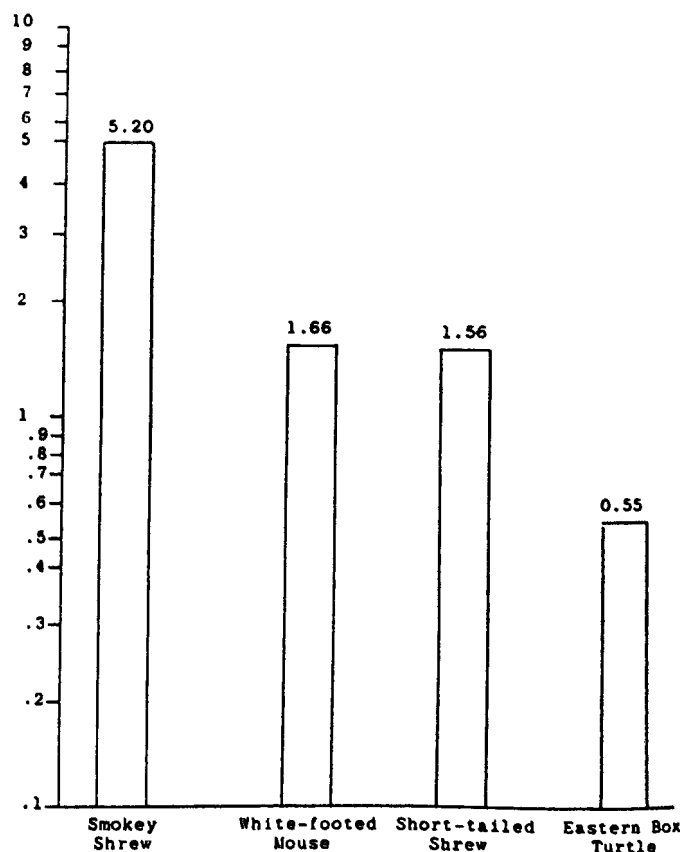


Figure 4
Total Gamma Radionuclide Concentrations by Species Concentrations in pCi/g

contamination. The samples were analyzed for gamma-emitting radionuclides using a Nuclear Data 680 system.

RESULTS

The smokey shrew showed a gamma radionuclide concentration greater than any of the other species studied. The mean gamma radionuclide concentration for the smokey shrew was 5.19 pCi/g. The mean concentration of gamma-emitting radionuclides for the white-footed mouse was 1.66 pCi/g. The mean gamma-emitting radionuclide concentrations for the short-tailed shrew and the eastern box turtle were 1.56 pCi/g and 0.55 pCi/g, respectively (Fig. 4).

The most abundant gamma-emitting radionuclide encountered was potassium-40, with a mean concentration of 5.93 pCi/g. Radium-226 and cesium-137 showed mean concentrations of 0.68 pCi/g and 0.28 pCi/g, respectively (Fig. 5).

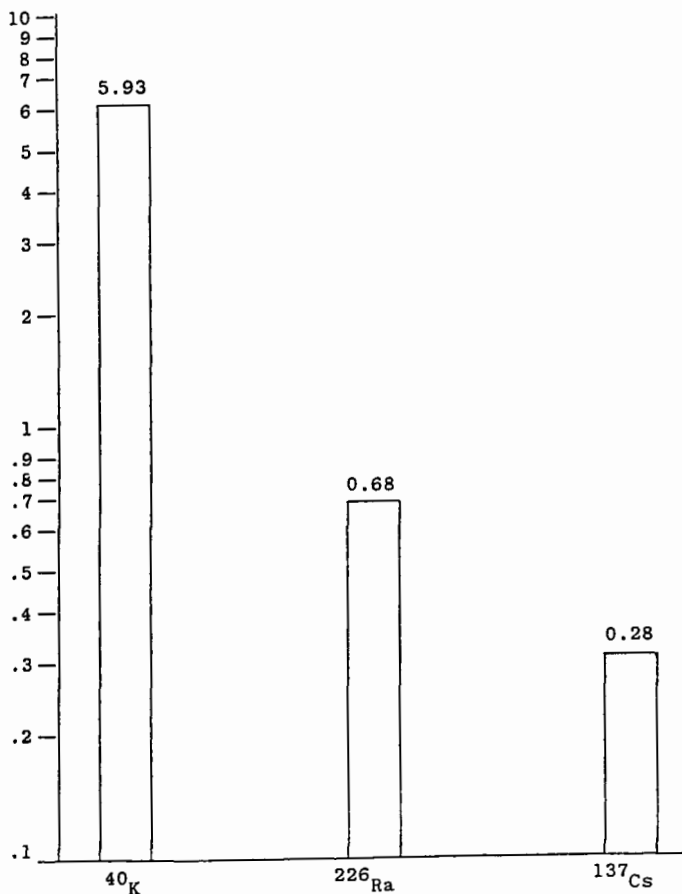


Figure 5
Variable Gamma Radionuclide Abundance in pCi/g

The smokey shrew exhibited the greatest concentrations of potassium-40, with a mean concentrations of 13.03 pCi/g. The mean concentration of potassium-40 for the white-footed mouse and the short-tailed shrew were 4.49 pCi/g and 4.13 pCi/g, respectively. The mean concentration of potassium-40 assimilated by the eastern box turtle was 1.28 pCi/g (Fig. 6).

The smokey shrew exhibited the greatest concentrations of radium-226, with a mean concentration of 1.87 pCi/g. The mean concentration of radium-226 assimilated by the short-tailed shrew was 0.38 pCi/g. The mean concentrations of radium-226 for the white-footed mouse and the eastern box turtle were 0.34 pCi/g and 0.16 pCi/g, respectively (Fig. 7).

The smokey shrew exhibited the greatest concentrations of cesium-137, with a mean concentration of 0.67 pCi/g. The white-footed mouse exhibited the lowest concentrations of cesium-137, with a mean concentration of 0.14 pCi/g. The mean concentrations of cesium-137

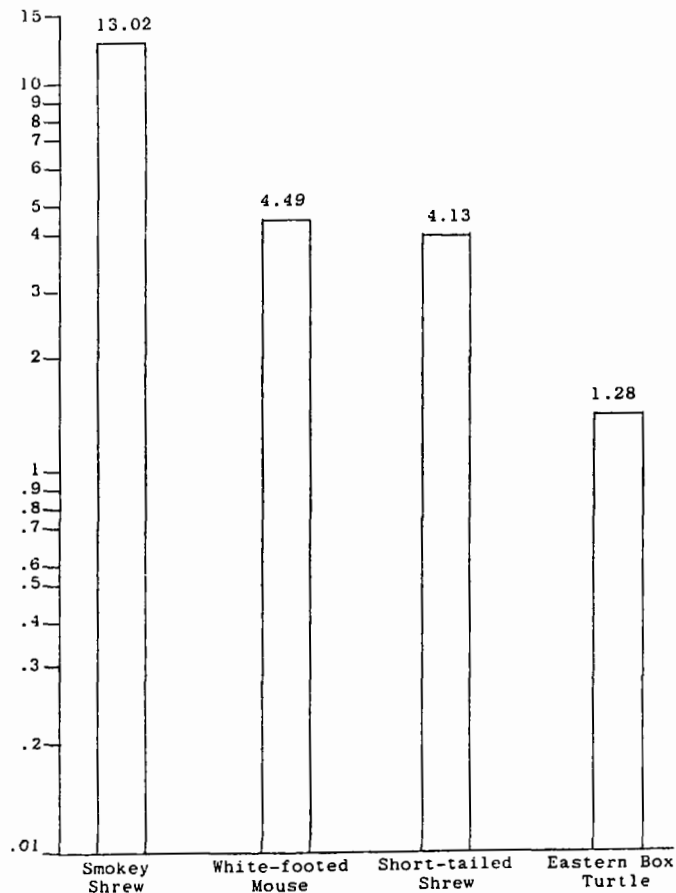


Figure 6
Variable ^{40}K Concentrations by Species Concentrations in pCi/g

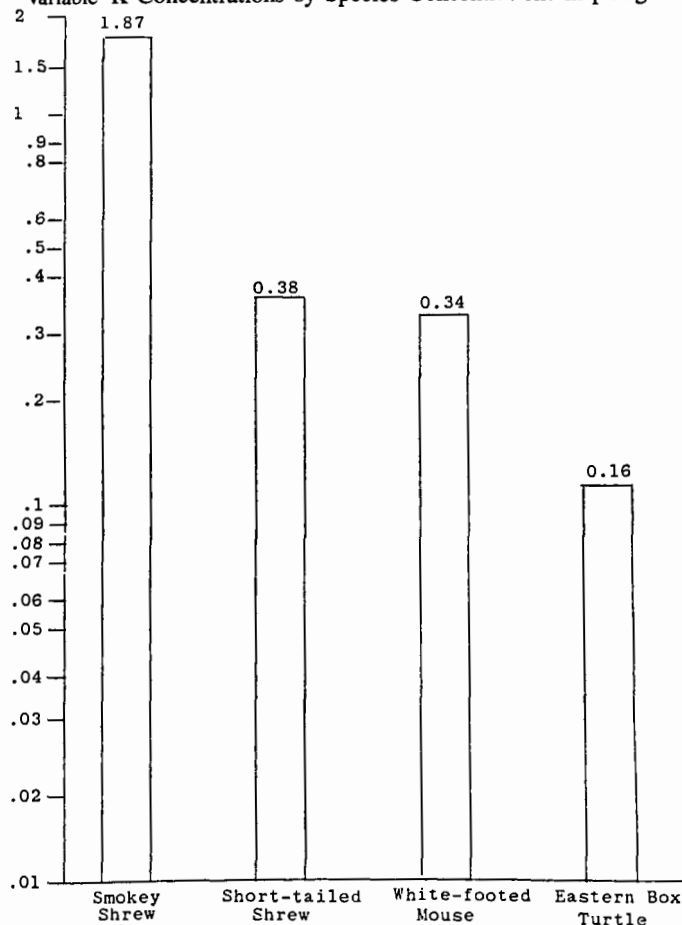


Figure 7
Variable ^{226}Ra Concentrations by Species Concentrations in pCi/g

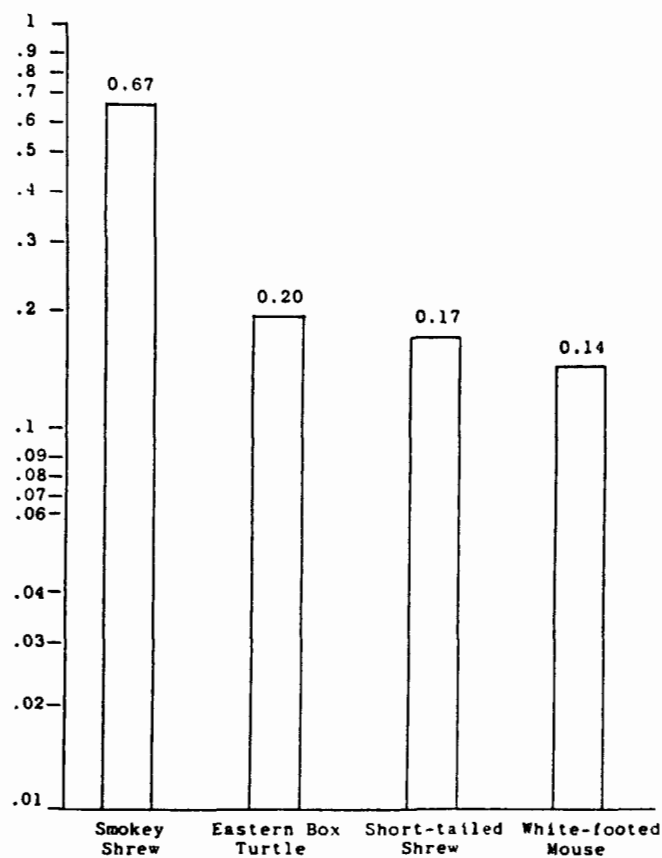


Figure 8

Variable ^{137}Cs Concentrations by Species Concentrations in pCi/g

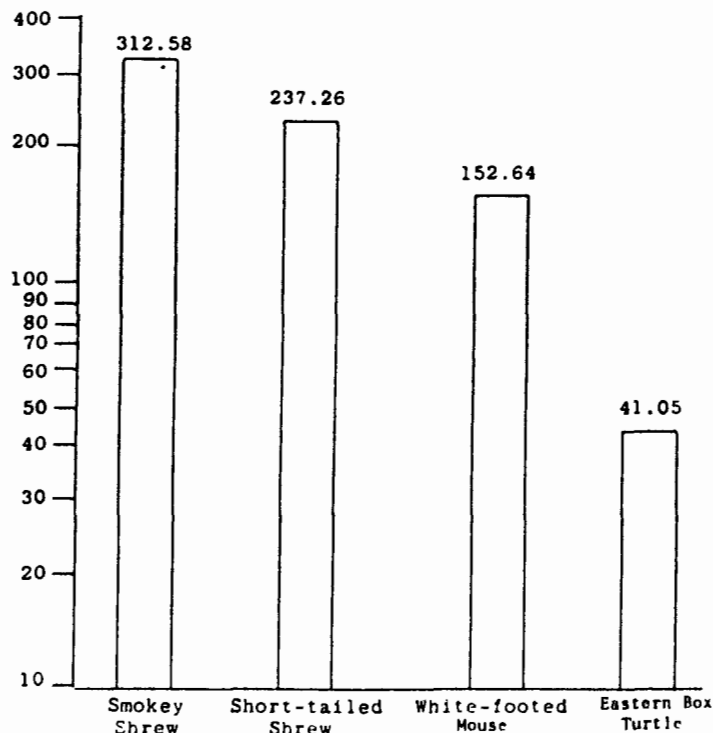


Figure 9

Variable ^3H Concentrations by Species Concentrations in pCi/mL

assimilated by the eastern box turtle and the short-tailed shrew were 0.20 and 0.17 pCi/g, respectively (Fig. 9).

The smokey shrew exhibited a concentration of tritium greater than any of the species studied. The mean concentration of tritium assimilated by the smokey shrew was 312.58 pCi/mL. The eastern box turtle exhibited a concentration of tritium less than any of the species studied.

The mean tritium concentrations assimilated by the eastern box turtle was 41.05 pCi/mL. The mean concentrations of tritium assimilated by the short-tailed shrew and white-footed mouse were 237.26 pCi/mL and 152.64 pCi/mL, respectively (Fig. 9).

DISCUSSION AND CONCLUSIONS

Extensive radiological monitoring studies of botanical species have been performed by Battelle Pacific Northwest Research Laboratory at the Maxey Flats Disposal Facility. In the fall of 1981, potassium-40 was found in newly fallen leaf samples collected from the perimeter of the site. These concentrations ranged from 1 to 3 pCi/g dry weight. Cesium-137 was measured in the newly fallen leaf samples, with concentrations ranging from 0.02 to 0.20 pCi/g dry weight¹⁰.

In 1981, tritium concentrations present in leaf water extracted from oak trees growing around the perimeter of the disposal facility indicated that tritium from the facility had entered the transpiration processes of these trees. The tritium concentrations ranged from 48 to 560 pCi/mL. Maple tree sap was also analyzed for tritium concentrations. These concentrations ranged from 30 to 151 pCi/mL for the 1981-82 sampling period¹⁰.

Soil samples from the immediate area surrounding the facility have been analyzed for gamma-emitting radionuclides. These analyses have shown the presence of potassium-40, with concentrations ranging from 17 to 26 pCi/g. Radium-226 was present, with concentrations ranging from 0.95 to 2.2 pCi/g. Exogenous cesium-137 concentrations ranged from 0.47 to 0.51 pCi/g¹⁰.

Potassium-40 was measured in all faunal samples collected. These concentrations ranged from 0.83 to 21 pCi/g and had a mean concentration of 5.93 pCi/g. Analysis of fauna showed that the amount of radium-226 assimilated ranged from 0.01 to 4.40 pCi/g, with a mean concentration of 0.68 pCi/g. Cesium-137 measured in fauna showed concentrations ranging from 0.03 to 1.40 pCi/g. The mean faunal concentration for cesium-137 was 0.28 pCi/g. Tritium was present in the species analyzed. These concentrations ranged from 2.3 to 562.0 pCi/mL, with a mean concentration of 153.92 pCi/mL.

With the exception of cesium-137, the gamma-emitting radionuclides encountered in this study were endogenous. The concentrations of cesium-137 assimilated by fauna indigenous to the environs of the disposal facility may be attributed to fallout from nuclear bomb testing; they do not appear to be influenced by the disposal facility.

The concentration of tritium assimilated by fauna appears to be comparable to the concentrations in the sample trees surrounding the disposal facility which were reported by Kirby, in 1983, to be in excess of background concentrations. A control leaf sample from the vicinity of Cave Run Lake, Kentucky, showed a tritium concentration of 2.4 pCi/mL. The tritium concentrations found in leaves near the Maxey Flats Shallow Land Burial Facility ranged from 48 to 560 pCi/mL. Concentrations of tritium assimilated by faunal species ranged from 2.3 to 562 pCi/mL. This indicates that tritium from the disposal facility has entered the biological systems of fauna in the immediate area.

REFERENCES

1. Kirby, L. J., *Research Program at Maxey Flats and Consideration of Other Shallow Land Burial Sites*, United States Nuclear Regulatory Commission Rept. No. NUREG/CR-1982.
2. Murphy, E. S. and Holter, G. M., *Technology, Safety, and Costs of Decommissioning a Reference Low-Level Waste Burial Ground*, United States Nuclear Regulatory Commission Rept. No. NUREG/CR-0570, 1980.
3. Operational Records, 1981.
4. Operational Records, 1981.
5. Operational Records, 1981.
6. Operational Records, 1981.
7. Razor, J. E., Personal Communication, 1982.
8. Clark, D. T., *Radioactivity Concentrations at the Maxey Flats Area of Fleming County, Kentucky*, Commonwealth of Kentucky, Department for Human Resources, Frankfort, KY, 1976.
9. Operational Records, 1981.
10. Zenher, H. H., *Preliminary Hydrologic Investigation of the Maxey Flats Radioactive Waste Burial Site, Fleming County, Kentucky*, USGS Rept. No. 79-1329, USGS, Louisville, KY, 1976.

11. Zenher, H. H., *Preliminary Hydrologic Investigation of the Maxey Flats Radioactive Waste Burial Site, Fleming County, Kentucky*, USGS Rept. No. 79-1329, USGS, Louisville, KY, 1976.
12. Clark, D. T., *A History and Preliminary Inventory Report on the Kentucky Radioactive Waste Disposal Site*, Commonwealth of Kentucky, Department for Human Resources, Frankfort, KY, 1973.
13. Clark, D. T., *Radioactivity Concentrations at the Maxey Flats Area of Fleming County, Kentucky*, Commonwealth of Kentucky, Department for Human Resources, Frankfort, KY, 1976.
14. Horrocks, D. L., Measuring Tritium with Liquid Scintillation Systems, in *Tritium*, ed. A. A. Moghissi and M. W. Carter, pg. 807, Messenger Graphics, Phoenix, AZ and Los Vegas, NV, 1973.
15. Kirby, L. J., A. P. Toste, W. H. Richard, D. E. Robertson, *Radionuclide Characterization, Migration and Monitoring at a Commercial Low Level Waste Disposal Site*, Battelle Pacific Northwest Research Laboratory Rept. No. IAEA-CN-43/470, Richland, WA, 1983.
16. Kirby, L. J., A. P. Toste, W. H. Richard, D. E. Robertson, *Radionuclide Characterization, Migration and Monitoring at a Commercial Low Level Waste Disposal Site*, Battelle Pacific Northwest Research Laboratory Rept. No. IAEA-CN-43/470, Richland, WA, 1983.
17. Operational Records, 1981.

Framework for Assessing Baseline Human Health Risks at Superfund Sites Contaminated with Chemical and Radiological Wastes

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ABSTRACT

Historically, U.S. Department of Energy waste disposal practices have resulted in the contamination of numerous sites with chemical and radiological wastes. In many instances, a single site will contain both types of waste, presenting unique risk assessment challenges. Currently, protocols for uniformly assessing risk from both types of contaminants at such sites do not exist. Consequently, the approach presented in this paper was developed to provide a uniform assessment of the risk to human health from sites contaminated with both hazardous chemical substances and radiological materials.

INTRODUCTION

This paper presents a suggested framework for assessing risk at U.S. Department of Energy (DOE) federal facility Superfund sites contaminated with both chemical and radiological wastes. Historically, the principal contaminants of concern have been the radioactive materials, with less or no emphasis placed on hazardous chemical contaminants. However, with the passage of the SARA in 1986, and with greater concern for the characterization and cleanup of federal facilities, both chemi-

cal and radiological contamination are now being assessed at these DOE sites.

The baseline human health assessment is an analysis of site conditions in the absence of remedial action (i.e., "no action" alternative). This evaluation requires an understanding of the nature of contaminant releases from the site, the pathways of human exposure and a measure of the potential risk to human health as a result of the releases¹. The process includes identification of potential exposure scenarios for media-specific pathways, selection of indicator contaminants, exposure assessment, toxicity assessment and risk characterization.

As part of the baseline human health assessment, several types of effects can be evaluated relative to radioactive and chemical contaminants. This paper will address radionuclide carcinogenic (e.g., stochastic) effects and chemical carcinogenic and non-carcinogenic effects. The radionuclide non-carcinogenic (e.g., non-stochastic) effects of radioactive contaminants will not be discussed since they are the result of relatively higher doses, hence are only of interest in special and limited risk assessment scenarios. Further, effects from radionuclide and chemical contaminants may be combined to obtain mixed waste carcinogenic and non-carcinogenic effects. However, consideration of mixed waste effects are beyond the scope of this discussion and will not be addressed.

Each of the five major components of the baseline human health assessment presented in Figure 1 is discussed in the following sections for chemical and radiological contaminants.

IDENTIFICATION OF EXPOSURE SCENARIOS

The exposure scenarios describe the components for potential human exposure pathways. The pathways describe the mechanisms by which a receptor may be exposed to contaminants originating from a site. An exposure pathway is comprised of the following components: source; mechanism of contaminant release; an environmental transport medium; likely route of human intake or exposure; and potential human receptor or exposure point. Figure 2 presents an example of the components used in the development of an exposure scenario. To be considered as a potential exposure scenario, all of these components of the source-pathway-receptor scenario must be present.¹

Under the authority of CERCLA, the U.S. EPA requires that a site-specific risk assessment be conducted to characterize current and potential threats to human health². This assessment involves the development of a current exposure scenario for each site (e.g., resident nearest to site, nearest population magnet and sensitive individuals), as well as a reasonable maximum exposure scenario (e.g., resident/population at point of highest contaminant concentration). It should be noted, however, that the reasonable maximum exposure scenario can be determined in a number of ways besides maximizing concentration.

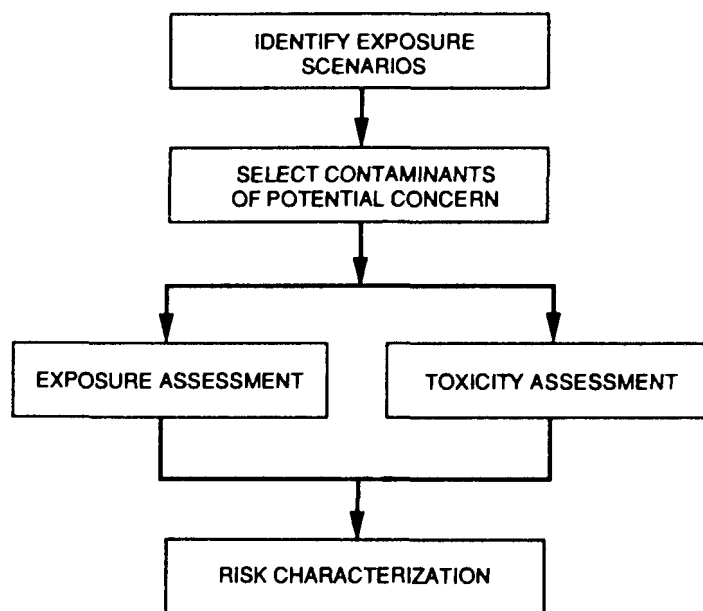


Figure 1
Baseline Human Health Assessment Process

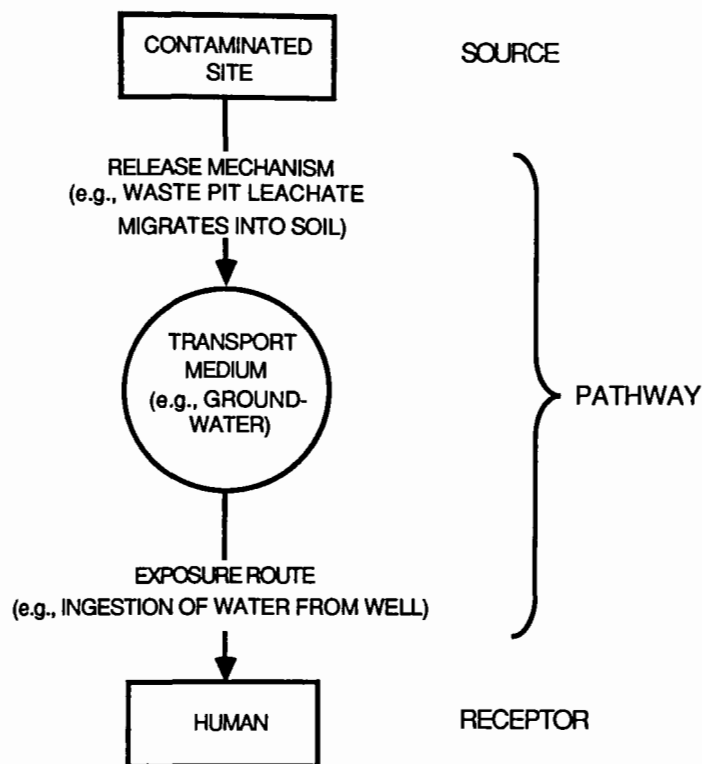


Figure 2
Exposure Scenario Components

For example, exposure can, in some cases, be more sensitive to individual activities (e.g., ingestion rates) than to contaminant concentration³. In many exposure assessments, adjusting all parameters to their limiting values would certainly maximize exposure but may not have a realistic chance of happening in the real world. For this reason, the concept of "reasonable maximum" scenario is used. In such cases, the exposures may be high, but the combination of exposure parameters for an individual are those that are more likely to occur in the actual population³.

The U.S. EPA also requires consideration of all potential pathways of radiation exposure from a disposal system to a receptor. This may include inadvertent and intermittent human intrusion into a radioactive waste disposal system by exploratory drilling for resources⁴. For this scenario, the U.S. EPA assumes that passive institutional controls (e.g., markers, intrusion barriers and fences) or the intruders' own exploratory procedures would be adequate for the intruders to detect, or be warned of, the incompatibility of the area with their continued activities.

Other agencies also have established regulatory guidance pertaining to potential receptor scenarios at radioactive waste disposal sites. The NRC assumes that after loss of institutional controls (i.e., the responsible agency no longer has control of the site), an intruder may unintentionally access a closed waste disposal site and subsequently modify it for a specific purpose⁵. Oztunali and Roles have identified several intruder scenarios relative to the NRC regulations, including a housing construction scenario and an agriculture scenario⁶. As a result of intrusion into the waste, short- and long-term radiation exposures to the individual could occur.

In addition, DOE has identified two general human receptor scenarios for assessment of dose resulting from DOE on-site operational releases from nuclear facilities: the population and maximally exposed individual in the vicinity of DOE-controlled facilities⁷, and individuals who inadvertently may intrude into a disposal facility after the loss of institutional controls⁸. Occasional exposure of inadvertent intruders has also been considered at DOE sites if restricted public use of the land is permitted during the controlled period⁹. For example, deer hunters, hikers, campers, wildlife enthusiasts or joggers in or near contaminated areas may receive external and inhalation exposures if they intrude into or near contaminated areas.

When developing exposure scenarios at sites contaminated with radioactive and chemical contaminants, consideration of institutional control time periods may be necessary. Institutional control time periods refer to the time during which controls (e.g., physical, deed, regulatory restrictions, etc.) are placed upon a site by an institution (e.g., government agency, private party, etc.). Institutional control time periods have been established by the U.S. EPA⁽⁴⁾⁽¹⁰⁾⁽¹¹⁾, NRC⁵, and DOE³.

CONTAMINANTS OF POTENTIAL CONCERN

Contaminants of potential concern are those contaminants that are site related and for which data are of sufficient quality for use in a quantitative risk assessment. For the human health assessment at sites contaminated with both chemical and radiological substances, chemical and radionuclide contaminant data must be evaluated and validated prior to selection of the contaminants of potential concern.

EXPOSURE ASSESSMENT

Exposure assessment is the determination or estimation (qualitative or quantitative) of the magnitude, frequency, duration and route of exposure. Numerous variables are used to quantify exposure. These include estimation of exposure point concentrations, estimation of contaminant intakes/exposures and quantification of pathway specific exposures.

Exposure point concentration is the average concentration contacted over an exposure period. Methods for estimating exposure point concentrations include direct use of environmental media monitoring data and use of environmental fate and transport models. These models help to predict contaminant release and migration when monitoring or characterization data are unavailable at specified points of exposure. They also help assess future risks to receptors from hazardous substances present in the environmental media.

Chemical intake is the amount of contaminant at the exchange boundaries of an organism that is available for absorption. These data are normalized for time and body weight and expressed as mg chemical/kg body weight-day. The generic equation for calculating chemical intake is presented in Table 1.

Table 1
Generic Equations for Calculation of Intakes/Exposures

CHEMICAL INTAKES

$$I = (C \times CR \times EF \times ED) / BW \times AT$$

where: I Intake (mg/kg body weight-day)
C Chemical concentration at the exposure point
CR Contact rate
EF Exposure frequency (days/year)
ED Exposure duration (years)
BW Body weight of exposed individual (kg)
AT Averaging time (days; period over which exposure is averaged)

RADIONUCLIDE INTAKE/EXPOSURE

$$ETF = I \times C \times O \times \exp(-D \times T)$$

where: ETF Environmental transport factor
I Annual intake of contaminated environmental medium
C Average concentration of contaminant in environmental medium
O Other pathway specific factors (e.g., occupancy factors, transfer factors, depth factors, etc.)
D Radiological decay constant for contaminant
T Time for decay

Radionuclide intake/exposure is determined by an environmental transport factor (ETF). This transport factor consists of pathway factors that affect the migration of a radionuclide or transmission of ionizing radiation along a pathway from the source to the point of human exposure. The generic equation for estimating the ETF is presented in Table 1.

Specific chemical and radionuclide intakes can be calculated for many different exposure scenarios. A partial compilation for possible residential exposures is presented in Table 2.

Table 2
Possible Residential Exposure Scenarios

1. Ingestion of contaminants in drinking water
2. Ingestion of contaminants in surface water while swimming
3. Dermal contact with contaminants in water
4. Ingestion of chemicals in soil
5. Dermal contact with contaminants in soil
6. Inhalation of airborne (vapor phase) contaminants
7. Ingestion of contaminated fish and shellfish
8. Ingestion of contaminated fruits and vegetables
9. Ingestion of contaminated meat and dairy products

TOXICITY ASSESSMENT

Toxicity assessment is the determination of the potential for adverse effects resulting from human exposure to the contaminants. If possible, an estimate of the relationship between the extent of exposure to a contaminant and the incidence of disease also is provided. Components of the toxicity assessment include estimation of effects from exposure to both chemicals and radionuclides.

Effects from Exposure to Chemicals

A reference dose, RfD, is the toxicity value used most often to evaluate non-carcinogenic chemical effects resulting from exposures at Superfund sites. Various types of RfDs are available, depending on the exposure route (oral or inhalation), the critical effect and the length of exposure being evaluated (chronic, sub-chronic or single event). The length of exposure may include exposures lasting 7 yr to a lifetime (i.e., chronic RfD), exposures lasting 2 wk to 7 yr (i.e., sub-chronic RfD), exposures lasting less than 2 wk (i.e., 1- or 10-day health advisories) and exposures from a single event (generally 1 day) (i.e., developmental RfD).

A slope factor and the accompanying weight-of-evidence determination are the toxicity data most commonly used to evaluate potential human chemical carcinogenic risks. The weight-of-evidence determination is used to determine the likelihood that the agent is a human carcinogen. The slope factor represents a toxicity value that quantitatively defines the relationship between dose and response. The slope factor is used to estimate an upper bound probability of an individual developing cancer as a result of a lifetime of exposure to a particular level of a potential carcinogen.

Effects from Exposure to Radionuclides

There are two broad classes of effects resulting from radiation exposures: (1)stochastic and (2)non-stochastic. Non-stochastic effects are those that have observable thresholds and that increase in severity with increasing dose. Examples of non-stochastic effects include cell death, lens opacification, cosmetically-unacceptable changes in the skin and amenorrhoea. These effects, observable only at relatively high doses, would only be of concern in certain inadvertent intruder scenarios. Stochastic effects are those effects that are random (e.g., probabilistic) in nature, for which linearity in dose response is assumed, and for which the degree of severity is independent of dose. Stochastic effects can be divided into three broad classifications: (1)genetic effects,

(2)teratological effects and (3)carcinogenic effects. For the purpose of this discussion only, the risk from carcinogenic stochastic effects will be considered. Teratological effects data are insufficient to predict a linear dose-response relationship at low doses¹². The International Commission on Radiological Protection (ICRP) places the risk of genetic effects at approximately a factor of two lower than the risk of carcinogenic effects (e.g., 4×10^{-3} rem⁻¹ versus 10^{-4} rem⁻¹)¹³. Further, the ICRP states that risk assessment of the detriment due to hereditary damage should be made over the total population. Most risk assessment scenarios, however, will not include populations sufficiently large to represent a potential threat to the gene pool.

The ICRP and the National Council on Radiation Protection and Measurements (NCRP) make the assumption that the frequency of occurrence of health effects per unit dose at low-doses is the same as at high doses. This linear, non-threshold hypothesis assumes that the risk of radiation-induced effects (i.e., cancer) is linearly proportional to dose, no matter how small the dose might be. Since no threshold associated with exposure to ionizing radiation is assumed, any dose, no matter how low, might give rise to cancer.

Ideally, human epidemiological data and animal data regarding radiation-induced cancer are used in the calculation of numerical risk estimates. However, since the epidemiological data are incomplete in many respects, mathematical models are used to estimate the risk. The result from the model is an effective dose equivalent for external radiation pathways or a committed effective dose equivalent for internal radiation pathways.

RISK CHARACTERIZATION

Risk characterization uses information from the exposure assessment and toxicity assessment to assess risks to human health from contaminants at a site. Components of the risk characterization include reviews of toxicity and exposure assessments, quantification of risks from individual contaminants, quantification of risks from multiple contaminants, combining risks across exposure pathways and assessment and presentation of uncertainties associated with the estimation of risks.

Quantification of Chemical Risks

Chemical risks from carcinogenic substances are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. For low risk levels (i.e., for estimated risks below 0.01), the linear low-dose cancer risk equation presented in Table 3 can be used to estimate risk. Where risk levels are greater than 0.01, the one-hit equation for high carcinogenic risk levels can be used (Table 3). The total cancer risk from multiple carcinogenic substances can be obtained by summing the individual substance risk estimates.

Table 3
Estimation of Carcinogenic Risks

LINEAR LOW-DOSE CANCER RISK EQUATION

$$\text{Risk} = \text{CDI} \times \text{SF}$$

where: Risk = unitless probability of fatal cancers
 CDI = Chronic daily intake averaged over 70 years, expressed as mg/kg-day
 SF = slope factor, expressed as (mg/kg-day)⁻¹

ONE-HIT EQUATION

$$\text{Risk} = 1 - \exp(-\text{CDI} \times \text{SF})$$

where: Risk = unitless probability of fatal cancers
 exp = exponential
 CDI = chronic daily intake averaged over 70 years, expressed as mg/kg-day
 SF = slope factor, expressed as (mg/kg-day)⁻¹

The potential for non-cancer health effects is evaluated by comparing an exposure level over a specified time period with a reference dose derived for a similar exposure period. This ratio of exposure to toxicity is called a hazard quotient. The generic equation for calculation of hazard quotient is presented in Table 4. The total non-carcinogenic hazard index from multiple substances can be obtained by summing individual substance hazard quotients.

Table 4
Generic Hazard Quotient Equation

$$\text{Noncancer Hazard Quotient} = E/RfD$$

where: E = exposure level (or intake)
RfD = reference dose

E and RfD must:

- (1) be expressed in the same units
- (2) represent the same exposure period (i.e., chronic, sub-chronic, or shorter-term)

If $E/RfD < 1$, it is unlikely that even sensitive populations would experience adverse health effects from the contaminant. If $E/RfD > 1$, there may be concern for potential non-cancer effects.

Quantification of Dose from Radionuclides

The annual dose for each radionuclide can be estimated as illustrated in Table 5. By summing the external and internal radiation doses individually for all contaminants at an exposure point, the annual external and internal dose to individuals is obtained. Further, the annual external and internal doses are summed resulting in a total individual annual effective dose equivalent at an exposure point.

The annual effective dose equivalent may be converted to a health risk by using the risk coefficient of 2×10^{-4} risk of fatal cancer per person-rem of radiation dose as calculated using the linear non-threshold model¹⁴. The lifetime risk is based upon the further assumption that the exposure level is the same for each year of a 70-yr lifetime.

Combining Risks Across Pathways

Whether risks or hazard indices for two or more pathways should be combined for a single total exposure point can be determined by considering: (1) the identification of reasonable exposure pathway combinations and (2) the likelihood that the same individuals would consistently face the reasonable maximum exposure by more than one pathway. If it is reasonable to combine risks across pathways, the cancer risks and the non-cancer risks must be combined separately.

UNCERTAINTIES

There are many uncertainties that are inherent in the baseline risk assessment process. Each component of the process, identified in Figure 1, has uncertainties associated with the input parameters, the evaluation methodology and the results. Specifically, some sources of uncertainty in the baseline risk assessment include input variable uncertainties modeling uncertainties, scenario uncertainties, and risk estimate uncertainties.

The process of analyzing the uncertainty can be either quantitative or qualitative depending on the time, resources and parameters or processes being analyzed. Selecting the appropriate way to characterize an uncertainty depends upon the type of decision the analysis supports, confidence level required, model type, quantity type, extent and quality of information and understanding available and the method used to propagate uncertainty.

Table 5
Annual Effective Dose Equivalent for Radionuclides

$$D = DCF \times ETF$$

where: D = Annual Dose to an individual from external or internal exposure from a radionuclide
DCF = Dose Conversion Factor
ETF = Environmental Transport Factor

Dose Conversion Factor: The dose conversion factor is the committed effective dose equivalent per quantity of a radionuclide inhaled or ingested (for internal exposure) or the effective dose equivalent rate per concentration of a radionuclide in the air, water, or ground (for external exposure).

Dose Equivalent: Dose equivalent is the product of absorbed dose in tissue, a quality factor, and other modifying factors.

Effective Dose Equivalent: Effective dose equivalent is the sum of the products of dose equivalent and weighting factor for each tissue.

Weighting Factor: The weighting factor is the decimal fraction of the risk arising from irradiation of a selected tissue to the total risk when the whole body is irradiated uniformly to the same dose equivalent.

Committed Effective Dose Equivalent: Committed effective dose equivalent is the sum of the committed dose equivalents to various tissues in the body each multiplied by the appropriate weighting factor.

Committed Dose Equivalent: The committed dose equivalent is the predicted total dose equivalent to a tissue or organ over a specified time period after an intake of a radionuclide into the body. It does not include contributions from external dose.

REFERENCES

1. U.S. EPA, *Superfund Public Health Evaluation Manual*, EPA/540/1-86/060 (OSWER Directive 9285.4-1), Office of Emergency and Remedial Response, Office of Solid Waste and Emergency Response, Washington, D.C.
2. U.S. EPA, *National Oil and Hazardous Substance Pollution Contingency Plan*, 40 CFR 300, Proposed Rule, 50 FR 38066, Dec. 21, 1988.
3. U.S. EPA, *Proposed Guidelines for Exposure-Related Measurements*, 53 FR 48830, Dec. 2, 1988.
4. U.S. EPA, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, 40 CFR 191, Final Rule, 50 FR 38866, Sept. 19, 1985.
5. U.S. Nuclear Regulatory Commission, *Licensing Requirements for Land Disposal of Radioactive Waste*, 10 CFR 61, Final Rule, 47 FR 57482, 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 61, 70, 73, and 170, Preamble, 47 FR 57446, Dec. 27, 1982.
6. Oztunali, O. I., and G. W. Roles, *Update of Part 61 Impacts Analysis Methodology*, NUREG/CR-4370, Vol. 1, EnviroSphere Company, Prepared for the U.S. Nuclear Regulatory Commission, Jan. 1986.
7. U.S. Department of Energy, *Radiological Effluent Monitoring and Environmental Surveillance*, DOE Order 5400.xy, Draft, Sept. 14, 1988.
8. U.S. Department of Energy, *Radioactive Waste Management*, DOE Order 5820.2A, Effective Nov. 28, 1988.
9. Bechtel National, Inc., *Remedial Investigation Plan for ORNL Waste Area Grouping 7*, ORNL/RAP/Sub-87/99053/16&R1, Prepared for Oak Ridge National Laboratory, Oak Ridge, TN, Nov. 1988.
10. U.S. EPA, *EPA Interim Status Standards for Owners and Operators of Hazardous Waste Facilities*, 40 CFR 265, Effective Nov. 19, 1980, 45 FR 33232.
11. U.S. EPA, *Environmental Protection Standards for Uranium Mill Tailings*, 40 CFR 192, Final Rule, Effective Apr. 22, 1980, 45 FR 27366.
12. United Nations, Scientific Committee on the Effects of Atomic Radiation, *Source and Effects of Ionizing Radiation: 1977 Report to the General Assembly*, New York.
13. International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, Pergamon Press, Oxford, England, 1977.
14. U.S. Nuclear Regulatory Commission, *Policy Statement on Exemptions from Regulatory Control*, 53 FR No. 238, pp. 49886-49891, Dec. 12, 1988.

Decontamination and Decommissioning of a Plutonium Fabrication Facility

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ABSTRACT

EcoTek, Inc. was contracted in July, 1987 to manage an active project involving the decontamination and decommissioning (D&D) of a plutonium fabrication facility at Nuclear Fuel Services, Inc. (NFS) in Erwin, Tennessee. Approximately 10,500 ft² of currently unused plutonium fabrication facilities are located in two separate buildings on the NFS-Erwin site.

Waste processing strategy centers around decontamination and sectioning with an ultra-high pressure water jetting system incorporating a recirculated medium; volume reduction in a high capacity shear/baler; and material control accountability utilizing a five station active-passive neutron non-destructive assay (NDA) system. A stainless steel containment structure has been constructed to house the sectioning and decontamination station. This containment structure attaches directly to the shear/baler, which has been modified to encapsulate all surfaces subject to contamination. The NDA system consists of five stations: (1) pre-decontamination inventory station, (2) decontamination assay station, (3) nuclear safety and accountability monitoring system, (4) bale and drum counter and (5) bulk mixed uranium-plutonium oxide assay system. The majority of waste consists of 136 gloveboxes containing process equipment. Additional sources are ventilation ductwork, piping, conduit, scabbled concrete and soil. This paper will present a brief synopsis of the overall decommissioning approach which received United States Nuclear Regulatory Commission (USNRC) approval on June 20, 1989.

INTRODUCTION

The primary objective of the decontamination and decommissioning effort is to remove all transuranic (TRU) waste by Apr. 15, 1992. By contract, all TRU waste must be received by the Department of Energy—Idaho National Engineering Laboratories (DOE-INEL) no later than this date. Specific plan objectives are:

- To restore the existing facilities and site to levels of contamination which will permit "unrestricted" use, including possible use for future NFS requirements
- To accomplish the work in a safe and environmentally acceptable manner in accordance with all applicable federal and state regulations
- To minimize the volume of waste shipments
- To keep the TRU waste volume below 5,500 ft³
- To complete all shipments to DOE no later than Apr. 15, 1992
- To meet the above objectives while performing the work in the most cost-effective manner
- To maintain exposures As Low As Reasonably Achievable (ALARA)

BACKGROUND

Site Description

The NFS site encompassing approximately 58 ac, is located within

the Erwin city limits. The City of Erwin has a population of approximately 5,600 people and is the seat of Unicoi County (population approximately 16,000). The area is within the mountainous region of east Tennessee. The site occupies a relatively level area 25 to 50 ft above the Nolichucky River. To the north, east and south, the mountains rise to elevations of 3,500 to 5,000 ft within a few miles of the site.

Plutonium Facilities History

The plutonium facilities at NFS-Erwin were constructed in 1964 and 1965. Figure 1 shows the plutonium facilities in relation to the Erwin plant site. Table 1 provides a description of the plutonium facilities. Between 1965 and 1972, NFS processed 812 kg of plutonium for four primary customers. The largest order covered the manufacture of approximately 2,000 PuO₂-UO₂ mixed oxide (MOX) fuel rods for the Southwest Experimental Fast Oxide Reactor (SEFOR). This project was a joint undertaking of General Electric, the AEC and several utility companies. The GE-SEFOR order (746 kg Pu) and the DuPont-SROO order (16 kg Pu) comprised 94% of the Erwin job orders which utilized plutonium as shown in Table 2.

In the years following completion of the final order (1973 to 1985), NFS was unsuccessful in finding a disposal site for TRU wastes that would be generated from decommissioning activities. NFS was finally successful in negotiations with the DOE-INEL office in 1985. These efforts culminated on Apr. 15, 1986, with the signing of the contract which allows NFS to ship its TRU wastes to DOE-INEL.

Process and Equipment Description

Capabilities of the NFS-Erwin plutonium facilities included: dissolution of plutonium metal and oxide; co-precipitation of uranium-plutonium; blending of MOX powders; pellet production and inspection; rod loading, welding and inspection; scrap dissolution; and full laboratory services.

Equipment in the facilities is located primarily in gloveboxes or in a single limited-entry cell adjacent to the conversion area. In addition to gloveboxes, the plutonium facilities contain equipment such as: metal tanks (some containing Raschig rings); glass columns; pumps; mixing vessels; blenders; drying, conversion and sintering furnaces; pellet press; cut-off machine and centerless grinder; outgassing equipment; inspection jigs; welders; leak test equipment; liquid and high efficiency particulate air (HEPA) filters; miscellaneous laboratory equipment; ventilation fans; wet scrubbers; and piping. Figures 2 and 3 show detailed layouts of equipment in Building 234 and Building 110, respectively. Equipment listings by type and volume for each building are shown in Tables 3 and 4.

Radiological Status

Initial radiological surveys were made in each building to provide

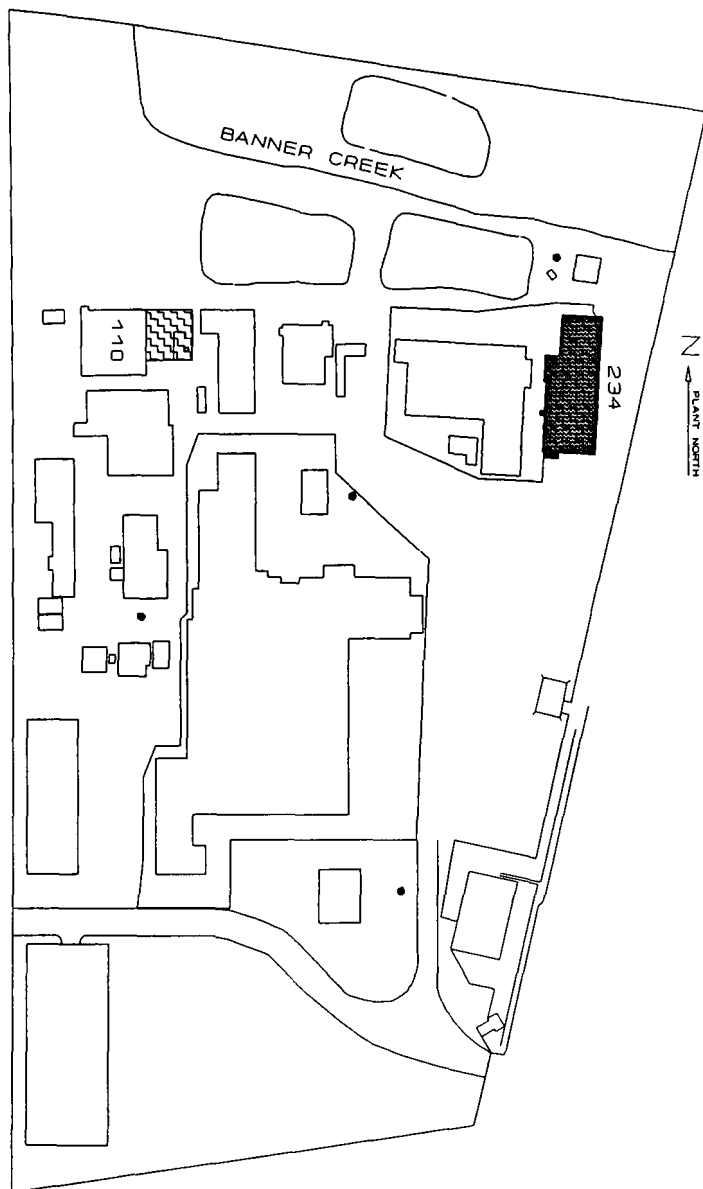


Figure 1
Plutonium Facilities NFS-Erwin Plant Site

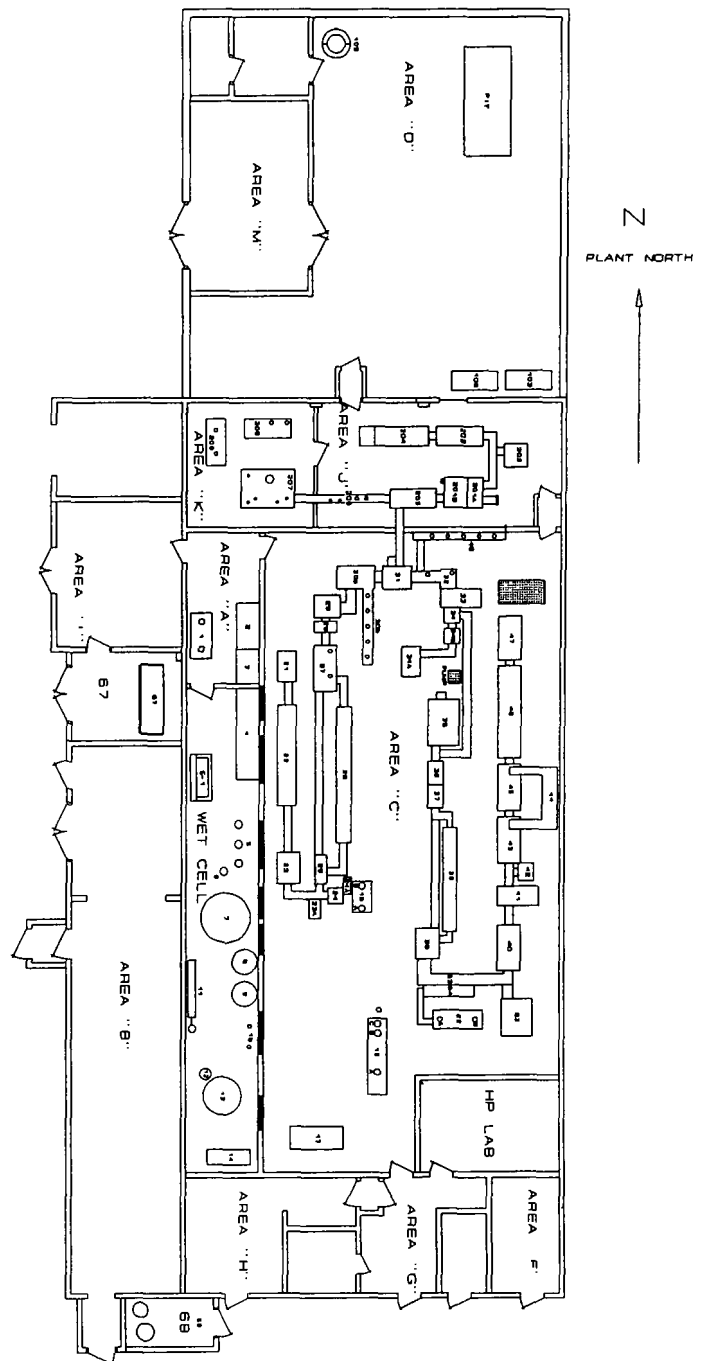


Figure 2
Building 234: Detailed Equipment Layout

input to planning efforts. Continuous radiological surveillance is performed at each building to maintain exposures ALARA, to prevent spread of contamination, to determine extent of decontamination required and to segregate radioactive waste. A final radiological survey will be made at each facility at the conclusion of decontamination and decommissioning (D&D) operations in compliance with the USNRC "Guidelines for Decontamination of Nuclear Facilities and Equipment Prior to Release for Unrestricted Use or Termination of License for Byproduct, Source, or Special Nuclear Material," Division of Fuel Cycle and Material Safety, July, 1982.

Facility Disposition

As previously discussed, the primary objective of the NFS D&D project is to reach an "unrestricted" use status for all remaining equip-

ment/facilities after completion of the Final Survey. The equipment that is not contaminated or has been successfully decontaminated will either be retained for use by NFS or processed as excess equipment. There is no intent during D&D to remove the building structures since any remaining structures should meet the unrestricted release criteria.

Decommissioning Project

The purpose of the project is to decommission the NFS facilities and dispose of all contaminated waste generated at off-site burial and/or storage locations. The waste material is weighed and assayed to determine the concentration of radioactivity. The three waste classifications are Class A (<10 nCi/gm), Class C (10-100 nCi/gm) and Greater Than Class C (>100 nCi/gm) of TRU. Following dismantling, decontamination, shearing, baling, packaging and classifying, the waste is sent

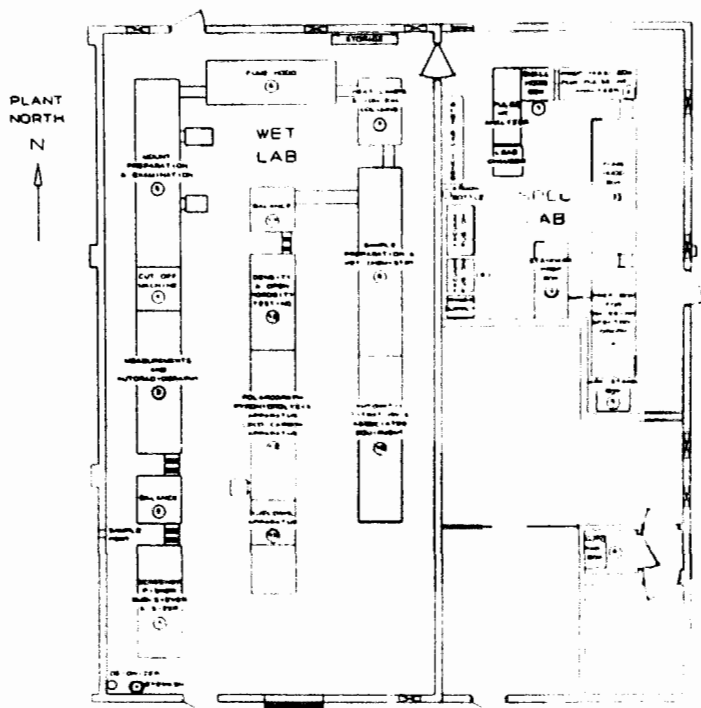


Figure 3
Building 110: Detailed Equipment Layout

to one of the approved disposal or storage sites. INEL's facility will be used for Greater Than Class C materials. Class A and Class C material will be disposed of at an approved commercial burial facility.

As decommissioning progresses, bulk quantities of MOX will be encountered. As that occurs, these materials will be collected under rigid criticality, security and material control conditions. Processing of these materials, such as screening, cleaning and drying, will be required. Bulk MOX material will be packaged, stored and shipped to the Department of Energy (DOE).

Modifications to Building 234, Area D have been performed in order to construct a decontamination and volume reduction area (Fig. 2). The existing plant ventilation systems and criticality monitoring systems have been supplemented to support this area.

DECONTAMINATION AND VOLUME REDUCTION FACILITY

The Decontamination and Volume Reduction Facility (DVRF) located in Area D of Building 234 is utilized to decontaminate and volume reduce gloveboxes and other components and equipment. The major pieces of equipment associated with the DVRF are the General Dynamics Corporation PERMA-CON™ enclosure (decontamination cell), the ADMAC® JETPAC™ ultra-high pressure water jetting system, the MAC Corporation Shear Power Baler™ Model 5200, Pajarito Scientific Corporation Five Station Active-Passive Neutron NDA System, General Electronics digital scales, the data acquisition system (DAS) electronics and the bale packaging and storage areas. Figure 4 shows the layout of the DVRF.

Decontamination Cell

The decontamination cell is a modified version of General Dynamics PERMA-CON™ enclosure. The enclosure consists of interchangeable, modular panels constructed of a carbon steel frame sheathed with stainless steel.

The overall dimensions of the containment structure are 30 ft long and 10 ft wide. It is divided equally into two 10- x 15-ft rooms. The first room is a material receipt airlock. The airlock is 12 ft high. The second room is the main decontamination area which is 16 feet high. Bi-fold doors lead into the airlock and provide access between the airlock and decontamination room.

Table 3
Equipment Listing and Volume

Building 234			
AREA	STATION #	STATION DESCRIPTION	VOLUME (CU. FT.)
A	1	Pu Nitrate Load-in Box	199
	2	Pu Scrap Prep. Box	89
	3	Pu Scrap Prep. Box	48
B	4	Scrap Dissolution	260
	5	Nitrate Storage Columns	60
	6	Nitrate Pump	1
	7	Pu U Master Mix Tank	294
	8	Surge Tanks	85
	9	Surge Tanks	85
	10	Evaporator	26
	11	Vacuum Pump	28
	13	Evaporator Tank	183
	14	Condenser Receiver	40
B	S-1	Scrubber Columns	85
C	15	Precipitation Box	334
	16	Filtrate Column Box	91
	17	Precipitation Box	212
	21	Pu ADU Furnace Load Box	102
	22	Drying Furnace	90
	23	Pu ADU Unloading Box	175
	24	Storage Box	58
	25	Tray Load	38
	26	Oxide Conversion Furnace	141
	27	Tray Unload/Return Box	134
	28	Dumb Waiter Station	50
	29	Twin Shell Blender	232
	30A	Oxide Loading Station	141
	30B	Storage Rockets	139
	31	Oxide Slugging Press	100
	32	Oxide Transfer Box	359
	33	Pellet Press	263
	34A	Inspection & Tray Return	11
	34B	Inspection	131
	34C	Pellet Press	116
	35	Pellet Press	438
	36437	Pellet Inspect/Tray Load	83
	38	Sintering Furnace	153
	39	Unload Box & Tray Return	83
	40	Pellet Inspection	83
	41	Pellet Cut-off Station	144
	42	Density Check Station	29
	43	Pellet Wash Station	116
	44	Pellet Storage	62
	45	Pellet Storage	104
	46	Fuel Loading Station	188
	47	Rod Cleaning Station	16
	48	Oxide Storage Rockets	116
	62	Pellet Grinder	177
	63464	Pellet Transfer/Storage	212
	65	Pellet Out-gas Station	115
I	67	Condensate Station	209
H	68	Condensate Station	27
J	201AAB	Oxide Prep. Station	206
	202	Drum Unload Station	214
	203	Scrap Prep. Station	177
	204	Leaching Station	193
	205	Oxide Load Station	128
	206	Oxide Storage Rockets	62
K	207	Oxide Dissolution Station	370
	208	Pu Nitrate Storage	202
	209	Pu Nitrate Load-Out	212
D	103	Rod Cleaning Station	46
	109	Rod Cleaning Station	80
		Rod Welder	240

TOTAL CUBIC FEET FOR BUILDING 234 8,883

Both rooms are serviced by 1 ton capacity bridge cranes. Lighting is provided from above through polypropylene panels in the ceiling of the containment structure. Access ports for ventilation, supplied breathing air lines, pneumatic tool air lines and ultra-high pressure water jetting lines are provided through the modular panels with sealable bulk-head penetrations.

The foundation of the floor is a built up concrete pad, sloped to a sump in the middle and covered with stainless steel. A metal grating cover provides traction on a level surface and prevents water used in the decontamination process from pooling around the operators' feet.

Air is supplied to the containment from conditioned room air in Area D. The air is pulled in at 500 cfm with an exhaust fan. The exhaust

is discharged to the atmosphere through a HEPA-filtered exhaust stack. Routine stack samples are taken to monitor airborne contaminants discharged to the atmosphere. The air intakes to the containment are also HEPA filtered to prevent spread of contamination into Area D in the event of positive pressure in the cell.

All personnel operating in the cell wear supplied air encapsulated suits which provide protection with a safety factor of 2,000. Careful personnel surveying by radiation monitors and decontamination techniques during transition out of the containment prevent the spread of contaminants outside the cell.

Table 4
Station Descriptions and Estimated Volumes

BUILDING 110			
AREA	STATION #	STATION DESCRIPTION	VOLUME (CU. FT.)
110-C	1	Screening & Sizer	27
110-C	2	Balance Box	178
110-C	3	Autoradiography	318
110-C	4	Cut-Off Machine	144
110-C	5	Mount Prep. Box	397
110-C	6	Fume Hood	273
110-C	7	Ion-Exchange	232
110-C	8	Sample Prep/Wet Chemistry	389
110-C	10	Auto Titration	351
110-C	11	Balance	174
110-C	12	Density & Porosity Test	207
110-C	13	Polarograph Box	331
110-C	14	Kjeldahl Apparatus	350
110-D	1	Small Hood Box	59
110-D	2	Prep. Box for Pulse Height Analyzer	149
110-D	3	Fume Hood Box	225
110-D	4	Prep. Box for Emission Spectrography	239
110-D	5	Arc Stand Box	72
110-D	6	Auto Radiography	23
110-D	7	Standard Prep. Box	148
110-D	8	Vacuum Fusion Box	62
TOTAL CUBIC FEET FOR BUILDING 110			4,346

Table 2
Summary of Erwin Plutonium Processes

DATE	CUSTOMER	PRODUCT	KGS. PLUTONIUM
1965	DuPont/SROO	MOX	16
1966		Fuel rods	
1967	SEFOR/GE/AEC	MOX	746
1971		Fuel rods & scrap dissolution	
Sub-Total AEC Programs:			762
1972	Halden/NFS/RFD	MOX Fuel rods	3
1972-1973	Big Rock Point/Consumers/NFS/RFD	MOX fuel assemblies	47
Sub-Total NFS Programs:			50
TOTAL ALL PROGRAMS:			812

Table 1
Description of Plutonium Facilities

234 BLDG.	FUNCTION	SQUARE FEET
Area C	Pelleting	3,000
Area A	Batch Weigh	108
Area B	Former U-233 Process	994
Area D	Fabrication	1,550
Area E	Lab	228
Area F	Office	135
Area G	Clean Change	246
Area H	Process Change	249
Area I	Material Unloading	288
Area M	Air Lock	360
Area 67	Condensate Station	168
Area 68	Condensate Station	66
Wet Cell	Cell	630
TOTAL		8,022
110 BLDG.	FUNCTION	SQUARE FEET
Area C	Wet Chemistry Lab	1,800
Area D	Spectrographic Lab	617
TOTAL		2,417

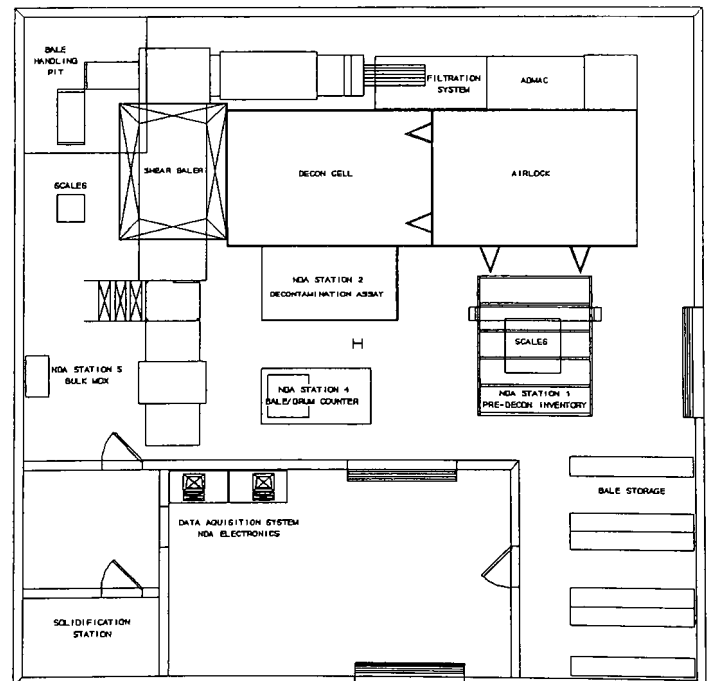


Figure 4
Decontamination and Volume Reduction Facility

ADMAC® JETPAC™ Ultra-High Pressure Water Jetting System

The ADMAC® JETPAC™ provides the primary means of decontamination for gloveboxes, piping and equipment. The JETPAC™ produces up to 40,000 psi of water pressure at a 2 gpm flow rate. This system has effectively decontaminated hard surfaces at nuclear facilities across the country. Additionally, the JETPAC™ can be fitted with options that provide sectioning and concrete scaling capabilities.

During operation, the residual water from the decontamination process is picked up from the floor sump through the metal grating by a slurp pump. The water is processed through a series of filters and ion exchanges and stored for re-use by the JETPAC™.

MAC Corporation Shear Power Baler™ Model 5200 (Modified)

A shear/baler, with modifications specified to ensure containment of contaminants, has been purchased from the MAC (Mobile Auto Crusher) Corporation. The shear/baler provides 377 tons of shear capacity and 180 tons of compaction force. The shear/baler can accept gloveboxes, piping, conduit and other equipment into its loading hopper, perform shearing and compacting operations with an extremely efficient hydraulics package and deliver a 16-in. square bale of variable thickness. The thickness is determined by the amount of material sheared before the compaction stroke.

Major modifications have been specified to the basic shear/baler unit to ensure that contaminants are kept within the shear and compaction chambers. All internal wear plates have been seal welded to form a continuous chamber from the loading hopper to the outlet chute. A sheet metal enclosure surrounds the sliding plate and area behind the shear ram head. All hydraulic ram pistons have been fitted with bellows assemblies to prevent adhesion of airborne contaminants to the piston walls which would lead to contamination of the hydraulic system.

The top of the hopper has been fitted with a sheet metal enclosure over the top and three sides. The fourth side is flanged, fitted with a gasket and mated to the decontamination cell. The bridge crane installed in the decontamination cell extends over the top of the loading hopper to assist the operator in loading material into the shear/baler. Additionally, the side of the loading hopper adjacent to the decontamination cell has been hinged with electrically driven worm gears installed to lower the side, allowing easier access for the operator to the charging box of the shear/baler. A vertical extension, which rides in a track and folds down with this side, has been installed to provide protection to the operators in the decontamination cell from small pieces of material which might break loose and become projectiles during the shearing operation.

The controls for the shear/baler are located at a central panel outside of the containment. A Lexan™ window has been installed in the containment to allow the shear/baler operator a clear view of the loading area. Emergency shut-off switches have been installed at the control panel, inside the decontamination cell and at the bale outlet chute.

A glovebox is attached to the outlet chute to provide an enclosure to seal the bales in plastic as they emerge from the shear/baler. The bale is subsequently bagged out of the glovebox to provide a double seal. Gravity roller conveyors have been installed in the glovebox to assist the operator in handling the bales.

Pajarito Scientific Corporation's Five Station Non-Destructive Assay System

Pajarito Scientific Corporation designed and fabricated a non-destructive assay (NDA) system that consists of five stations. The stations utilize combinations of passive neutron detectors, an active neutron generator and a Canberra® Big MAC™ (multi-attitude cryostat) hyper-pure germanium detector.

Station 1 is a series of passive neutron detectors used to provide an initial inventory of holdup in equipment prior to entering the decontamination cell airlock. This inventory is used to verify holdup measurements taken during the in situ characterization effort and to localize holdup to optimize decontamination efforts. The equipment also is weighed at this station with electronic scales to determine an overall concentration. This station can detect 200 mg of plutonium.

Station 2 is an active-passive neutron differential die-away station utilizing a neutron generator to induce reactions in the contaminated material which can be detected by ³He neutron detector tubes. Station 2 is located in a chamber immediately adjacent to and accessible from the decontamination cell. This station is utilized to determine decontamination effectiveness and can detect 10 mg of plutonium.

Station 3 consist of two passive neutron detector packages used for real-time nuclear safety monitoring of holdup and material accountability. These detectors are placed on the water recirculation system and the shear/baler. In addition to providing continuous monitoring, the detectors trigger an alarm at a threshold of neutron activity well below nuclear safety concern. Station can detect 200 mg of plutonium.

Station 4 is an active-passive neutron differential die-away station used to assay bales and drums. The bales are accurately weighed, assayed, measured and labeled with a bar code. The labeled bales are stored in identifiable locations in a shelving area. As sufficient bales are produced, packaging is accomplished in a batch mode. A computer program optimizes the packaging of the drums based on bale height and concentration, selecting bales that, when packaged together in a 55-gal drum, minimize void space and maximize specific activity within the waste acceptance criteria of the designated burial or storage site. Station 4 can detect 2 mg of plutonium.

Station 5 is a passive neutron detection chamber for assaying bulk mixed plutonium-uranium oxide (MOX) retrieved from the process equipment prior to decontamination. A hyper-pure germanium detector is used for isotopic analysis of the bulk MOX which is processed and packaged for shipment to DOE.

Data Acquisition System

In order to provide an accurate history of decommissioning activity, every opportunity has been taken to utilize electronic monitoring, recording, retrieval and reporting. Equipment is tagged and tracked by bar code from the moment it is removed from the process line to the time it is placed in a drum for burial. This audit trail provides a validation of facility characterization, real-time material accountability control, and assists in management of the decommissioning effort. Records required for shipment, storage and disposal are generated by the Data Acquisition System (DAS) from the data base.

DECOMMISSIONING MATERIAL FLOW

Before gloveboxes and equipment are removed from the process areas, they are surveyed for contamination. All contamination is either removed or fixed in place to eliminate regeneration of airborne particulate. Gloveboxes or equipment that require dismantling or sectioning before removal are completely contained inside temporary containments (e.g., tents). All work associated with equipment removal or sectioning is conducted with respiratory protection and layered anti-contamination clothing.

All equipment removed from Building 110 is transported approximately 0.25 mi to Building 234 and the DVRF. Material transport is conducted in a 16-ft trailer pulled by a tow motor. The trailer has been lined with formica sheathing and linoleum with all cracks and crevices sealed. The equipment is transferred into and out of the trailer through dock seals attached to the buildings. The trailer is equipped with a roll up door. The equipment removed from Building 110 enters the DVRF through the Building 234, Area M airlock.

The equipment is then moved into the DVRF to NDA Station 1. The initial assay and weight are recorded in the data acquisition system. A determination is made to ensure that safe mass limits will not be exceeded by the introduction of the material being assayed into the decontamination cell. The initial assay also is used to validate the facility characterization and to localize material holdup for the decontamination effort.

The equipment is then introduced into the decontamination cell through an integral airlock. The material handling in the airlock and the decontamination cell is assisted by 1 ton bridge cranes. Once the equipment is in the decontamination cell, it can be sectioned as necessary, opened and cleaned. After initial decontamination is complete, NDA Station 2 is utilized to determine if decontamination has been effective and if further cleaning is required. The goal is to decontaminate

all equipment to below 10 nanocuries of TRU per gram of waste.

When the equipment is decontaminated to as low a level as achievable, it is hoisted into the loading hopper of the shear/baler. After each shearing cycle is completed, a baling cycle is performed. If additional shearing cycles are made before producing a bale, the bale becomes too thick and unmanageable. A single cycle bale is nominally 4 in. thick and weighs 50 lb. The 16-in. height and width are determined by the inner dimensions of the baling chamber.

The bale exits the shear/baler into a glovebox where it is sealed in flame retardant plastic. It is then bagged out of the glovebox and heat sealed in a second layer of flame retardant plastic. The sealed bale is weighed, assayed in Station 4 and the thickness is measured. A bar code label identifying the bale is attached and the associated information is recorded in the DAS. The bale is then placed in an identified cell in a temporary storage area. When sufficient bales are produced

to generate drums for shipping, the DAS is accessed and the computer selects bales for optimum packaging of 55-gal drums.

CONCLUSIONS

During the planning phase of the NFS Plutonium facilities decommissioning project, several alternative approaches to the ultra-high pressure jetting decontamination and shear/baler operation were evaluated. However, the D&D action presented in this paper provided the best means of disposing of the contaminated materials in an environmentally sound manner in association with the implementation of a program that minimized the amount of TRU and low level waste (LLW) materials requiring disposal. Costs were substantially reduced due to the decreased volume of the waste to be buried, the reduced time schedule and the fewer number of personnel required to accomplish the tasks.

Mixed Funding as an Enforcement Tool in Superfund Settlements

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INTRODUCTION

The goal of the U.S. EPA in implementing CERCLA, as amended by SARA, is to achieve effective and expedited cleanup of as many uncontrolled hazardous waste sites as possible. To meet this goal, the U.S. EPA may enter into settlement agreements with PRPs to carry out cleanups, or, where such agreements are not reached, use enforcement actions to order such cleanups. Where enforcement actions are not available for a variety of reasons, however, the Agency may conduct Fund-financed cleanups and subsequently initiate litigation against PRPs to recover the costs of cleanups. The U.S. EPA's objective is to have the party responsible for the release undertake the actions necessary to mitigate such releases.

For this reason, response actions undertaken by PRPs are essential to the Government's goal of achieving effective and expedited cleanup of hazardous waste sites. Prior to the enactment of 1986, SARA, the Agency issued the "Interim CERCLA Settlement Policy (50 FR 5034 *et seq.*, Feb. 5, 1985). The Interim CERCLA Settlement Policy set out the conditions under which the government may settle for less than 100% of the costs of a cleanup authorized by CERCLA through its strict, joint and several liability. This guidance states that the U.S. EPA will negotiate only if the initial offer from the PRPs constitutes a substantial proportion of the response action costs or a substantial portion of the needed remedial action.

To provide additional incentives for voluntary cleanups, Congress through SARA provided the Agency with the authority to allow private parties (including PRPs) to carry out a response action and then reimburse the parties for the costs incurred. CERCLA Section 122 provides the U.S. EPA with the authority to enter into negotiated settlements with PRPs that provide for: (1) conduct of the response action by the settlors in return for the reimbursement of a portion of the costs of the response action from the Fund (i.e., "preauthorization"); (2) the conduct of discrete portions of the work by the settlors in satisfaction of their liability (i.e., "mixed-work"); and (3) cash payments by the settlors in satisfaction of liability for the release at issue (i.e., "cash-outs"). In the broadest sense, these three different types of settlements are referred to as "mixed funding" agreements. The Agency, at its discretion, may enter into these agreements with PRPs to conduct and/or pay for a portion of a response action.

In summary, the three types of mixed funding agreements to be discussed in this paper are:

- *Preauthorization* is an arrangement in which the PRP agrees to conduct the response action, and the U.S. EPA agrees to allow the PRP to assert a claim against the Fund for a portion of his response costs
- *Cash-out* is an arrangement in which a PRP pays the U.S. EPA for a portion of the response action and the U.S. EPA agrees to conduct

or arrange for the conduct of the response action

- *Mixed-Work* is an arrangement in which the PRP and the U.S. EPA agree to conduct discrete portions or segments of the response action.

While Section 122 of CERCLA authorizes mixed funding settlements, Section 122(b)(1) also requires that the U.S. EPA make all reasonable efforts to recover Fund reimbursements from other parties through the authority of Section 107 of CERCLA.

MIXED FUNDING IN SETTLEMENT NEGOTIATIONS

After mixed funding settlements were expressly established by statute as settlement tools for the U.S. EPA in the 1986 amendments, the U.S. EPA published guidance on "Evaluating Mixed-Funding Settlements Under CERCLA (53 FR 8279 *et seq.*, Mar. 14, 1988). This settlement guidance provides that the criteria of particular importance include the strength of the liability case against settlors and any non-settlors, the size of the portion for which the Fund will be responsible, and other mitigating and equitable factors.

Shortly after it issued the settlement guidance, the U.S. EPA elected to implement the authority of Section 122(b)(1) to reimburse parties to settlement agreements in the same manner as claims for response costs authorized pursuant to Section 111(a)(2) of CERCLA. Specifically, Section 111(a)(2) of CERCLA authorizes the U.S. EPA to any claim for response costs incurred by "any other person" as a result of carrying out the National Contingency Plan. The NCP requires, among other things, U.S. EPA's prior approval, referred to as "preauthorization."

THE PURPOSE OF A MIXED FUNDING SETTLEMENT

The purpose in pursuing a mixed funding settlement is as follows:

- Provides the government with an additional means to initiate response activity
- Provides a means to expedite cleanup, thereby avoiding protracted litigation
- Provides up-front financing of a cleanup by the PRPs

CRITERIA FOR ELIGIBILITY

The following criteria are specified in the guidance document *Evaluating Mixed Funding Settlements Under CERCLA* (Oct. 20, 1987) and the ten-point settlement criteria contained in the *Interim CERCLA Settlement Policy*. These criteria should be used in the evaluation of any mixed funding settlement proposal.

- *The strength of the liability case against settlors.* This criterion includes any litigative risks in proceeding to trial against settlors as well as the nature of the case remaining against nonsettlors after the settlement.
- *The size of the portion or operable unit for which the Fund will be responsible or the amount of the PRPs' offer.* A substantial cost of

cleanup should be offered by the PRPs usually over 50%. The higher the PRPs' portion, the greater the incentive for them to keep their costs down.

- *Good-faith negotiations and cooperation* of settlors and other mitigating and equitable factors.
- *The government's options in the event settlement negotiations fail.* There should be some assurance, for example, that if negotiations break down, a State cost share will be available for a Fund-lead action.

PREAUTHORIZATION IN SETTLEMENT NEGOTIATIONS

The preauthorization process in settlement negotiations consists of three distinct but interrelated steps:

- Mixed funding offer, negotiation and U.S. EPA/PRP agreement in principle
- Submittal of the application for preauthorization and review by the U.S. EPA
- Final negotiation of the consent decree and development of the PDD by the U.S. EPA.

Before the U.S. EPA will consider preauthorization of a response action by a PRP, the PRP and the U.S. EPA must be involved in settlement negotiations. The first step that a PRP may take to initiate the preauthorization process is to propose a mixed funding settlement offer through the appropriate U.S. EPA Regional Office. This proposal typically takes the form of a "good faith" offer in response to a special notice letter from the U.S. EPA, pursuant to Section 106(b) of CERCLA, through which the U.S. EPA advises the PRP that he is liable for response costs as a result of a release or threat of release. Such an offer should be substantial and provide a basis for evaluation by the U.S. EPA.

The Interim CERCLA Settlement Policy contains the "Ten-Point Criteria" the U.S. EPA will use in determining whether it is appropriate to settle for less than 100% of response action costs. The U.S. EPA will evaluate the PRP's offer against these criteria. If the offer appears acceptable, the Regional Office will determine if preauthorization, or some other mixed funding approach, is appropriate. Once the Regional Office determines that preauthorization is appropriate, an agreement in principle is generally sent to the PRP. At this point, the Regional Office may also provide the PRP with guidance on the next step—the Application for Preauthorization.

The Application for Preauthorization, consistent with Section 300.25(d) of the NCP [300.700(d) of the proposed revision to the NCP], formally notifies the Agency of the PRP's intent to submit a claim against the Fund, demonstrates the PRP's knowledge of the NCP and the site-specific remedy and demonstrates the PRP's technical, financial and other capabilities to carry out the response action in a safe and effective manner. Once the PRP submits an acceptable application, the U.S. EPA will formulate the Preauthorization Decision Document (PDD).

The development of the Consent Decree and the PDD is the final step in the preauthorization process. The Consent Decree sets out the requirements of the parties to the agreement and is enforceable by the court. The non-negotiable, site-specific PDD, an attachment to the Consent Decree, sets forth the terms and conditions for reimbursements from the Fund, including the maximum amount of such reimbursements and the schedule for reimbursements.

To date, the U.S. EPA has authorized six design and construction mixed funding agreements through court approved consent decrees: the Re-Solve site in Region I; the McAdoo, Harvey & Knotts and Tybouts Corner sites in Region III; the Motco site in Region VI; and the Colbert site in Region X. In addition, a Consent Decree was lodged in September 1989 for the Bailey Waste Disposal site in Region VI. The U.S. EPA has authorized one mixed funding agreement for an Area-wide RI/FS through an Administrative Order on Consent (Peak Oil/Reeves/Bay Drums in Region IV). The costs of design and construction range from \$7 to \$45 million. The maximum reimbursement from the Superfund ranges from \$1.4 to \$9.3 million.

SUBMITTAL OF A CLAIM UNDER PREAUTHORIZATION

Claims will be awarded from the Fund in accordance with the terms

and schedule contained in the Consent Decree. An important component of the claims award process is the presentation of the claim to non-settling PRPs (i.e., other parties liable for the release that are not parties to the settlement). Section 112(a) of CERCLA states that a claim may not be submitted against the Fund unless it is first presented to the owner, operator or guarantor of the vessel or facility from which the hazardous substance has been released (if known) and to any other person who may be liable under Section 107 of CERCLA. If additional PRPs are unknown, the potential claimant must make a good-faith effort to identify any other parties believed responsible for the release. If the claimant cannot locate other PRPs or the claim remains unsatisfied for 60 days after presentation, the potential claimant may then submit the claim to the U.S. EPA.

Once the U.S. EPA has received the claim and has determined that the claim contains the information and documentation necessary for evaluation (i.e., it has been "perfected"), the Agency will review and analyze the claim according to the criteria set forth in the proposed CERCLA Response Claims Procedures (54 FR 37892 *et seq.*, Sept. 13, 1989). The Agency may use the services of a claims adjusting firm in reviewing the claim to determine that the costs are "necessary."

The Agency's proposed Response Claims Procedures defines "necessary" response costs as: (1) required (based on site-specific circumstances), (2) reasonable (nature and amount do not exceed that estimated or which would be incurred by a prudent person), (3) allowable (incurred specifically for the site at issue) and (4) otherwise allowable (consistent with the Federal cost principles). If the claim fulfills the established criteria, the Agency will award the claim and reimburse the claimant the amount of the approved response costs.

If the U.S. EPA determines that the claim has not fulfilled the requirements contained in the Consent Decree, the claim will be denied in whole or in part. As provided by Section 112(b)(2) of CERCLA, if the claimant is dissatisfied with the award from the U.S. EPA, that claimant may request a hearing before an Administrative Law Judge. All decisions by such an ALJ shall be final, but either party may appeal a decision within 30 days of notification of the award or decision to the Federal district court. Pursuant to Section 112(b) of CERCLA, decisions by an ALJ shall not be overturned except for arbitrary and capricious abuse of discretion.

To date, settling defendants have not filed any preauthorized claims against the Superfund.

MIXED WORK SETTLEMENTS

As stated above, a mixed work settlement involves an agreement which addresses the entire response action, but the PRPs and the Agency agree to conduct and pay for discrete portions of the remedial action.

Evaluation of a Mixed Work Proposal

Mixed work may be appropriate for cases in which the U.S. EPA can identify discrete phases or operable units of the remedial action and when PRP cooperation can be assured. Frequently, a removal action or an RI/FS (where it involves an area-wide contamination) is the most plausible situation to consider mixed work since specific tasks are broken out easily. The U.S. EPA may agree to conduct soil removal actions at one specific portion of the site (such as an impoundment area), while PRPs would concentrate their activities removal at other areas of the site (such as a building complex). Mixed work also can be a settlement option in a RD/RA scenario. In the Love Canal, New York mixed work agreement, the PRPs agreed to implement portions of the sewers and creeks remedial program associated with implementation and the State, through a Cooperative Agreement, implemented remaining portions of the remedy (construction of a dewatering containment facility and excavation of the creeks).

One approach used in carrying out a mixed work settlement is the use of a "carve out." A "carve out" is a form of mixed work where a particular task or tasks will be carved out by settling PRPs or by the U.S. EPA from those tasks the settlors objected to carrying out. The "carve out" tasks can be imposed exclusively on the non-settlors through a Unilateral Administrative Order (UAO). Settlors would have tasks(s)

stipulated in the consent decree. If the recalcitrant fails to comply with the Administration Order (AO), the U.S. EPA can either sue for injunctive relief seeking compliance with the Order or judicial referral with daily penalties imposed, or carry out the work itself using the Fund. The U.S. EPA would follow by suing for cost recovery and treble damages under Section 107.

Consent Decree Language Requirements

Since the implementability and overall management of a mixed work settlement is based largely on how well each activity is defined, Consent Decree language should be developed with the same objectives in mind. Any covenants not to sue should be clearly limited to the operable unit(s) addressed in the Consent Decree; areas of responsibility and timeliness should be delineated in the agreement. The covenant not to sue in the Love Canal, New York decree is extremely narrow and only covers claims under CERCLA, RCRA and State common law for work actually performed or costs actually paid by the PRPs under the Decree. The Decree also contains the standard "reopeners" provision for information or conditions that emerge after entry of the Decree or completion of the work. In the Ottati and Goss, New Hampshire settlement, the reopeners also limit the PRPs' liability consistent with the Decree of any additional work that must be done at the site.

State Cost Share Requirements

When the Federal government uses its response authority to conduct a remedial action, Section 104 (C)(3) of CERCLA requires the State to share a percentage of the cost of the remedial action. Since response actions through mixed work may be carried out under Section 104 (C), State cost share is required, including all future maintenance.

There are a variety of ways the State can "pay" or "assure payment" of its cost share. For instance:

- the State and the PRPs may enter into an agreement under State law and CERCLA where the PRPs pay 10% to the State and the State obligates funds for use at the site; or,
- the State may use its own funds to pay for any portion of its share that cannot be paid for by the PRPs.

State involvement in mixed work settlements are best illustrated in the Ottati and Goss, New Hampshire, the PRPs undertook the soils portions of the remedy, e.g. the aeration, incineration, soil replacement and regrading, and establishment of the site cover. The State agreed to conduct the necessary post-closure maintenance. The PRPs also agreed to pay a portion of past and future oversight costs and a percentage to the State for long-term maintenance of the site.

At Love Canal, New York, the State entered into a cooperative agreement to conduct specific portions of the remedy (excavation of sewer and creek sediments) while the PRPs processed, bagged and transported materials from the Love Canal site to the PRP's main plant site for temporary storage and incineration.

In either case, the U.S. EPA and the State should enter into a State Superfund Contract (SSC) to assure cost share and O&M responsibility. The State cost share does not have to be incorporated into the Consent Decree between U.S. EPA and the PRPs. In general, mixed work settlements should only be considered when the State cost share is reasonably certain.

CASH-OUT SETTLEMENTS

The third type of mixed funding arrangement described in Section 122 (b)(3) is a cash-out. A cash-out occurs when the U.S. EPA conducts the response action and the PRPs pay U.S. EPA for a portion of the costs. A cash-out settlement can be prepared at any time in the remedial process. One common use of cash out settlements involves PRPs who have contributed a low percentage of waste to a site, and who are not technically or financially capable of conducting the entire response action. Once the PRPs pay their allocated share of costs, they are no longer liable for any further participation in site remediation.

Evaluating A Cash-Out Proposal

Since the U.S. EPA conducts the response action in a cash-out set-

tlement, factors such as the proposed remedy and public interest are not decisive in evaluating a cash-out by all or some of the PRPs. The Interim Settlement Policy (Section III) does, however, identify the following key concerns that should be considered when evaluating such a settlement:

- The U.S. EPA should have a high level of confidence in the information concerning liability at the site and expected cost of the remedy to determine an appropriate cash out settlement.
- The U.S. EPA should have sufficient information related to both settlors and nonsettlors to determine a settlement amount for the settlors requesting a cash-out (should be based on the settlement policy, including waste contribution).
- The U.S. EPA should ensure that the percentage of total costs to be paid by settlors is "substantial."

While cash-out settlements do not have to involve *de minimis* parties as defined in Section 122(g), they do share many of the same analytical factors. The U.S. EPA guidance entitled, "Interim Guidelines on settlements with De Minimis Waste Contributors under Section 122(g) SARA" should be consulted when reviewing cash-out proposals.

Consent Decree Language Requirements

As mentioned previously, a key the U.S. EPA concern related to cash-out settlements is the strength of the information related to PRP liability and the cost and development of the remedy. These issues have particular bearing on the scope of any covenant not to sue in such an argument—particularly, early in the remedial process when information is limited.

The Regions should ensure that the covenant not to sue, if any, is carefully drafted to cover only the specific response action covered by the mixed funding settlement and is otherwise consistent with Section 122(f) and the "Covenants Not to Sue Under SARA," (52 FR 28038 July 27, 1987). This provision would include the standard reopeners for unknown conditions and new information indicating that the remedial action is not protective and which reopeners would be triggered in the event of remedy failure. It also would include a provision ensuring that the PRPs are responsible for contributing toward any cost overruns arising during completion of the mixed-funded response action (in at least the same percentage as the initial agreement), unless a risk premium payment is received. Further, if information relating to the settling PRP's waste contribution to the site is limited, then the Region should also consider including a reopener which would allow the Agency to seek additional funds from the settling PRP if new information relating to its waste contribution to the site is discovered.

State Cost Share Requirements

The State cost share requirements apply as in mixed work settlements. (See Section on *mixed work*). Prices Landfill, New Jersey is an example of a cash-out where a 10% State cost share was provided. The settlement included PRP payment for a portion of the remedy, (the U.S. EPA is implementing it) plus accrued back interest to the United States, the State of New Jersey and the Atlantic City Municipal Utilities Authority (ACMUA) in exchange for a covenant not to sue for past and future liability, subject to limited reopeners. In addition, a future Order of the U.S. District Court provides that some money be set aside for future remedial expenses, a percentage returned to the Superfund, the State and the ACMUA. It should be noted that in the Prices case, the PRPs are paying a sum of money which is not high enough to constitute a "premium" and, yet, for which they will be relieved of future liability at the site unless materially different information about the landfill or new findings on imminent and substantial endangerment emerges. Provisions in the Consent Decree are also included to maximize government access to evidence linking additional generators to waste at the site.

CONCLUSION

Settlement agreements incorporating mixed funding provisions offer an alternative to either up front Fund financing of the total costs of a response action from the Superfund, or possible delays in initiating a response action as a result of litigation to compel a action by a PRP.

Mixed funding is only one of the settlement tools available to the U.S. EPA. Before one can begin an assessment of mixed funding for a particular site, he must first determine whether under the Ten-Point Settlement Criteria it is appropriate to settle for less than 100% of response action costs.

Mixed funding is not appropriate for all circumstances and requires a site/case-specific determination by the parties. Some of the considerations to be made by parties to any settlement include:

- Whether the PRP desires to conduct the response action. If the PRP is willing to conduct the cleanup, both mixed-work and preauthorization may be considered.
- The knowledge and capabilities of the PRP to carry out the remedy as designed. The more technical the remedy, the more important the capabilities of the PPR.
- The amount of the work to be conducted by the PRPs. This may enable the U.S. EPA to authorize a mixed-work settlement and conduct the balance of the work, or “carve-out” the work to be conducted by

a subsequent settling PRP.

- The portion of the costs to be assumed by the PRPs. A cash-out may be the appropriate result if the PRP is liable only for a small proportion of the cost. Liability for a significant portion of the costs may enable the use of mixed funding. The incentive for the PRP to manage the response action in a manner to control costs is diminished when the Fund pays a higher proportion of the costs.
- The most critical consideration is the PRP’s “good faith offer” to implement the response action, a significant portion of the work and/or pay a significant portion of the costs.

Mixed funding settlements will be encouraged and adopted by the Agency when such settlements are in the best interest of the Government, the general public and the environment.

DISCLAIMER

The contents and conclusions of this paper are those of the authors and do not necessarily reflect the views and policies of the U.S. EPA.

The U.S. Army's Installation Restoration Program: Achievements and Initiatives

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ABSTRACT

The Congress, the U.S. EPA, the States and the public have clearly stated that Federal agency facilities should be the model of environmental compliance for the regulated community. In an effort to meet this challenge in the hazardous waste program area, the Defense Environmental Restoration Program (DERP) was established in 1984 to expand the Department of Defense's (DOD) existing efforts to clean up contamination from hazardous waste sites. SARA of 1986 provided continuing authority for the Secretary of Defense to carry out this program in consultation with the U.S. EPA. Furthermore, Executive Order 12580 on Superfund Implementation delegated authority to the Secretary of Defense to carry out the DERP within the overall framework of SARA and CERCLA.

A component of the DERP is the Installation Restoration Program (IRP) which is designed to identify and remediate contamination from hazardous substances and wastes on DOD installations and at formerly used properties. The objective of this paper is to outline the Army's Installation Restoration Program which has evolved since its inception in 1974 to be comprised of projects at over 401 installations involving 3,208 sites. The paper highlights some of the success the Army has achieved in its quest to clean up its hazardous waste sites. Efforts underway at Anniston Army Depot are used to illustrate remedial actions taken at an Army NPL site and the degree to which the Army is committed to restoring the environment.

INTRODUCTION

Pick up any newspaper or magazine and you will almost certainly find an article addressing some sort of major environmental compliance issue: the conviction and sentencing of three senior civilian managers at Aberdeen Proving Ground, Maryland on multiple felony counts for violating the Resource Conservation and Recovery Act; the FBI's conduct of "Operation Desert Glow", where more than 70 agents searched the Rocky Flats nuclear weapons plant for evidence of illegal disposal of radioactive and hazardous materials; and the Exxon Valdez striking a reef off Prince William sound to create the largest oil spill in United States history.

The magnitude of the hazardous waste problem is so great that it almost defies comprehension. In addition to what lies buried in the thousands of disposal sites that have been identified nationwide, the U.S. EPA estimates that hazardous waste is generated in this country at the rate of 700,000 tons/day; more than 250 million tons/yr. Recognizing that Federal laws were needed to address the potential dangers of abandoned hazardous waste sites, lawmakers passed CERCLA. As the first major piece of legislation to address the problem on a national level, CERCLA had the following key objectives:

- To establish priorities for cleaning up the worst hazardous waste sites

- To hold responsible parties liable for payment for those cleanups (where possible)
- To establish a \$1.6 billion Hazardous Waste Trust Fund (Superfund) to perform cleanups when responsible parties could not be held accountable, and to respond to emergencies involving hazardous materials
- To improve scientific and technological capabilities in all aspects of hazardous waste management, treatment and disposal.¹

SARA, passed in 1986, outlined the framework for CERCLAs Superfund hazardous waste cleanup program during the next five years. A major feature of the re-authorization was the clarification that "each department, agency and instrumentality of the United States . . ." was required to comply procedurally and substantively with the statute to the same extent as private entities (Section 120(a)(1)).

The RCRA, an amendment to the Solid Waste Disposal Act, was passed in 1976 to regulate the transportation, storage and disposal of hazardous wastes that are being generated now. Passage of these and a number of other statutes covering virtually all forms of pollution serve as positive testimony to the serious regard with which the issue of environmental protection is being taken.

Within the regulated community, the Congress, the U.S. EPA and the public have clearly stated that Federal agency facilities should serve as models of environmental compliance. In an effort to meet this challenge in the hazardous waste area, the Department of Defense (DOD) has continued to expand its effort through a wide array of initiatives implemented as part of the Defense Environmental Restoration Program (DERP). A component of the DERP is the Installation Restoration Program (IRP), which is designed to identify and remediate contamination from hazardous substances and wastes on DOD installations as well as at formerly used defense sites (FUDS).

THE ARMY INSTALLATION RESTORATION PROGRAM

As one of the largest real estate holders in DOD (12,000,000 ac of land on 1391 installations), the Army is keenly aware of its responsibilities to protect and enhance the environment. In consonance with its defense mission, the Army has established environmental quality goals that will ensure the long-term protection of the land and resources entrusted to its care. These environmental quality goals are:

- Demonstrate leadership in environmental protection and improvement
- Minimize adverse environmental and health impacts while maximizing readiness and strategic preparedness
- Assure that consideration of the environment is an integral part of Army decision-making
- Initiate aggressive action to comply with all Federal, State and local environmental quality laws
- Restore lands and waters damaged through our past waste disposal

activities

- Support Army programs for the recycle and reuse of materials to conserve natural resources, prevent pollution and minimize the generation of waste
- Pursue an active role in addressing environmental quality issues in our relations with neighboring communities.

This philosophy has been carried forward from the initiation of the Army IRP in 1974, a full 6 yr before the Superfund statute was even on the books. From the first actions taken to clean up the monumental problems at Rocky Mountain Arsenal to current research activities in waste minimization, the Army has led the way in DOD's efforts concerning hazardous waste site remediation². Figure 1 recaps Army IRP performance as of the end of Fiscal Year 1988. It is obvious that substantial resources have been allocated to the program and the positive results that have been obtained serve as the best testimony to its success³.

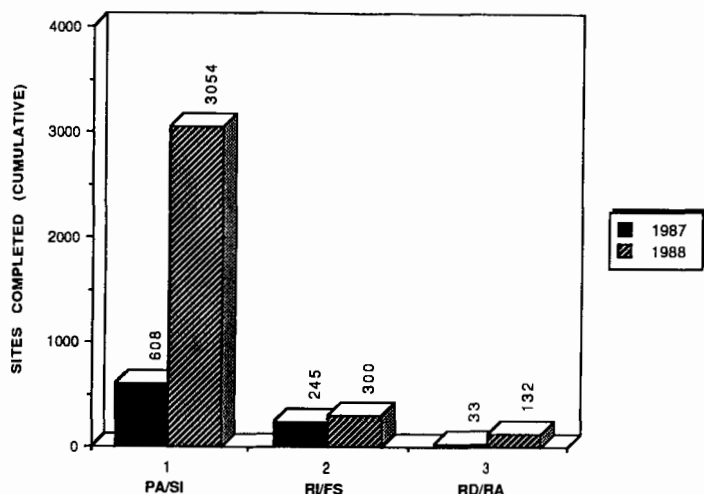


Figure 1
Army IRP Progress

Under the direction of the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), Preliminary Assessments/Site Inspections (PA/SI) have been completed on almost all potential contamination sources. The purpose of the PA/SI is to determine which sites may pose a threat and require further cleanup action. Where remedial action is anticipated, an RI/FS has been initiated to determine the extent of contamination and develop a range of options to remediate the site. Working with State authorities and U.S. EPA Regional and Headquarters offices, a remedy will then be selected and documented in a Record of Decision. As shown in Figure 1, over 28% of those sources scheduled for remedial action have been cleaned up. All remedial actions are programmed for initiation by 1994.

In some cases, the magnitude of the hazardous waste problem has warranted placement of Army IRP sites on the NPL. The NPL identifies abandoned or uncontrolled hazardous waste sites that warrant further investigation to determine if long-term "remedial action" is necessary. Sites on the NPL are eligible for such action under CERCLA. However, CERCLA Section 111(e)(3) generally prohibits use of Superfund dollars for remedial action at Federally owned facilities. As of the July 1989 update, there are 18 Army facilities promulgated on the NPL and an additional 17 Army facilities proposed for listing. The installations proposed/final on the NPL are listed in Figure 2a and Figure 2b.

In conjunction with the cleanup of NPL sites, the Army has worked closely with U.S. EPA Regional and Headquarters offices and the States to execute several comprehensive cleanup agreements referred to as Inter Agency Agreements (IAG). These agreements were first authorized under Section 120 of the 1986 amendments and are binding, enforceable documents that cover the entire cleanup process from investigation through construction and operation of the remedy. IAGs are generally designed to meet all of the facility's cleanup obligations under

1. ROCKY MOUNTAIN ARSENAL, CO
2. MILAN ARMY AMMUNITION PLANT, TN
3. ANNISTON ARMY DEPOT (SE IND. AREA), AL
4. CORNHUSKER ARMY AMMUNITION PLANT, NE
5. SACRAMENTO ARMY DEPOT, CA
6. SHARPE ARMY DEPOT, CA
7. SAVANNA ARMY DEPOT ACTIVITY, IL
8. LETTERKENNY ARMY DEPOT (PDO AREA), PA
9. FORT DIX (LANDFILL SITE), NJ
10. ALABAMA ARMY AMMUNITION PLANT, AL
11. JOLIET ARMY AMMUNITION PLANT (LAP AREA), IL
12. LETTERKENNY ARMY DEPOT (SE AREA), PA
13. FORT LEWIS (LANDFILL NO. 5), WA
14. LAKE CITY ARMY PLANT (NW LAGOON), MO
15. JOLIET ARMY AMMUNITION PLANT (MFG. AREA), IL
16. LONE STAR ARMY AMMUNITION PLANT, TX
17. UMATILLA ARMY DEPOT (LAGOONS), OR
18. LOUISIANA ARMY AMMUNITION PLANT, LA

Figure 2a
Army National Priority List Sites (Final)

1. FORT WAINWRIGHT, AK
2. FORT ORD, CA
3. RIVERBANK ARMY AMMUNITION PLANT, CA
4. SCHOFIELD BARRACKS, HI
5. IOWA ARMY AMMUNITION PLANT, IA
6. FORT RILEY, KS
7. FORT DEVENS, MA
8. FORT DEVENS - SUDBURY TRAINING ANNEX, MA
9. ABERDEEN PROVING GROUND - EDGEWOOD AREA, MD
10. ABERDEEN PROVING GROUND - MICHAELSVILLE LANDFILL, MD
11. WELDON SPRING FORM. ARMY ORDDNANCE WORKS, MO
12. PICATINNY ARSENAL, NJ
13. SENECA ARMY DEPOT, NY
14. TOBYHANNA ARMY DEPOT, PA
15. LONGHORN ARMY AMMUNITION PLANT, TX
16. TOOELE ARMY DEPOT (NORTH AREA), UT
17. FORT LEWIS LOGISTICS CENTER, WA

Figure 2b
Army National Priority List Sites (Proposed)

CERCLA, RCRA and applicable State laws, and serve as "regulatory blueprints" for the cleanup of the facility. In addition, they provide for State and U.S. EPA oversight of the cleanup process and generally provide for reimbursement of State costs associated with the agreement.

In June, 1988, the U.S. EPA and DOD agreed to model language for IAGs which resolved a number of national policy issues that were hampering facility-specific cleanup negotiations. These model provisions, to be included in each agreement, provide specific language on jurisdiction, funding, enforceability, dispute resolution, stipulated penalties and RCRA/CERCLA integration. The agreements establish U.S. EPA and State jurisdiction at the facility, provide for State and citizen enforcement, as well as the assessment of penalties for failure to comply with the schedule or terms and conditions of the cleanup, and for the U.S. EPA Administrator to make the final decisions on cleanup or any dispute arising under the agreement. By mid Fiscal Year 1989, seven of the 16 IAGs in place with the U.S. EPA were for Army facilities. In addition, the Army and the U.S. EPA currently are negotiating eight additional agreements.

In August 1987, the Army, the U.S. EPA and the State of Minnesota made history when all three parties signed the Twin Cities Army Ammunition Plant (TCAAP) Federal facility InterAgency Agreement. The TCAAP agreement was the first of its kind under Section 120 of SARA. This agreement was the culmination of negotiations between the Army, the U.S. EPA and the State and established provisions for:

- Coordination of overlapping requirements of RCRA and CERCLA
- Policies and procedures consistent with those for non-Federal

facilities

- U.S. EPA approval of selected remedies
- U.S. EPA and State oversight of the Army's activities at the site.

In addition to TCAAP, the Army has six other tri-party IAGs that have been signed to-date, including:

- Joliet Army Ammunition Plant, Illinois (June 9, 1989)
- Letterkenny Army Depot, Pennsylvania (Feb. 3, 1989)
- Louisiana Army Ammunition Plant, Louisiana (Jan. 31, 1989)
- Milan Army Ammunition Plant, Tennessee (July 25, 1989)
- Sacramento Army Ammunition Depot, California (Oct. 27, 1988)
- Sharpe Army Depot, California (Mar. 16, 1989)

Besides evaluating its own installations, the Army, in particular the U.S. Army Corps of Engineers (COE), is the DOD Executive Agent for the implementation of Environmental Restoration Program operations at formerly used properties. As Executive Agent, the COE (working through its Huntsville Division) is responsible for hazardous waste cleanup activities, building demolition and debris removal, and unexploded ordnance removals on lands formerly owned or used by any of the DOD components. The investigation and cleanup procedures at formerly used sites are similar to those at currently owned installations. Determinations must be made as to the origin of the contamination, land transfer and current ownership before a site is considered eligible for restoration by the DOD.

ANNISTON ARMY DEPOT—A TYPICAL SUCCESS STORY

Situated on more than 15,000 ac in Calhoun County, Alabama, Anniston Army Depot is one of 13 depots in the Army's Depot System Command (DESCOM). Anniston's primary mission includes combat vehicle rebuild and conversion programs, small arms and artillery rebuild, maintenance of numerous missile systems and the storage of large quantities of ammunition. It is principally involved in the rebuilding of main battle tanks for the U.S. Army and allied nations.

The industrial processes inherent with daily operations at the plant result in the generation of several hazardous waste streams. Primarily these wastes are degreasing solvents and metals processing sludges. For many years, these wastes were disposed of either through: (1) being placed in lagoons, trenches or pits which were later capped with earth, or (2) being sealed in metal drums which were then buried. Groundwater monitoring wells were emplaced around the chemical sludge disposal trenches and old lagoon sludge piles (Fig. 3 and 4) in 1979 and 1980 to determine whether any contamination had migrated from the disposal sites. It was subsequently determined that both sites had a high potential for migration.

In February, 1981, DARCOM (now AMC) asked USATHAMA to conduct an assessment at Anniston to determine the extent of contamination and to develop plans for appropriate remedial action. USATHAMA worked in close coordination with U.S. EPA Region IV in Atlanta to establish a program that would ultimately accomplish four main tasks:

- Conduct a geotechnical evaluation
- Prepare a contamination survey and assessment
- Conduct an alternatives analysis
- Effect closure operations

The first three tasks were completed by August, 1981, with USATHAMA concluding that the most feasible technical/economic remedial action would call for physical removal of contaminated soil and other wastes from both sites. The wastes would then be transported to a permitted hazardous waste disposal/treatment facility located in Emelle, Alabama.

Closure operations began in March, 1982 with completion of hazardous waste excavations by May, 1983. In all, more than 62,000 tons of waste were transported to Emelle without a single incident or spill during the process. After completion of the excavations, extensive soil sampling was conducted to insure that complete removal was attained. The remediation process was completed by backfilling the entire area, regrading to match the natural contours surrounding the site and seeding to restore vegetative cover. According to Ron Grant, Chief of the Environmental Management Division, Directorate of

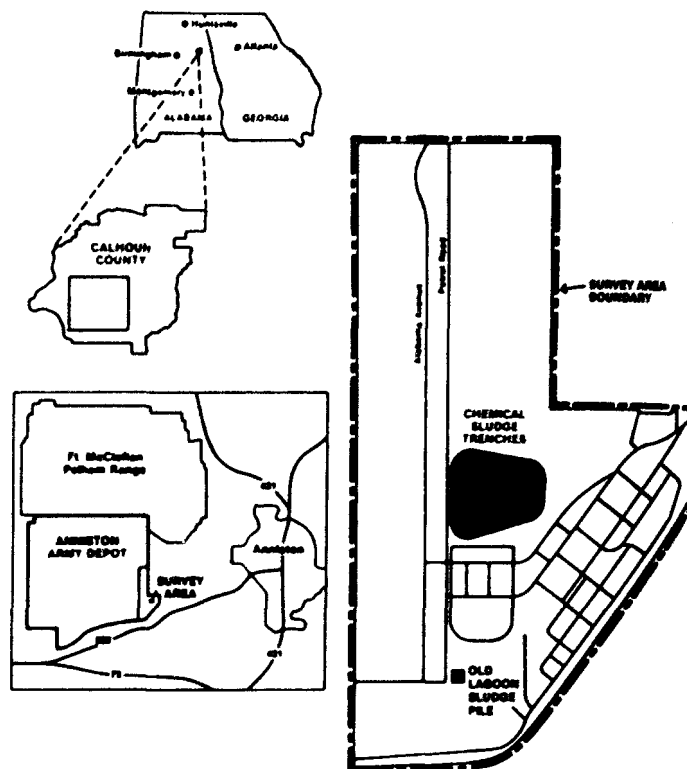


Figure 3
Location of Survey Area: Calhoun County, Alabama

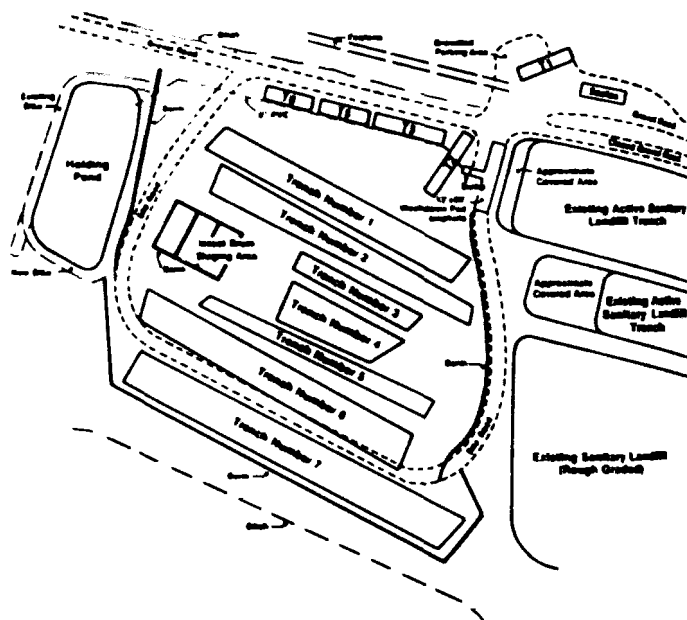


Figure 4
Site Layout Plan: Hazardous Waste Trenches

Engineering and Logistics for Anniston, work is now underway to remediate contaminated groundwater by air stripping and returning it to the environment⁴. The bulk of this work was completed 6 yr prior to the Anniston site being listed by the U.S. EPA on the NPL.

NEW TOOLS FOR TRACKING ENVIRONMENTAL COMPLIANCE

The preponderance of environmental legislation that Congress has generated over the past decade has been instrumental in insuring that

our past mistakes will ultimately be rectified and that the likelihood of future contamination will be greatly reduced or eliminated. Next to passage of the landmark Superfund law, no other single statute has had a more pronounced effect on the regulated community than RCRA. Its broad application to the multitude of Army TSD (transport, storage and disposal) facilities and the potentially severe consequences of non-compliance have dictated the need for managers at all levels to have immediate access to timely, accurate compliance data.

To establish such a data base from scratch would have been cumbersome and resource intensive. A better solution would be to tap the existing compliance data bases maintained by EPA. Housed on a large mainframe system at Research Triangle Park, N.C., RCRA compliance information could be accessed through modem by both DA staff elements and field commanders as well. Known as the Hazardous Waste Data Management System (HWDMS), it tracks the complete compliance history of all RCRA regulated facilities to include inspection performance, enforcement actions taken and progress made to return facilities to full compliance.

In July, 1989, an Interagency Agreement was signed between EPA and DOD establishing a special account on the system for use by DOD agencies. Use of this information will enable Army managers to maintain up to date status of all facilities, identify problem installations and conduct long range planning to correct minor compliance problems before they result in major enforcement actions.

In addition to HWDMS, EPA has also made available to both DA and DOD use of a new PC-based multimedia data base called the Federal Facility Tracking System (FFTS). Recently fielded in each of the 10 EPA Regional offices, FFTS enables the agencies to track compliance in all media program areas. The systems' flexibility also allows the user to access permitting data, enforcement histories, A-106 pollution prevention project records and progress reports relating to the cleanup of hazardous waste sites under the IRP. The capability to generate reports in virtually any format, both on and off line rounds out the systems attributes.

Use of both systems will enable the Army to closely monitor progress made in all areas and to ensure better compliance in accordance with the full spectrum of environmental regulations.

THE U.S. ARMY/U.S. EPA ENVIRONMENTAL EXCHANGE PROGRAM

In early 1987, recognizing the need to expand the technical competence of his environmental staff, John Shannon, Assistant Secretary of the Army (Installations and Logistics), and Lee Thomas, U.S. EPA Administrator, sought to initiate an exchange program. Established under the purview of Training With Industry (TWI), the program would afford selected Army officers the opportunity to study environmental policy and regulatory requirements while working within the major program offices of the U.S. EPA.

The program is co-sponsored and administered through the Army Environmental Office/Assistant Chief of Engineers on the Army staff, and by the Office of Federal Activities at the U. S. EPA. Having just completed its second year, with a total of five officers participating (two at U.S. EPA HQ in Washington, D.C. and three at Regional offices around the country), the program has been a resounding success. Under the agreement established between the two agencies, these officers are free to develop their own programs of study based on personal preference and the job-specific requirements of their follow-on assignments. After completing a full year with the U.S. EPA, the officers return for a minimum 1 yr utilization tour to an environmental position within the Army. Assignment of U.S. EPA personnel has thus far been limited to DA staff in the Pentagon, but steps are being taken to place personnel on several MACOM staffs as well.

The Army has just begun to realize the benefits of the program, not only through the education of its environmental staff, but also through the improvement in communication between the two agencies. The program has done much to promote a willingness to work together in tackling the seemingly overwhelming task of cleaning up the environment. With the continuation of programs such as this, we hopefully will reach that end more quickly and efficiently.

CONCLUSION

Federal facility compliance with environmental laws and regulations is one of U.S. EPA's highest priorities. Overall, Federal facilities have made significant progress in improving their environmental compliance records and in establishing/expanding their environmental programs. The Army exemplifies the efforts being undertaken by the Federal sector to "be the model of compliance."

DOD has established the Defense Environmental Restoration Account (DERA), as outlined in SARA section 211, for the cleanup of its inactive hazardous waste sites. FY 90 DERA funding for Army is expected to increase from the \$204.5 million allocated for FY 89. These funds are exclusively earmarked for CERCLA activities.

As part of the effort to ensure that Federal agencies meet their environmental obligations and complete required CERCLA actions, the U.S. EPA is dedicating significant resources to the Federal facilities program as part of the effort to ensure high levels of environmental compliance.

REFERENCES

1. *Superfund: Looking Back, Looking Ahead*, EPA Journal, April 1987.
2. *Environmental Quality 1987-1988*, Annual Report of the Council on Environmental Quality, Washington, DC
3. *Defense Environmental Restoration Program*, Annual Report to Congress for Fiscal Year 1988, Office of the Deputy Assistant Secretary of Defense (Environment), Washington, DC, Mar. 1989.
4. *Remedial Action of Hazardous Waste Sites*, Anniston Army Depot, Anniston, AL, brochure published by the U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, June 1983.

Assessing a Potentially Responsible Party's Ability to Pay Superfund Cleanup Costs

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ABSTRACT

This paper presents a methodology for assessing a PRP's ability to pay past and future costs under CERCLA as amended. The objective of the Superfund program is to impose the ultimate liability for the cost of cleanup of hazardous waste sites on the responsible parties who generated the waste and on those who owned or operated the sites. The U.S. EPA's enforcement program can accomplish this goal in two ways. No matter how the U.S. EPA chooses to proceed with enforcement, an accurate financial assessment of the PRP's ability to pay developed early in the enforcement process will assist the U.S. EPA in determining the most effective enforcement strategy and in establishing the most realistic settlement or cost recovery amounts.

This paper presents an approach to assessing a PRP's ability to pay based on the PRP's operating and financial statements. The paper goes on to describe four types of standard financial indicators, measured according to eight standard financial ratios, that can provide an overall picture of a PRP's past and present financial condition and ability to pay. These four financial indicators or ratios are: (1) liquidity, (2) leverage, (3) solvency and (4) profitability. After discussing and interpreting these financial indicators, the paper illustrates the methodology through a hypothetical assessment of a PRP's ability to pay. This case study: (1) analyzes a hypothetical PRP's ability to pay CERCLA cleanup costs by calculating and interpreting the financial ratios, (2) presents the results of sensitivity analyses that measure the impact of various cost recovery schedules on the hypothetical PRP's current financial condition and (3) discusses the sources of information on a PRP's financial status.

INTRODUCTION

The Superfund program attempts to place the ultimate responsibility for the cost of cleaning up hazardous waste sites on responsible parties who generated the wastes and on those who owned or operated the sites. The U.S. EPA can accomplish this goal in two ways, but in either case will seek to directly impose the cost of cleanup on responsible parties. The Agency can conduct the cleanup using money from the Superfund and later seek to recover the cleanup costs through cost recovery actions; or the U.S. EPA can use a variety of CERCLA enforcement authorities to directly compel responsible parties to finance or conduct cleanups. The U.S. EPA's recent 90-day management review of the Superfund program further indicates that the U.S. EPA's increasing emphasis on enforcement will further induce PRPs to rapidly achieve enforceable agreements to finance or carry out more cleanups under the U.S. EPA direction.

The U.S. EPA will rely on the various enforcement authorities to pursue responsible parties to recover costs and replenish the Superfund when the Agency conducts a Fund-financed cleanup without a

negotiated settlement. Congress authorized the U.S. EPA in Section 104 of CERCLA to spend Superfund monies to clean up a site and in Section 107 to pursue responsible parties for recovery of cleanup costs. Although the U.S. EPA does not hesitate to pursue cost recovery actions or litigation in the interest of public health and the environment, the Agency still prefers to negotiate settlements with responsible parties. Section 122 of CERCLA provides the U.S. EPA with the discretion to enter into settlement agreements with PRPs, establishes procedures for negotiating settlements with PRPs for financing or conducting Superfund site cleanups and codifies, with some additions, the settlement process established under the U.S. EPA's interim settlement policy.

The U.S. EPA's Interim CERCLA Settlement Policy (50 FR 5034) sets as the U.S. EPA's objective in Superfund negotiations the collection of 100% of cleanup costs or complete conduct of cleanup from PRPs. The Agency recognizes, however, that in certain circumstances, exceptions to this goal may be appropriate. The interim CERCLA settlement policy sets forth 10 criteria for determining when such exceptions are allowed. Based on a full evaluation of the facts and a comprehensive analysis of the 10 criteria, the U.S. EPA may consider accepting offers of less than 100% of the total amount. One of the ten criteria the U.S. EPA may consider in evaluating a settlement proposal is the ability of the settling parties to pay.

Determining a PRP's ability to pay cleanup costs is important whether the U.S. EPA conducts the cleanup and seeks cost recovery or obtains a negotiated settlement with PRPs to finance or conduct the cleanup. Assessing the PRP's ability to pay early in the settlement negotiation process is an important step toward achieving rapid and effective settlements. An accurate financial assessment of PRPs early in the enforcement process will assist the U.S. EPA to determine the most cost-effective enforcement strategy, establish realistic settlement or cost recovery amounts, decide whether a PRP is financially sound enough to conduct future remedial work, obtain corporate information that can facilitate a rapid and effective negotiation process and verify whether a PRP has a genuine ability-to-pay problem.

DISCUSSION OF AN APPROACH TO PRP FINANCIAL ASSESSMENT

The proposed methodology for evaluating a PRP's financial condition and ability to pay is based on a standard method used by the financial community. The methodology relies on four financial indicators commonly used by the financial community (for example, bank loan officers, investment bankers, security analysts, a firm's management and stockholders) to measure corporate performance, generally to assess a firm's viability where possible bankruptcy is not an issue. (In bankruptcy, the same liquidity, leverage, solvency and profitability ratios are used to check a reorganization plan and to monitor progress.)

Managers generally monitor liquidity to determine the timing of payments, while lenders generally focus on leverage and solvency (or coverage) ratios as decision-making criteria for establishing new lines of credit or loans. Conversely, stockholders generally look at profitability to make stock buy/sell decisions⁷. Financial analysts measure a firm's financial indicators against industry norms to assess the firm's current financial condition and to identify positive or negative trends in a firm's liquidity, leverage, solvency and profitability positions.

Limitations of Financial Ratio Analysis

Financial analysts indicate that there are four key limitations to assessing a firm's financial condition using the financial ratio analysis methodology. First, values for financial ratios vary substantially across industrial sectors. Industry-specific norms or averages should therefore be used as benchmarks for comparison when evaluating individual firms. To overcome this limitations, data base reports can provide information on industry norms for liquidity, leverage, solvency and profitability indicators. These norms are fairly stable from year to year in the absence of extreme economic conditions.

Second, no single ratio or indicator is a perfect test of ability to pay, particularly when a firm is in distress⁸. However, a set of indicators that considers liquidity, leverage, solvency and profitability will generally be informative^{1,7}. Third, analysts have established minimum acceptable or threshold levels for financial ratios that reflect values the financial community considers "red lights" signaling possible financial distress. Fourth, historical ratios over the past 3 to 5 yr should be checked for trends and unique occurrences.

One approach to assessing a PRP's current financial condition and ability to pay is based on the firm's operating and financial statements and four types of financial indicators designed to measure a PRP's financial condition and performance. In the proposed approach, a set of standard financial indicators is calculated to measure a PRP's past and present financial performance and to determine its ability to pay past and future response costs. Generally, four types of financial indicators are calculated: (1) liquidity, (2) leverage, (3) solvency, and (4) profitability.

To conduct the financial assessment, eight standard financial ratios are examined, including two each that measure liquidity, leverage, solvency and profitability. First, a financial spreadsheet is developed from the PRP's audited financial statements to calculate historical and current financial ratios to obtain an overall picture of a PRP's past and present financial condition and ability to pay. Each of the PRP's ratios is then compared with industry ratio averages. An assessment of a PRP's financial condition and ability to pay is made in part by comparing a PRP's ratios relative to the average ratio values for other firms in its industry. Finally, the ratios are subjected to a sensitivity analysis to determine the effect of various CERCLA cost recovery levels on the PRP's financial viability. The eight financial ratios used in the proposed approach are discussed below.

1. Liquidity Ratios

Liquidity ratios measure a firm's ability to meet its short-term expenses and other financial obligations in a timely manner. The current ratio (CR) and quick ratio (QR) described below are two standard liquidity ratios that measure a firm's resources or available cash⁷.

Current Ratio: $CR = (\text{Current Assets})/(\text{Current Liabilities})$

The CR is the sum of cash and cash equivalents (principally, accounts receivable and inventories) divided by current liabilities (principally, accounts payable, taxes and short-term bank loans); that is, the CR test is calculated as the ratio of current assets to current liabilities. The CR measures liquid assets available to pay expected invoices and monthly and periodic bills; it is equivalent to the multiple of a firm's current assets to its liabilities.

A CR greater than 3.0 indicates more than adequate cash and cash equivalents to meet short-term requirements. A CR in the range of 2.0 to 3.0 generally indicates sufficient resources. A CR value of less than 2.0 generally signifies potential future liquidity problems¹.

Quick Ratio: $QR = (\text{Current Assets} - \text{Inventories})/(\text{Current Liabilities})$

The QR is the current ratio adjusted for the value of inventories by excluding inventories in process because finished and unfinished projects generally cannot be converted into cash immediately to pay current liabilities. The QR is also known as the "acid test" ratio. A QR greater than 1.0 indicates sufficient liquidity for expected short-term business expenses.

2. Leverage Ratios

Leverage ratios provide information on the extent of debt in the company's capital structure, the long-run ability of the firm to repay borrowed funds and, indirectly, management's degree of risk aversion and its business philosophy. These ratios reflect the firm's financing or capitalization by comparing debt to equity and debt to assets; large debt balances indicate a higher probability of credit risk and default plus substantial debt servicing costs. Two standard indicators of a firm's degree of leverage are the debt to equity ratio (DER) and debt to assets ratio (DAR).

Debt to Equity Ratio: $DER = (\text{Long Term Debt} + \text{Capitalized Leases})/(\text{Stockholders' Equity})$

The DER is defined as long-term debt plus capitalized lease obligations divided by stockholders' equity or net worth. Capitalized lease obligations are included because leases are, in many respects, equivalent to secured loans⁴. For blue-chip Fortune 500 companies, the DER is substantially less than 1.0 and is generally in the 0.3 to 0.4 range⁷. A DER greater than 1.5 signals possible debt servicing problems¹⁴.

Debt to Assets Ratio: $DAR = (\text{Current} + \text{Long Term Liabilities})/(\text{Current} + \text{Long Term Assets})$

The DAR is defined as total debt or total liabilities (the sum of current liabilities and long-term debt) divided by total assets (the sum of current assets plus long-term assets). A DAR greater than 0.65 and increasing in subsequent years is evidence that the firm has doubtful ability to service its debt². A value of 1.0 (or greater) demonstrates that the firm has zero equity (or negative equity or net worth) since liabilities equal (or exceed) assets.

3. Solvency Ratios

Solvency or coverage ratios measure a firm's ability to remain in business without substantial infusions of new equity, major liquidation of corporate assets or other significant changes in operations or corporate behavior. Solvency ratios are designed to evaluate the firm's ability to cover its financing charges and debt exposure. Two principal indicators of solvency are the fixed charge coverage (FCC) and cash flow coverage (CFC) ratios.

Fixed Charge Coverage Ratio: $FCC = (\text{Earnings Before Interest \& Income Tax})/(\text{Fixed Payments plus Current Debt Due})$

The FCC ratio is calculated as the ratio of earnings before interest and income tax to fixed charges that must be "covered." These fixed expenses include lease payments, insurance, interest charges on debt and current-period principal payments due on long-term debt. An FCC ratio greater than 2.0 signifies acceptable coverage or solvency. Values less than 1.5 generally point to questionable viability¹⁴. Negative values indicate inability to pay fixed expenses and potential imminent financial insolvency.

Cash Flow Coverage Ratio: $CFC = (\text{Cash Flow}/\text{Total Liabilities})$

The CFC ratio is calculated as cash flow (net income after tax plus depreciation and amortization) divided by total liabilities. This indicator represents internally generated sources of funds that are available to meet the company's long-term debt obligations and current liabilities^{2,9,10}. A CFC ratio greater than 0.4 indicates more than sufficient cash flow to service liabilities with internal resources. A value in the 0.2 to 0.4 range reflects adequate cash flow, and a CFC ratio

less than 0.15 indicates serious financial uncertainty.

4. Profitability Ratios

Profitability indicators reflect operating performance as measured by net earnings or after-tax income in relation to capital supplied by the firm's owners or in relation to assets deployed. These ratios compare profitability to funds invested in the firm. Two accepted measures of profitability are return on equity (ROE) and return on assets (ROA)⁷.

Return on Equity: ROE = (Net Income After Tax)/(Stockholders' Equity)

The ROE is calculated as net earnings or income after tax divided by stockholders' equity. The ROE measures the percentage return to the firm's owners or stockholders and is an index of the productivity or efficiency or shareholders investment. ROE values must be higher than the firm's cost of capital for long-term continued viability.

Return on Assets: ROA = (Net Income After Tax)/(Total Assets)

The ROA is calculated as net earnings or income after tax, adjusted for the tax savings associated with debt financing divided by total assets (current and long-term). The ROA measures the productivity or efficiency of asset deployment and corresponds to the net operating profit margin. A value less than 0.06 may be a sign of doubtful viability⁸.

SENSITIVITY ANALYSIS

Once an assessment of the firm's overall financial condition has been completed by calculating the eight financial ratios, the analyst can perform a sensitivity analysis to determine the impact of different levels of cost recovery or cleanup payments on the financial condition of the firm. The current-year financial data, and the ratios derived from them, serve as a "baseline" for completion of the sensitivity analysis. Generally, the impact of a one-time, lump-sum payment on the current-year condition is analyzed, but it also is possible to examine the impact of a "structured settlement," periodic payments over a specified number of years.

There are two primary ways in which a company could fund a cost recovery or cleanup payment; by drawing on current assets, (assuming that these assets can be liquidated) or by securing a loan. The analyst can calculate the effect of both scenarios on a company's baseline financial condition. Generally, four different levels of cost recovery payments are analyzed to provide an indication of the maximum amount that the company could afford to pay without imposing a severe financial burden on the firm's operations.

To analyze a payment funded from a firm's current assets, the analyst will first revise the firm's financial spreadsheet to reflect the reduction in current assets that would result from each level of payment examined. Then, the financial spreadsheet is used to calculate revised liquidity ratios for the current year that reflect the impact of each of the four payment levels. Finally, the revised liquidity ratios are compared with the firm's baseline ratios and industry averages.

A payment funded by long-term debt affects the firm's leverage and solvency ratios. To analyze this situation, the financial spreadsheet is revised again, this time to reflect the addition to the firm's liabilities. The financial spreadsheet is then used to recalculate the ratios, and these new ratios are compared with the baseline ratio and the industry averages to provide an indication of how the financial status of the firm would be affected by different payment levels.

CASE STUDY: XYZ COMPANY

A hypothetical case was created to illustrate how the financial assessment methodology presented in this paper may assist the U.S. EPA to assess a PRP's financial position and determine its ability to pay past and future CERCLA cleanup costs. This hypothetical case was patterned after several real CERCLA cases involving settlement negotiations for future RI/FS work and cost recovery for past costs.

Background on the Hypothetical XYZ Company Case

The hypothetical XYZ Company (hereafter XYZ) has owned and operated a small manufacturing plant in the eastern United States for

more than 30 yr. XYZ has approximately \$25 million in annual revenue and has experienced net income losses for 2 yr, primarily because of unplanned plant shutdowns to repair aging manufacturing equipment; however, sales continue to be strong and XYZ managers are confident they can modernize the plant and restore profits in the near future. XYZ is the major employer in a small rural town, employing approximately 700 people.

Over the years, XYZ has stored or disposed of a variety of hazardous contaminants on-site in surface impoundments, waste piles and drums. Hazardous waste is known to be migrating off-site, contaminating groundwater below the site and at least one nearby off-site well. The U.S. EPA believes that XYZ is the sole PRP.

To date, the U.S. EPA has conducted a preliminary assessment and site investigation (PA/SI) at the site and has proposed the site for inclusion on the NPL. The U.S. EPA currently is developing a work plan with details for conducting future RI/FS work at the site. The U.S. EPA has incurred approximately \$1 million in past costs at the site and has placed a \$1 million lien on XYZ's real property. The U.S. EPA and XYZ are negotiating to allow XYZ to assume lead responsibility for future RI/FS work at the site.

Before allowing XYZ to take on the RI/FS work, the U.S. EPA intends to recover its past costs. In negotiations with the U.S. EPA, XYZ has been cooperative and willing to fund future RI/FS work out of future earnings or bank loans, but professes an ability-to-pay problem to currently repay past costs. Furthermore, the U.S. EPA's lien prevents XYZ from borrowing from commercial banks. During settlement negotiations, XYZ requested that the U.S. EPA allow the company to repay past costs over time and fund RI/FS work out of future earnings starting in 1989. To successfully resolve the settlement negotiations, the U.S. EPA must quickly assess whether XYZ has a genuine ability-to-pay problem, establish a realistic amount that XYZ can pay without bankrupting the company and determine whether XYZ is financially sound enough to complete the future RI/FS work the company hopes to undertake.

Conducting the Hypothetical Financial Assessment

To prepare the hypothetical ability-to-pay analysis for XYZ, a spreadsheet is constructed to calculate the eight financial ratios using the financial ratio formulas previously discussed. The spreadsheet (Lotus 123) allows the analyst to quickly calculate the ratios and conduct sensitivity analyses. Data from XYZ's audited 1984-1988 financial statements are entered into the financial spreadsheet. Using the spreadsheet, the analyst first calculates XYZ's historical (1984-1987) and current (1988) financial ratios to observe the trends in XYZ's financial position. These ratios are then compared with XYZ's industry norms for the eight ratios (compiled yearly and published in standard financial reference books and by Dun & Bradstreet⁹, and potential problems are identified. The analyst then conducts sensitivity analyses on XYZ's 1988 financial ratios to test the impact of various cost recovery payments on XYZ's current financial position.

Table 1 summarizes the results of the spreadsheet analysis. It presents XYZ's eight historical financial ratios (1984-1987) and XYZ's current financial ratios (1988), XYZ's industry average for each of the eight financial ratios, and generally accepted danger zone levels for the financial ratios. Table 1 also shows the impact of four different cost recovery payments (\$250,000, \$500,000, \$750,000 and \$1 million) on XYZ's 1988 financial ratios. The cost recovery payments used in the sensitivity analysis were selected by the analyst based on the facts of the case and the range of costs that the analyst considered possible for use in settlement negotiations. The 1984-1988 financial ratios provide an overall picture of XYZ's historical and present financial condition and ability to pay. XYZ's 1988 financial ratios are compared with industry ratio averages; Table 1 shows XYZ's industry average for each of the eight financial ratios. An assessment of XYZ's financial condition and ability to pay is made using professional judgment by comparing XYZ's financial ratios to the average ratio values for other firms in its industry and assessing the impact of various cost recovery payments on XYZ's financial condition through sensitivity analysis.

Table 1
XYZ Company Financial Ratios (1984-1988) and Impact of Various Cost
Recovery Payments
On the 1988 Financial Ratios

Financial Ratio	Year					1988 Ratios with Payment to EPA				Industry Ratio Norm	Danger Zone
	1984	1985	1986	1987	1988	25%	50%	75%	100%		
Liquidity											
1. Current Ratio	0.90	2.13	3.80	2.60	1.90	1.75	1.67	1.59	1.51	1.90	<1.5
2. Quick Ratio	0.30	1.80	2.47	2.12	0.90	0.82	0.74	0.66	0.54	1.00	<0.5
Leverages											
3. Debt/Equity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	>1.5
4. Debt/Assets	0.39	0.26	0.23	0.24	0.31	0.32	0.33	0.34	0.35	0.50	>.65
Solvency											
5. Fixed Charged Coverage	1.45	2.10	0.88	-3.03	-2.53	-2.03	-1.73	-1.53	-1.40	1.5	<1.0
6. Cash Flow Coverage	0.55	0.80	0.32	-0.12	-0.10	-0.16	-0.22	-0.28	-0.34	0.15	<.15
Profitability											
7. Return on Equity	0.10	0.30	0.09	0.01	-0.10	-0.13	-0.17	-0.21	-0.26	0.05	<.03
8. Return on Assets	0.12	0.14	-0.01	-0.08	-0.15	-0.17	-0.19	-0.22	-0.25	0.6	<.05

Interpreting the Hypothetical Financial Assessment

The financial ratio calculations presented in Table 1 assist the analyst to understand historical trends in XYZ's financial position over time and enable the analyst to make professional judgments about XYZ's current financial position and ability to pay. The sensitivity analyses assist the analyst to determine the impact of various cost recovery payments on XYZ's current financial ratios and present a range of possible cost recovery amounts to be suggested in settlement negotiations. By interpreting the financial ratios, the analyst is able to decide the U.S. EPA's strategy in negotiations with XYZ. Although it is beyond the scope of this paper to discuss all the results shown in Table 1, an example related to a specific financial ratio (the cash flow coverage ratio) will illustrate the concept.

Table 1 summarizes XYZ's cash flow coverage (CFC) ratio for the years 1984-1988 and at the four different cost recovery payment levels for 1988. The industry norm for the CFC is approximately 0.15⁶. A CFC ratio greater than 0.4 generally indicates that a company has more than sufficient cash flow to service liabilities with internal resources. A value in the 0.2 to 0.4 range reflects adequate cash flow, and a CFC ratio less than 0.15 indicates serious financial uncertainty. By reviewing Table 1, the analyst determines that the CFC ratio for XYZ varies from year to year depending on fluctuations in XYZ's net income. The CFC ratio was excellent in 1985 and more than adequate, compared to the industry norm, in 1984 and 1986. The negative CFC ratios for 1987 and 1988 reflect XYZ's net losses as a result of reduced revenues from plant shutdowns and increased expenses from plant maintenance. By reviewing the CFC ratio in Table 1, the analyst is able to determine that if the U.S. EPA imposes a cost recovery payment in 1988, XYZ's CFC ratio would drop into the "danger zone." This indicates that XYZ would be unable to fund a payment from current net income generated by operations, without seriously affecting existing operations. A negative CFC ratio indicates that XYZ may be headed toward bankruptcy, since the ratio must be positive for financial viability. As a result of the analysis, the analyst concludes that even a cost recovery payment in the range of \$250,000 to \$500,000 may seriously impede XYZ's ability to maintain current operations and could force XYZ into bankruptcy.

To complete the analysis, the analyst must review all eight ratios and assess their meaning in relation to XYZ's historical ratios, industry norms and danger zone levels. In summary, XYZ's liquidity position is good and should not be severely affected by a cost recovery payment in the range of \$250,000 to \$500,000. Although liquidity ratios would fall below industry averages, they would not drop into the "danger zone" for the financial ratios discussed previously. A cost recovery payment above \$500,000 may, however, seriously impair XYZ's current operations and may lead to bankruptcy. Table 1 indicates that XYZ's leverage indicators are strong, but that the company's ability to borrow additional funding for a cost recovery payment is doubtful because of the U.S. EPA lien on XYZ's real property. The solvency ratios indicate

XYZ's cash flow is insufficient, so that current obligations may be difficult to meet. Finally, XYZ's profitability ratios are negative, indicating an inability to raise new capital through stock issues and reflecting current, and possibly future, financial problems.

It is apparent from the financial ratio analysis presented in Table 1 that XYZ may be able to fund an immediate cost recovery payment only from current assets. Both the solvency ratios and the profitability ratios are negative, indicating an inability to fund a cost recovery payment by using earnings from XYZ's operations or by raising new capital. In addition, the lien on XYZ's real property discourages prudent lenders from providing XYZ with additional funds. As a result, XYZ cannot borrow money to make a cost recovery payment or fund future RI/FS work. If XYZ makes a cost recovery payment of \$250,000 to \$500,000, it is possible the company may be forced to raise additional funds from external sources to continue existing plant operations. This may be unlikely for XYZ in the short term. The analysis indicates that if the U.S. EPA wishes to recover a portion of past costs immediately, a lump-sum cost recovery payment from XYZ appears possible in the range of \$250,000 to \$500,000. However, given the company's current tenuous solvency, the U.S. EPA may risk hastening XYZ's insolvency by imposing even this range of cost recovery payment on XYZ at this time.

AVAILABLE FINANCIAL INFORMATION SOURCES

It is necessary to gather financial information on the PRPs to accurately assess their ability to pay. Depending on the level of analysis required, many sources of financial information are available to assist the U.S. EPA in establishing the financial viability of PRPs. To assess a PRP's ability to pay CERCLA cleanup costs, a minimum of three financial information sources should be examined: (1) National Enforcement Information Center (NEIC) Superfund Financial Assessment System (SFFAS) financial information, (2) recent audited financial statements of the PRP and (3) commercial financial data bases and financial references. This section discusses these three primary sources of financial information on PRPs and briefly reviews other common sources of financial information.

NEIC SFFAS Financial Information

NEIC provides financial information to the U.S. EPA personnel to assist them in determining a PRP's financial status. NEIC operates SFFAS on publicly held companies as a tool to assist enforcement personnel in negotiating with PRPs. SFFAS was designed to: (1) calculate the amount of response action costs a PRP can afford to pay and (2) provide a concise financial evaluation of the PRP.

The model consists of two components. First, it calculates a PRP's ability to pay by measuring the cash flows from the company's operations and their variability to determine the company's ability to maintain its current business and pay response costs. Second, it applies three standard financial ratios to assess whether additional debt may be feasible for the firm. SFFAS requires a minimum of 3 yr of annual data on net income and depreciation, and data on the company's current liabilities, long-term debt, net worth, interest expense and income tax rate for the most recent year.

The NEIC SFFAS does not include privately held companies, where financial information is not readily available. In these cases, NEIC can usually provide Dun and Bradstreet reports for privately held companies not listed in the SFFAS data base. The Dun and Bradstreet reports⁶ can be used to initially determine various aspects of a PRP's financial status; however, in-depth financial analysis based on the PRP's actual financial statements is recommended to determine ability to pay.

Recent Operating and Audited Financial Statements of the PRP

If the PRP's capital stock is publicly traded, it is required under the Security Acts of 1933 and 1934 to file various reporting forms with the Securities and Exchange Commission (SEC) in Washington, D.C. These forms contain valuable information about the company's operation, financial condition and ownership that can be used to assess a PRP's current and future financial condition. Three primary SEC forms

are discussed below:

- Form S-1:** This is the most comprehensive form that companies may be required to file with the SEC under the 1933 Act. The S-1 provides specific information on a company's use of the proceeds when it issues capital stock. Generally, this information helps investors to make an informed decision. The S-1 contains financial statements and descriptions of the filing company's property, directors and executive officers, and security ownership of management.
- Form 10:** This form is similar to the S-1. Companies that issue capital stock, and are not required to file under the 1933 Securities Act, file under the 1934 act using Form 10. Form 10 contains similar, though less detailed, information as the S-1.
- Form 10-K:** This is the annual report that most reporting companies file with the SEC. It provides a comprehensive overview of the registrant's business, including a description of the business, select financial data, financial statements, management's discussion and analysis of the financial condition and results of operations, and security ownership of management.

These documents may be obtained by contacting the company directly, or from the SEC in Washington, D.C. The SEC is located at 450 5th Street NW, Washington, D.C., (202) 272-7450; documents must be obtained in person at the Public Reference Room (PRR) in room 1024. An information data base in the PRR provides key word searches for companies included and describes the forms these companies have filed.

The most important source of financial information needed to conduct a financial ability to pay assessment are the PRP's audited financial statements. Generally, the past 5 yr of a PRP's audited financial statements (including balance sheets, income statements, sources and uses of funds) should be obtained to assess the PRP's financial condition and ability to pay. The financial statements should be audited by a certified public accountant to ensure their validity. PRPs may voluntarily submit financial statements, or they may be demanded in CERCLA 104(e) notice letters.

The annual report is another valuable source of information about a PRP's financial position. The financial information in an annual report is, however, usually unaudited. Annual reports can be obtained from state corporation commission offices in the state where the company is incorporated or located. The corporation commission may be the only alternative for information about PRP companies whose stocks are not publicly traded and, therefore, do not report financial information to the SEC.

Commercial Financial Data Bases and Financial References

Commercial financial data base services can expedite the search for financial information when PRPs are privately held and their financial statements are not readily available, or when the analyst must screen a large number of PRPs. Standard financial references also can provide valuable information on historical and future trends on the PRP's financial position. Several commercial financial data base services and standard financial references are available to assist in determining a PRP's ability to pay. The primary financial data base services and references are briefly discussed below.

Dun & Bradstreet Financial Data Base

The Dun & Bradstreet (D&B) data base provides financial statements for up to 3 yr on more than 850,000 United States companies, both public and private. Along with financial statements, D&B provides key business ratios for more than 800 industries. These ratios compare the company's performance to others in its industry, providing insights into its financial condition. The ratios show a company's solvency, busi-

ness efficiency and profitability, providing a basis to evaluate a PRP's financial condition quickly according to objective, quantitative measures of performance. It should be noted, however, that D&B reports are not always available for many privately held companies and may lag as much as 6 to 12 mo behind the company's most current financial data.

D&B also can provide a financial profile report. This report shows financial trends, profit performance and a company's relative position within its industry. This report also contains industry norms that provide the analyst the ability to compare quickly each item on the financial statement with the industry's average.

Information America Financial Data Base

Information America provides on-line Secretary of State Corporate and UCC filings, local county records, U.S. bankruptcy court filings, as well as on-line document ordering services. Duns Business Records Plus reports can be obtained through Information America. The Duns report provides in-depth historical information on the operation and finances of private and public United States businesses. An analyst can quickly obtain information on businesses of any size, and financial data on more than 750,000 private and public companies. Information America's main advantage over a strictly financial data base is that it offers multiple information services from one source.

Standard & Poors Data Bases

Standard and Poors (S&P) maintains a number of data bases on United States businesses. These data bases are available through the Dialog Information Retrieval Service and include financial information on 36,000 corporations and 340,000 "key executives," with 74,000 profile biographies. S&P also can provide substantial information on financial institutions.

Standard Financial References and Directories

Standard financial references and directories may provide another excellent source of historical financial information. These references generally are available through business libraries. While too numerous to discuss in this paper, some of the more common standard financial references include America's Corporate Families, America's Corporate Families and International Affiliates, Directory of Companies Filing Annual Reports With the Securities and Exchange Commission, Directory of Corporate Affiliations—Who Owns Whom, Dun and Bradstreet's Middle Market Directory and Million Dollar Directory, Funk and Scott's Index of Corporations and Industries, Moody's Industrial Manual and other publications, Standard & Poor's Register of Corporations, Directors and Executives, Value Line, Almanac of Business and Industrial Financial Ratios, Handbook of Business and Financial Ratios, the Directory of Public High Technology and Medical Corporations, the International Directory of Company Histories, and the Corporate Technology Directory.

Other Potential Sources of Financial Information

When conducting a financial assessment, it may be necessary in some cases to research a variety of other information sources to gain a clear picture of the PRP's financial position and ability to pay. Additional financial information often can be obtained by contacting various agencies at the county, city, state and federal levels. Although these sources are too numerous to discuss in this paper, a U.S. General Accounting Office publication, "Investigator's Guide to Sources of Information" (GAO/OSI-88-1), provides a wealth of information on the types of financial information available from governments, governmental agencies and commercial sources.

CONCLUSION

Assessing a PRP's ability to pay early in the enforcement process is an important first step toward achieving rapid and effective cleanups and settlements. An accurate financial assessment of a PRP's ability to pay early in the enforcement process will assist the U.S. EPA to determine the most cost-effective enforcement strategy, determine realistic settlement or cost recovery amounts, obtain corporate information that can help to facilitate a rapid and effective negotiation process.

determine whether a PRP is financially sound enough to conduct future remedial work and verify whether a PRP has an ability-to-pay problem.

This paper has discussed one approach to assessing a PRP's ability to pay. The approach is based on the PRP's operating and financial statements and four types of standard financial indicators designed to measure financial condition and performance.

The objective of the financial assessment is to assist the U.S. EPA personnel to accurately determine a PRP's ability to pay past or future response costs. The approach can be adapted to a variety of CERCLA settlement or cost recovery cases involving individuals and single or multiple companies who are PRPs. The approach also can be used to determine appropriate RCRA penalty assessment levels to impose on companies facing penalties under RCRA.

DISCLAIMER

Any views or opinions expressed in this paper are the views of the authors and do not necessarily represent the views of the U.S. the U.S. EPA.

REFERENCES

1. Beaver, W. H., "Financial Ratios as Predictors of Failure. Empirical Research in Accounting: Selected Studies," *Supplement to J. of Accounting Res.*, pp. 77-111, 1966.
2. Beaver, W. H., "Alternative Accounting Measures as Predictors of Failure," *Accounting Rev.*, pp. 113-122, Jan. 1968.
3. Beaver, W. H., "Market Prices, Financial Ratios, and the Prediction of Failure," *J. of Accounting Res.*, pp. 179-192, Autumn, 1968.
4. Brealey, Richard, et al., *Principles of Corporate Finance*, McGraw-Hill Book Company, New York, NY, 2nd Edition, pp. 195-226, 1984.
5. Davidson, Sidney, *Financial Accounting: An Introduction to Concepts, Methods, and Uses*, Third Edition, Dryden Press, Chicago, IL, pp. 202-229, 1982.
6. Dun & Bradstreet, *Industry Profile*, Oct. 17, 1988.
7. Foster, G., *Financial Statement Analysis*, Prentice-Hall, Englewood Cliffs, NJ, Chapters 2, 14, 1978.
8. Hartley, W.C.F. and Meltzer, Yale L., *Cash Management, Planning, Forecasting, and Control*, Prentice Hall, Englewood Cliffs, NJ, pp. 90-123.
9. Industrial Economics, Inc. (IEC), *Superfund Financial Assessment System*, Technical Support Document, U.S. EPA/Office of Policy and Resource Management, Washington, DC, Chapter 4, 1982.
10. International Research & Technology (IR & T), *Financial Tests as an Option for Demonstrating Financial Responsibility*, U.S. EPA/Office of Solid Waste, Washington, DC, 2, pp. 4-18, 1980.
11. Johnson, M., Mason, R., "Structured Settlements: A New Settlement Incentive," *Proceed. of the 9th National Conference on Hazardous Waste and Hazardous Materials*, Washington D.C., HMCRI, Silver Spring, MD, pp. 23-29, 1988.
12. Mays, R.H., "Revised Hazardous Waste Bankruptcy Guidance," U.S. EPA/Office of Enforcement and Compliance Monitoring, Washington, DC, May 23, 1986.
13. Morris, R., *1988 Annual Statement Studies*, Robert Morris Associates, Philadelphia, PA, p. 135, 1988.
14. Putnam, Hayes and Bartlett (PHB), *Financial Screening Criteria for Privately Held Firms*, U.S. EPA/Office of Policy Analysis, Washington, DC, pp. 19-21, 1984.
15. Schnepfer, J.A., *The New Bankruptcy Law, A Professional's Handbook*, Addison-Wesley Publishing Company, Philippines, 2nd Ed, pp. 67-100, 1982.
16. Siegel, J.G., *How to Analyze Businesses, Financial Statements and the Quality of Earnings*, Prentice Hall, Englewood Cliffs, NJ, pp. 93-168, 1987.
17. Tyran, M.R., *Handbook of Business and Financial Ratios*, Prentice Hall, Englewood Cliffs, NJ, pp. 145-162, 1986.
18. Troy, L., *Almanac of Business and Industrial Financial Ratios*, Prentice Hall, Englewood Cliffs, NJ, pp. 122-123, 1989.
19. The U.S. EPA, Office of Waste Programs Enforcement, *Technical Enforcement Support Potentially Responsible Party Search Orientation Manual*, Washington, DC, pp. 20-24 and C-1 to C-2, July, 1989.
20. Vichas, R.P., *Handbook of Financial Mathematics, Formulas, and Tables*, 13th Edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, pp. 341-372, 1979.
21. Vickman, T.M., *Handbook of Model Accounting Reports and Formats*, Prentice Hall, Englewood Cliffs, NJ, pp. 4-16 and 241-245, 1987.

Development of a Projection Model for State Hazardous Waste Disposal Capacity Assurance

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ABSTRACT

Section 104(c)(9) of CERCLA as amended requires states to demonstrate adequate capacity for the destruction, treatment or secure disposal of all hazardous wastes that are reasonably expected to be generated within the state during the next 20 yr. States that fail to provide an adequate capacity assurance plan (CAP) face loss of Superfund monies for remedial actions. To demonstrate capacity, states first calculated hazardous waste generation and disposal capacity for a "base year" and then projected generation over a 20-yr period. The projection considered the impact of economic growth or contraction, waste minimization and new regulations on the state's waste generation rates and disposal capacity. Few states, however, had comprehensive data available or the technical resources necessary to complete the CAP.

Through its Alternative Remedial Contracting Strategy contract, Region 5 of the U.S. EPA commissioned Planning Research Corporation (PRC) Environmental Management, Inc., to assist states in the CAP projection. This paper discusses the approach PRC conceived to devise reliable methods for calculating the impact of economic change, waste minimization and new regulations despite the absence of comprehensive data and discusses future research needs and problems encountered in completing the CAP projection.

INTRODUCTION

CERCLA Section 104(c)(9) requires each state to assure by Oct. 17, 1989, that adequate RCRA Subtitle C hazardous waste management capacity will be available for waste generated within the state during the next 20 yr. The legislative history for the 1986 CERCLA amendments indicates that Congress enacted Section 104(c)(9) because political pressures or public opposition prevent some states from siting or issuing permits for adequate hazardous waste management capacity within their boundaries, perhaps leading to the creation of future Superfund sites.¹ The perceived inaction over hazardous waste siting and permitting prompted Congress to require the state capacity assurance plans (CAPs) and to make future Superfund assistance for remedial actions contingent on the capacity assurance.

In December, 1988, guidance,² U.S. EPA specified that states not able to demonstrate capacity could provide the required assurance by:

- Demonstrating the intent to site new facilities
- Describing or implementing, and demonstrating the effectiveness of, a waste minimization program
- Assuring access to facilities in other states through interstate or regional agreements

To complete the CAP, states first calculated capacity and generation for a "base year"—usually 1987 — and then projected hazardous waste generation for 1989, 1995 and 2009, finally comparing projected waste generation to current capacity to determine where surpluses or short-

falls exist. For the base year and projection calculations, the more than 700 RCRA waste categories and the full array of available waste management techniques were compressed into 17 SARA waste types and 15 SARA management categories. The U.S. EPA's guidance asked states to modify the projections by considering expected economic growth or contraction, waste minimization activities and the impact of new federal and state regulations.

U.S. EPA Region 5 provided guidance and coordination among the Region 5 states and between the states and EPA Headquarters throughout the CAP process. Region 5 also commissioned PRC to support the states in methodology development and data manipulation and to provide a consistent approach to data manipulation methodologies.

To assist the states, PRC first developed an economic projection matrix that, in sum, calculated current waste volume, updated the figures to the projection year based on the factors in the U.S. EPA's guidance and measured projected demand for management capacity against available management capacity. Second, although several U.S. EPA Region 5 states intended to rely on waste minimization to assure capacity, none maintained waste minimization records that allowed measurement of the reduction in waste generation achieved. Therefore, to estimate waste minimization potential, PRC developed a strategy for modifying U.S. EPA research according to factors specific to each state and derived probable reduction coefficients. Third, PRC's research targeted pending regulations—in particular the RCRA "land ban" and newly listed RCRA wastes—likely to affect future hazardous waste management. The research was translated into coefficients that adjusted the capacity projection to account for the impact of future regulations. (Although the projection assessed future rates of waste generation rather than expected capacity, the undertaking was known commonly as the "capacity projection.") Finally, PRC produced computer software and an accompanying users manual and provided them to the states to implement the overall projection methodology. Subsequent sections discuss each component of the methodology.

ESTIMATING DEMAND FOR WASTE MANAGEMENT CAPACITY

As an aid in state CAP development, the U.S. EPA Office of Solid Waste developed software that calculated hazardous waste management capacity information for each state for the 1987 base year. The SARA Analytic Software (SARA-ASW) accepts data only in the format determined by the U.S. EPA Biennial Report Data System (BIRDS) derived from the U.S. EPA's RCRA biennial report forms. Depending on the amount of information available—whether comprehensive or limited—the SARA-ASW program applies varying levels of processing. Few states have adopted the biennial report form that is the basis for BIRDS, so PRC was first required in most cases to convert state data to the BIRDS format.

Predicting a state's future hazardous waste management capacity requirements involves comparing probable future generation to the current demand for, or utilization of, existing capacity. The general approach to projecting hazardous waste generation within the state consists of four features and assesses recurring and nonrecurring wastes (for example, wastes generated from spills or CERCLA remedial actions) separately:

- An initial estimate of future waste generation is developed based on the projected growth or decline in industrial activity for recurring wastes, on planned remedial actions for nonrecurring wastes and on wastes affected by new regulations.
- The estimates are then adjusted on the basis of the projected changes in waste generation per unit of activity (any constant measure of industrial output). This approach estimates change in the generation of specific wastes by specific industries or in remedial actions on the basis of information on waste minimization programs and new regulations.
- Projected waste generation is aggregated across all industry groups and remedial activities and divided into the 17 SARA waste types specified in the U.S. EPA guidance. (Examples of the SARA waste types include halogenated solvents, inorganic liquids with metals and non-halogenated organic liquids.)
- The total projected waste volumes are classified into demand for the 15 SARA waste management categories specified in the U.S. EPA guidance. (The SARA management categories include metals and solvents recovery, incineration, aqueous treatments and stabilization.)

The output of the projection is expressed as demand for the different types of waste management techniques. The demand estimates can be compared to existing waste management capacity to determine the state's future ability to handle instate waste production. Information on capacity deficits and surpluses also enabled judgments about the manageable level of interstate shipments of hazardous waste in the future for states that intended to rely on interstate agreements as a component of capacity assurance.

ECONOMIC PERFORMANCE

Economic performance must be incorporated when projecting a state's future recurring waste generation because, as a state's economy expands or contracts, waste generation is likely to react accordingly. For the CAP analysis, the most reliable measures of industrial activity are those that correlate most directly with waste generation, such as production in terms of physical unit or value of production. Value of shipments is a reliable indicator, but may include shipments out of inventories as well as current output and so is less effective as a measure of industrial activity. Other variables such as value added and employment can be used, but their relationships to production, and therefore to waste generation, may change over time on the basis of other factors such as labor productivity. If employment is used to measure industrial activity, production employment is preferable to total employment.

Many state agencies forecast industrial economic activity using methods such as regional input-output models that translate projected state demand for such elements as consumption, investment and government spending into industry production and employment estimates. In some cases, however, no state industry projection data were available beyond 5 yr. In those cases, 20-yr projections specific to each state, by industry group, were drawn from sources published by the U.S. Department of Commerce. PRC's flexible projection methodology allowed the states to rely on default values or to input economic data on a facility-specific basis.

For the default values, PRC selected employment projections by state at the two-digit Standard Industrial Classification (SIC) code level, prepared by the Regional Economic Analysis Division of the Department of Commerce Bureau of Economic Analysis. The projections, named OBERS for the offices formerly in charge of their preparation, use a "step-down" approach. The step-down approach is based on the premise that data for larger aggregates are generally more accurate than the same type of information for more detailed classifications. Thus, the OBERS program first develops national projections and then distributes them among states to arrive at state-level projections.

WASTE MINIMIZATION

The U.S. EPA guidance asked states to consider the potential for waste minimization in forecasting recurring waste generation. For purposes of the CAP projection, waste minimization was defined as the reduction of hazardous waste that is generated or subsequently requires treatment or disposal.

Most information produced so far on waste minimization potential is anecdotal only. The evaluation of the potential for waste minimization in the U.S. EPA Region 5 states, therefore, was based on review and analysis of the information the U.S. EPA developed for the *1986 Report to Congress on the Minimization of Hazardous Wastes*. No original research was conducted, although the general minimization factors developed as default values for the projection methodology were modified when information was available specific to the state. The generic information has limitations when applied to a specific facility, but the analysis represented a systematic approach to considering the potential for waste minimization in various industrial categories examined as a whole.

The analysis first deleted the data on the considerable quantities of contaminated rinse water. Then, for those industries identified as major generators of hazardous waste, an industry-specific waste reduction potential was extrapolated from the U.S. EPA Report to Congress and included in the software as a default value. This default value may be applied to all wastes the industry generates if no information on the nature of the waste by waste code is available, or it may be used for waste codes without waste-code-specific reduction factors.

Potential reductions were classified and adjustment factors derived according to two possible scenarios. Under the "most likely scenario," a particular type of industry would adopt a broad range of minimization techniques, resulting in a moderate reduction in the quantity of waste produced. Potential reduction factors in the most likely scenario generally ranged from 5% to approximately 20%. Under the "most optimistic scenario," the industry as a whole would adopt the most effective minimization techniques available, resulting in substantial reductions in waste generation. Potential reduction factors in the most optimistic scenario ranged from 18% to 50%; the most optimistic reductions would, however, probably not be achieved without a tough and aggressively enforced state program.

Default reduction factors were derived by two-digit SIC code where information was available in that form and were obtained by analyzing the industrial processes examined for the U.S. EPA Report to Congress. If the process generated a listed hazardous waste, the waste reduction potential for that process was averaged with the potential from other processes within the industrial category generating that waste. For the RCRA wastes not generated by a specific process (the "F" wastes), the methodology resulted in an aggregation of reduction potentials drawing on one to seven processes. No aggregation was required for the RCRA "K" wastes because the category refers to hazardous wastes generated during specific industrial processes.

IMPACT OF REGULATORY CHANGES

Regulatory changes may alter future waste generation and management in a variety of ways. New hazardous waste regulations may expand the universe of regulated hazardous waste or force a shift to new waste management techniques—for instance, moving wastes from land-filling to treatment by incineration. PRC used a two-step process to account for the effects of regulatory changes on capacity assurance, leading to development of a coefficients matrix to modify the CAP projection. First, the impact of regulatory changes on the types and quantities of hazardous waste generated was assessed. Second, the impact of regulatory changes on hazardous waste management options was evaluated. The assessment of the impact of new regulations for the current CAP analysis relied on the following assumptions:

- Newly listed wastes will be the primary regulatory change affecting the types and quantities of wastes generated.
- The RCRA land disposal restrictions, commonly known as the "land ban," are the primary regulations affecting hazardous waste management options.

- The analysis need examine only federal regulations because no state-specific new or proposed laws or regulations could be identified in EPA Region 5 that would affect hazardous waste management capacity.
- Given the uncertainties associated with proposed or anticipated rulemakings, only federal regulations considered final as of July 1, 1989, were considered. The statutorily required land ban, whose effects are both substantial and predictable, is an exception to the general approach.

Effects of Newly Listed Wastes

A process that includes use of a computer program was developed to project the impact of newly listed wastes on hazardous waste disposal capacity. First, the newly listed wastes that must be considered were determined: currently, the only wastes that are the subject of a final rulemaking are the six mining wastes listed Sept. 13, 1988.³ Each state in U.S. EPA Region 5 was asked to compare a list of industry types by SIC code that generate the newly listed wastes against a list of the industries active in each state. The comparison determined whether the mining wastes were likely to be generated within the state. The state determined responsible industries (or, when possible, specific facilities) and estimated the quantity of each newly listed waste currently generated. The information was incorporated into the base year data, and the program completed a projection of future generation identical to that for other wastes. The best management technique was identified for each newly listed waste, and the waste volume was apportioned among the suitable SARA waste management categories.

Effects of Land Ban

Future management of many wastes will be significantly affected by the land ban because it prohibits the land disposal of many untreated hazardous wastes and requires their management by alternative treatment technologies. The land ban is being implemented in three phases, each described as a "Third" of the total, that began in August, 1988 and will end in May, 1990. Because of certain provisions of RCRA, the phases do not always occur in discrete segments.

The best demonstrated available technology (BDAT) was identified for each waste affected by the land ban. In cases where the waste was generated in different forms — for example, wastewater versus non-wastewater—more than one BDAT was identified for each waste and a portion was assigned to each BDAT. Because BDATs have yet to be proposed for most Third wastes, the BDAT for the most closely analogous First Third and Second Third wastes was assigned.

Some management techniques produce residual wastes that require additional waste management. BDATs were identified for these residual wastes, and factors were developed to account for the increased waste management capacity they require. For example, incineration produces a residual waste, ash, that requires stabilization before landfilling so that total capacity would equal the original volume of waste, plus the residual volume, plus the volume of the treated residual. These factors were developed based on the regulatory development documentation for the land ban and on best engineering judgment.

Next, the SARA waste management category or categories corresponding to the BDAT for each affected waste were identified. The total volume of waste requiring alternative treatment (including residual volumes) was assigned to waste management categories, and total demand for each management technique in each projection year was calculated. As a final step, the waste generation data, identified by RCRA waste code, were aggregated into the 17 SARA waste types.

PROBLEMS, FUTURE DATA NEEDS, AND RESEARCH

Several problems and areas for future research became apparent during completion of the CAP. The lack of data on waste minimization already has been mentioned. In fact, the overall questionable quality of the data and inconsistencies among states presented a major problem throughout completion of the CAP. In addition, the interstate agreement required by the U.S. EPA's guidance raised legal questions about the prohibition under the commerce clause of the U.S. Constitution of state control of the interstate movement of hazardous wastes. Most

states attempted to reach some form of regional agreement, although the process was at best imperfect. Other research areas are briefly discussed below.

The U.S. EPA's guidance required states to include in the capacity analysis wastes considered "exempt" under RCRA, such as recycling of hazardous wastes during continuous industrial processes, discharges to facilities permitted under the Clean Water Act national pollutant discharge elimination system (NPDES) program and discharges to publicly owned treatment works. The exempt wastes are by definition excluded from the reporting requirements of RCRA, complicating the states' attempt to produce an acceptable CAP. Even where limited information was available on the exempt wastes, it was frequently incomplete or difficult to adapt to the CAP. For instance, records on NPDES flows show only pollutant levels in total gallons discharged and do not readily enable regulatory agencies to extrapolate influent levels of hazardous wastes. Furthermore, no clear statutory authority enables the states to collect the data on exempt wastes, and the effect of the exempt wastes on RCRA Subtitle C hazardous waste management facilities has not been demonstrated.

In addition, few state reporting systems could directly relate waste generation to industry types except in general terms. Enhanced state data collection that would accumulate data on a more detailed level, for example, at the four) rather than two-digit SIC code level, would aid the accuracy of future capacity plans.

CONCLUSION

The capacity assurance plan required development of a method to project future hazardous waste generation according to factors such as economic performance, waste minimization potential and impact of future regulations. The states desired consistent projection methodology and data manipulation. This paper reviewed one approach to preparing the CAP.

DISCLAIMER

The views expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Environmental Protection Agency.

REFERENCES

1. Senate Report No. 11, 1985, 99th Congress, 1st Session, p.22,23.
2. U.S. EPA/Office of Solid Waste and Emergency Response, *Assurance of Hazardous Waste Capacity: Guidance to State Officials. Assistance in Fulfilling the Requirements of CERCLA 104 (c)(9)*, Directive 9010.00, Dec., 1988.
3. U.S. EPA, *Final Rule Listing Six Mining Wastes*, Fed. Reg., 53, 35412, Sept. 13, 1988.

Other references used in development of capacity assurance plan methodology:

Economic Projections:

U.S. Bureau of Economic Analysis, Department of Commerce, *OBERS Regional Projections Volume 1: State Projections to 2035*, READ 85-01 (National Technical Information Service [NTIS] PB86-124526), 1985.

Waste Minimization:

U.S. EPA, *Report to Congress: Waste Minimization: Issues and Options*, U.S. EPA 53 SW 86-04 (NTIS PB87-114369), Oct. 1986.

Regulatory Change:

U.S. EPA, *Background Document for First-Third Wastes to Support 40 CFR 268 Land Disposal Restrictions Final Rule*, Aug. 8, 1988.

U.S. EPA, *Background Document for Second-Third Wastes to Support 40 CFR 268 Land Disposal Restrictions Proposed Rule*, Dec. 1988.

U.S. EPA, *Land Disposal Restrictions for First-Third Scheduled Wastes, Final Rule*, 53 Federal Register 31138, Aug. 17, 1988.

U.S. EPA, *Land Disposal Restrictions for Second-Third Scheduled Wastes, Proposed Rule*, 54 Federal Register 1056, Jan. 11, 1989.

U.S. EPA, *Regulatory Impact Analysis of Restrictions on the Land Disposal of First-Third Wastes*, Aug. 1988.

Implementation of Environmental Evaluation Policy In the Superfund Program

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ABSTRACT

In late 1988, the Directors of the U.S. EPA's Office of Emergency and Remedial Response and Office of Waste Programs Enforcement expressed concern "that thorough and consistent environmental evaluations are not always being performed at Superfund sites in both the removal and remedial programs." Pointing out that "the law calls for protection of human health and the environment," they asked the U.S. EPA Regional Offices to take steps to address this issue in all current and future Remedial Investigations and Feasibility Studies.

As part of the implementation of this policy, the U.S. EPA has issued *Risk Assessment Guidance for Superfund—Environmental Evaluation Manual*. The primary audience for this manual is U.S. EPA Regional Office Staff—the On-Scene Coordinator (OSC) for removal actions and the Remedial Project Manager (RPM) for remedial investigations and cleanup actions. The purpose of the manual is to provide a scientific and conceptual framework for overseeing environmental evaluations at Superfund sites. A key ingredient in the implementation of environmental evaluation at all relevant sites is the establishment of Biological Technical Assistance Groups (BTAGs) in the U.S. EPA Regional Offices. The manual is designed to facilitate communication between the RPM or OSC and the BTAG by describing:

- The statutory and regulatory basis of environmental evaluation in the Superfund program
- Basic scientific concepts relating to environmental evaluation of hazardous waste sites
- The role of the BTAGs and the information needed by specialists serving on the BTAGs
- Steps and information needed in planning an environmental evaluation
- An outline to guide the organization and presentation of the environmental evaluation in Superfund reports

The paper describes the respective roles of contractors, U.S. EPA staff and BTAGs in the planning, implementation and review of environmental evaluations. Progress in implementing the policy in the Superfund program also is discussed.

INTRODUCTION

From its inception, the Superfund program has relied on risk assessment to determine both the need for remediation and the level of remediation at uncontrolled hazardous waste sites. Until recently, formal Superfund risk assessments have focused almost exclusively on threats to public health. Beginning in 1988, the Superfund program has been increasing its concern for assessing and controlling environmental hazards as an integral part of the remedial process.

Environmental evaluation (ecological assessment), as it is applied in the Superfund program, is defined as the qualitative and/or quantitative appraisal of the actual or potential effects of a hazardous waste

site on plants and animals other than people and domesticated species. The program recognizes, however, that the health of people and domesticated species is inextricably linked to the quality of the environment shared with other species. Information from ecological studies may point to new or unexpected exposure pathways for human populations, and health assessments may help to identify environmental threats.

Ecological assessment of hazardous waste sites is an essential element in determining overall risk and providing protection of public health, welfare and the environment. The U.S. EPA considers ecological factors in hazard assessment and in reviewing alternative remedial actions because:

- Through the authority found in the Superfund legislation and other statutes, the U.S. EPA seeks to protect wildlife, fisheries, endangered and threatened species and valued habitats.
- From a scientific viewpoint, the U.S. EPA needs to examine ecological effects and routes of exposure so that: (1) important impacts and transport pathways are not overlooked, and (2) reasonable estimates are made of health and environmental effects.

CERCLA, as amended by SARA in 1986, requires the U.S. EPA to ensure the protection of the environment in: (1) selection of remedial alternatives and (2) assessment of the degree of cleanup necessary. Several sections of CERCLA make reference to protection of health and the environment as parts of a whole: Section 105(a)(2) calls for methods to evaluate and remedy "any releases or threats of releases . . . which pose substantial danger to the public health or the environment;" Section 121(b)(1) requires selection of remedial actions that are "protective of human health and the environment;" Section 121(c) calls for "assurance that human health and the environment continue to be protected;" and Section 121(d) directs the U.S. EPA to attain a degree of cleanup "which assures protection of human health and the environment."

CERCLA Section 104(b)(2) calls upon the U.S. EPA to promptly notify the appropriate Federal and State natural resource trustees about potential dangers to protected resources. Table 1 provides a partial listing of natural resource trustees. It is important for Federal trustees to identify and notify all cognizant trustees because co-trustees, such as States, Indian tribes or other Federal agencies, may have overlapping or primary jurisdiction over natural resources potentially affected by releases from any Federal facility.

Section 122(j) of the amended CERCLA requires the Agency to notify the Federal natural resource trustees of any negotiations regarding the release of hazardous substances that may have resulted in natural resource damage. Section 122(j)(1) also calls upon the U.S. EPA to encourage Federal natural resource trustees to participate in negotiations with potentially responsible parties (PRPs). If the U.S. EPA seeks to settle with a PRP by signing a covenant not to sue, the Federal natural

Table 1
Natural Resource Trusteeships

Department of the Interior

- Fish and Wildlife Service
 - Migratory birds
 - Anadromous fish
 - Endangered/threatened species
 - Critical habitats
 - National wildlife refuges
 - National fish hatcheries
- National Park Service (Including)
 - National parks
 - National seashores
 - National recreation areas
 - National historic sites
 - National battlefields
 - National scenic and recreational rivers

Department of Commerce

- Coastal environments and habitats
- Habitats (rivers and tributaries) of anadromous and catadromous fish
- Endangered/threatened species
- Tidal wetlands
- Marine sanctuaries
- Commercial and recreational marine fishery resources

Department of Agriculture

- National forests

Department of Defense

- Department of Defense installations

Department of Energy

- Department of Energy installations

States

- The responsibility of the states are state specific to be decided by each state Governor. Similarly, the Governor also designates the appropriate state agency to act as the Trustee. Contact should be made with the respective state environmental department or attorney general's office for the information regarding trustee designations and responsibilities.

Indian Tribes

- Tribal lands

resource trustee must agree to this covenant in writing. Section 122(j)(2) states that:

"The Federal natural resource trustee may agree to such a covenant if the potentially responsible party agrees to undertake appropriate actions necessary to protect and restore the natural resources damaged by such release or threatened release of hazardous substances."

In December, 1988, the Directors of the U.S. EPA's Office of Emergency and Remedial Response (OERR) and Office of Waste Programs Enforcement (OWPE) expressed concern "that thorough and consistent environmental evaluations are not always being performed at Superfund sites in both the removal and remedial programs." Pointing out that "the law calls for protection of human health and the environment," they asked the U.S. EPA Regional Offices to take steps to address this issue in all current and future Remedial Investigations and Feasibility Studies.

Implementation of U.S. EPA policy regarding environmental evaluation is proceeding through five initiatives: publication of a manual for U.S. EPA site managers; formation of technical assistance groups in the Regional Offices; development of additional information resources; production of training materials for U.S. EPA Regional staff; and communication of U.S. EPA policy to remedial contractors.

ENVIRONMENTAL EVALUATION MANUAL

In March, 1989, the U.S. EPA completed its manual on environmental evaluation¹. The primary audience for this manual is U.S. EPA Regional Office Staff—the On-Scene Coordinator (OSC) for removal actions and the Remedial Project Manager (RPM) for remedial investigations and cleanup actions. The purpose of the manual is to provide a scientific and conceptual framework for overseeing environmental evaluations at Superfund sites.

The approach taken in the *Environmental Evaluation Manual* differs significantly from its companion volume on human health evaluation². Whereas the *Human Health Evaluation Manual* contains considerable

technical detail on how to conduct a risk assessment with respect to health threats, the *Environmental Evaluation Manual* focuses on developing a general understanding of the concepts and strategy of ecological assessment. This difference stems from the key task of defining the scope of ecological investigations, which is inherently more complex than scoping human health evaluations. Due to the wide array of possible habitats, species and effects that may be involved, responsibility for planning and interpreting environmental evaluations needs to be shared with technical specialists who understand both the questions that need to be asked and the most efficient means of answering those questions. Hence, the *Environmental Evaluation Manual* is designed primarily as a means for facilitating communication between the OSC or RPM and these specialists.

The *Environmental Evaluation Manual* contains six chapters. Chapter 1, the introduction, defines environmental evaluation and its role in the Superfund program. The chapter also briefly discusses the relationship between environmental and human health evaluation.

Chapter 2 discusses the statutory and regulatory basis for environmental evaluation, including citations of the amended CERCLA and the proposed revisions to the NCP. This chapter also describes relevant sections of the U.S. EPA's guidances for removal actions and RI/FSs. Finally, the chapter lists numerous Federal laws that may contain applicable or relevant and appropriate requirements (ARARs). In addition to such commonly applied statutes as RCRA and the Clean Water Act, this section of the manual discusses such laws as the Fish and Wildlife Coordination Act, the Endangered Species Act and the Marine Mammal Protection Act.

Chapter 3 of the manual describes the basic scientific concepts underlying ecological assessment. It is intended to assist the RPM or OSC in working with the ecologists who will provide technical advice or perform the studies, by describing the conceptual framework within which these specialists make their judgments. This chapter defines numerous terms that are used later in the manual.

Chapter 4 details the role of technical specialists in ecological assessment. It discusses the kinds of information that the RPM or OSC should make available to these specialists so that a suitable characterization of the site and its contaminants can be made. This information is likely to include data on the site's location, the site's history, contaminants of concern and the site's environmental setting. The chapter goes on to discuss the assistance that technical specialists can provide in site screening, identification of information gaps, advice on Work Plans, data review and interpretation, advice on remedial alternatives and enforcement support.

Chapter 5 discusses the process of developing an appropriate study design for assessment of a site. It discusses the principal components of defining the scope and design of an environmental evaluation:

- Determination of the objectives and level of effort appropriate to the site and its contaminants
- Evaluation of site characteristics
- Evaluation of the contaminants of concern
- Identification of exposure pathways
- Selection of assessment endpoints

The outcome of the planning process is the Sampling and Analysis Plan, which specifies the methods for data collection and analysis and the procedures for QA/QC. If new data are to be collected for the environmental evaluation, it is essential that data quality objectives reflect specific programmatic goals and management objectives to ensure that time and funds spent to gather and analyze data are used efficiently and effectively.

Chapter 6 describes a basic outline for an assessment. Although each site's assessment will differ according to the details of the contaminants, exposure routes, potentially affected habitats and species, this chapter provides a checklist of items for the RPM or OSC to expect when overseeing the preparation of an assessment, including:

- Specifying the objectives of the assessment
- Defining the scope of the investigation
- Describing the site and study area

- Describing the contaminants of concern
- Characterizing exposure
- Characterizing risk or threat
- Describing the derivation of remediation criteria or other uses of quantitative risk information
- Describing the study's conclusions and any limitations of the analysis

The *Environmental Evaluation Manual* intentionally avoids detailed discussion of field and laboratory methods, concentrating instead on basic concepts, design strategies and information resources. Its intent is to foster communication between RPMs/OSCs and the Biological Technical Assistance Groups that have been established to provide the ecological expertise necessary for effective design, execution and interpretation of environmental evaluations.

BIOLOGICAL TECHNICAL ASSISTANCE GROUP

In the December, 1988 memorandum, the Directors of OERR and OWPE pointed to the successful use of biological technical assistance groups (BTAGs) in U.S. EPA Regions 2, 3, 4 and 10. In March, 1989, a workshop for Regional Superfund managers was held in Cherry Hill, New Jersey, sponsored by Region 3, which focused on the activities of BTAGs. As a result of these efforts, all U.S. EPA Regional Offices have now established BTAGs. Membership in the BTAG varies from Region to Region, but may include staff from:

- U.S. EPA Regional Environmental Services Divisions
- The U.S. EPA Environmental Response Team
- U.S. EPA Regional N.U.S. EPA coordinators
- Ecosystem-specific U.S. EPA programs, such as the Great Lakes National Program Office in Chicago, Illinois or the Chesapeake Bay Program Office in Annapolis, Maryland
- Laboratories of U.S. EPA's Office of Research and Development
- Regional and field offices of the U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration (especially NOAA's Coastal Resource Coordinators)
- Other Federal and State environmental and resource-management agencies (such as State fish and game departments)

Generally, specialists on the BTAG serve an advisory role. Their function is to assist the RPM or OSC with information collection and evaluation and to help ensure that ecological effects are properly considered in investigations and decisions. In specific cases, arrangements may be made for individual BTAG members to be involved directly in conducting the work.

BTAGs are expected to be consulted at all appropriate stages of the remedial process, from the Preliminary Assessment and Site Investigation to the review of Remedial Designs and Remedial Actions. Perhaps the most frequent and most important use of the BTAGs occurs during the RI/FS process, including site screening, review of Work Plans and review of data.

Following collection of existing data, the BTAG members should be in a position to determine the nature and extent of ecological assessment that will be necessary for the site. If no ecological exposure pathways have been revealed in this initial review, little or no additional work may be needed. Alternatively, certain exposure pathways might be eliminated from further study while others might require more data. For instance, if there is no surface water on the site and no opportunity for contaminants to reach surface waters off the site, further data on aquatic effects would very likely be pointless, even though concern about exposure to terrestrial organisms might warrant extensive sampling and testing.

Effective ecological assessment will require a design that is tailored to each site's specific characteristics and the specific concerns to be addressed. Choosing which of the many possible variables to investigate in the study will depend on the nature of the site, the types of habitats present and the objectives of the study. The BTAG is expected to assist the RPM in specifying technical objectives for the investigation. Such objectives might include:

- Determination of the extent or likelihood of impact
- Interim mitigation strategies and tactics

- Development of remedies
- Remediation criteria

The BTAG can then help the RPM develop data quality objectives to support these technical objectives.

Although each assessment is in some way unique, it is possible to outline the general types of data that may be required. For terrestrial habitats, the BTAG specialists may specify such data needs as:

- Survey information on soil types, vegetation cover, and resident and migratory wildlife
- Chemical analyses to be conducted in addition to any previous work done as part of a Preliminary Assessment or Site Investigation
- Site-specific toxicity tests to be conducted

For fresh-water and marine habitats, the information needed will most likely include:

- Survey data on kinds, distribution and abundance of populations of plants (phytoplankton, algae and higher plant forms) and animals (fish, macro- and micro-invertebrates) living in the water column and in or on the bottom
- Chemical analyses of samples of water, sediments, leachates and biological tissue
- Sediment composition and quality, grain sizes and total organic carbon
- Toxicity tests designed to detect and measure the effects of contaminated environmental media on indicator species, or on a representative sample of species

BTAG members will also provide guidance on such QA/QC issues as:

- The area to be covered in biotic and chemical sampling programs
- The number and distribution of samples and replicates to be drawn from each habitat
- The preferred biological analysis techniques to be used
- Adherence to the assumptions of predictive models used in the analysis
- The physical and chemical measurements (e.g., dissolved oxygen in a water sample, pH of water or soil, ambient temperature) to be taken at the time of the survey
- Any special handling, preservation methods or other precautions to be applied to the samples

The BTAG also may be called upon to review data and provide comments on the interpretation of data. In most situations, extensive and long-term ecological studies are unlikely to be undertaken, and informed professional judgment will be required to determine if the weight of evidence supports a particular decision regarding the site.

OTHER ACTIVITIES

Publication of the *Environmental Evaluation Manual* and establishment of BTAGs constitute the core of the U.S. EPA's implementation of its environmental evaluation policy. The Superfund program is also providing additional information to support environmental evaluation, revising its training program for RPMs and Regional risk assessors, and communicating its policy to remedial contractors.

While OERR and OWPE were developing the *Environmental Evaluation Manual*, the U.S. EPA's Corvallis Environmental Research Laboratory sponsored the preparation and publication of a companion volume³ containing detailed discussion of field and laboratory methods for ecological assessment of hazardous waste sites. This reference document covers such topics as:

- Types of ecological endpoints, criteria for selecting endpoints and defining assessment goals
- Assessment strategies and designs, and selection of appropriate assessment methods
- Field sampling design
- Quality assurance and data quality objectives
- Aquatic, terrestrial and microbial toxicity tests
- Use of biomarkers
- Field assessments of aquatic ecosystems, terrestrial vegetation, terrestrial vertebrates and terrestrial invertebrates
- Data analysis and interpretation

The U.S. EPA's Office of Information Resource Management is developing a data base for use by Regional and Headquarters staff which will list ecological expertise found throughout the Agency. These experts will include ecologists in other U.S. EPA program offices, scientists in the Office of Research and Development at Headquarters and in research laboratories, and specialists in the Regional Environmental Services Divisions and ecosystem-specific programs. This data base will be made available in electronic form to Regional Offices, allowing for rapid updates and ready recovery of the information contained in the directory.

The Superfund program currently is revising its training program for RPMs and Regional risk assessors to include material on environmental evaluation along with the updated approach to human health evaluation. Among the topics to be covered in the training are the following:

- Statutory and regulatory basis for health and environmental evaluations
- Ecological principles and concepts relevant to environmental evaluation
- The role of the BTAG
- Sampling and analysis for health and environmental evaluations
- Planning and evaluation of site assessments

The courses will include detailed examination of real and hypothetical case studies. For environmental evaluation, emphasis will be placed on directing and reviewing contractor products, rather than on conducting the studies themselves.

In April, 1989, Superfund ARCS contractors were invited to the U.S.

EPA for a day-long workshop on Superfund policy and procedures. At that time, the Chief of the Toxics Integration Branch for Superfund presented information on the revised *Human Health Evaluation Manual* and the *Environmental Evaluation Manual*. Contractors also were informed of the establishment of BTAGs in the Regional Offices and were encouraged to work with these specialists, through the site-specific RPM, to develop environmental evaluations that are both scientifically sound and capable of being conducted within program-mandated time and budget constraints.

Ecological assessment is, and will continue to be, a process combining careful observation, data collection, testing and professional judgment. Through close coordination with the RPM and BTAG, and by following U.S. EPA's guidance manuals and other reference materials, Superfund contractors should be able to conduct site assessments that will result in effective and efficient protection of environmental as well as human receptors.

REFERENCES

1. U.S. EPA, *Risk Assessment Guidance for Superfund. Volume II: Environmental Evaluation Manual. Interim Final*. U.S. EPA/540/1-89/001. U.S. EPA, Cincinnati, OH, March 1989.
2. U.S. EPA, *Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual Part A. (Review Draft)* OSWER Directive 9285.701A, July, 1989.
3. U.S. EPA, *Ecological Assessments of Hazardous Waste Sites: A Field and Laboratory Reference*. U.S. EPA/600/3-89/013. U.S. EPA, Cincinnati, OH, Mar., 1989.

Review and Comparison of State Statutes for Natural Resource Injury

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ABSTRACT

When a natural resource is injured due to release of a hazardous substance, restoration of that natural resource to pre-release levels is generally very expensive. CERCLA provided for use of the Hazardous Substance Response Fund to redress injury to natural resources, but SARA has taken away the use of the fund for this purpose. While the United States government is undoubtedly interested in the preservation of natural resources, it is the state wherein injury to a natural resource occurs that stands the greatest loss from unavailability of fund monies for restoration.

Because the burden of payment for restoration of a natural resource may rest ultimately with the state, it is important for all states to have statutory mechanisms in place that will provide the legal basis for recovery of damages for injury to a natural resource. This paper provides an overview of the current issues in the law relating to recovery for injury to natural resources. With this overview as background, the discussion then summarizes each state's statutes pertaining to a hazardous substance release injuring natural resources. Finally, this paper reviews certain state statutes that are especially sensitive to natural resource injury and provides recommendations for improvement by the states in this area.

INTRODUCTION

CERCLA as amended by SARA is a monumental piece of legislation that attempts to provide a framework for response to the release of a hazardous substance. The enormity of the task to draft such a complex public law had the understandable result of falling short when certain provisions were acted upon.

Much of CERCLA/SARA gave only the statutory basis for response to an event, and left for the President the task of drafting regulations that describe the methodology to be followed in implementing each section. One such example is the law and regulations related to release of a hazardous substance causing injury to natural resources.

Under CERCLA/SARA, the provision for liability in responding to natural resource injury can be found in §9607(a)(4)(C). This section is straightforward in its meaning, and complete in that it provides for recovery of costs in response to natural resource injury.¹ To implement recovery for injury to natural resources, the President was required by CERCLA to promulgate regulations for the assessment of injury to natural resources.² The regulations were finally published on Aug. 1, 1986.³ SARA was passed on Oct. 17, 1986, and Congress gave the President 6 mo from that date to revise the Aug. 1, 1986 regulations to conform with SARA.⁴ These revised regulations were published in February, 1988.⁵

The Type A and B regulations for assessment of damages to injury, destruction or loss of natural resources, as published by the U.S. Depart-

ment of the Interior, were immediately challenged in federal court. The U.S. Court of Appeals, D.C. Circuit, ultimately reached a decision in these cases on July 14, 1989.⁶ The opinions are extremely well reasoned and provide an excellent historical perspective of the CERCLA/SARA natural resource damage provisions. Generally, the holding in these opinions is that the U.S. Department of Interior must revise the assessment regulations and provide a broader approach to ensure injured, lost or destroyed natural resources are made whole.

The D.C. Circuit Court of Appeals realized that natural resources are not easily replaceable. As a result, when injury, destruction or loss occurs to a natural resource, any damages recovered to address the harm must, if possible, be sufficient to reestablish said natural resource in the environment. The message sent by the D.C. Circuit Court of Appeals is that natural resources are finite, and every legislative mechanism should be fully utilized to maintain those natural resources remaining in the environment.

A majority of the plaintiffs challenging the U.S. Department of the Interior's assessment provisions were state governments.⁷ It is the state that suffers the most immediate loss when harm to a natural resource occurs through release of a hazardous substance. A state is more personally involved in the natural resources existing within its boundaries. Often, it is the state that is uniquely knowledgeable about particular natural resources and their value to the public. As a result, it is the state that stands in the best position to promote the preservation and growth of its natural resources. A recent opinion confirms the state's role in enforcement of laws for the protection of the environment.⁸

States can avail themselves of the natural resource damage provisions within CERCLA/SARA to establish a claim for recovery of costs for injury to, destruction of or loss of natural resources. States can utilize those natural resource damage assessment provisions published as regulations. What the state cannot do is take money from the Hazardous Substance Response Fund to pay for assessment and resultant harm to a natural resource.⁹ With the forthcoming changes to promulgated natural resource damage assessment regulations, state reliance on this area of federal laws and regulations is problematic.

A state is not required by federal law to rely solely on the CERCLA/SARA natural resource damage laws and associated regulations. States are sovereigns, and as such can pass their own laws pertaining to natural resource injury and damage assessments. Generally, said laws cannot be less strict than federal laws, or conflict with the intent and purpose of the federal law. With the absence of Superfund monies to pay for injury to natural resources, a state must rely on other laws (i.e., state common law) that provide a basis for recovery. Or, as a number of states have done, they can pass their own laws pertaining to natural resource injury and recovery for damages.

The following sections provide a general discussion of state laws that

Table 1
State Statutes Pertaining to Release of a
Hazardous Substance and Natural Resource Injury

State Name	Statute Name	Environmental Statutes Cited	Natural Resource Injury Statutes Cited	State Name	Statute Name	Environmental Statutes Cited	Natural Resource Injury Statutes Cited
Alabama	Code of Alabama (1988)	22-224-4 through 4-16 22-22-1 through 22-22-24 6-6-1 et. seq. 9-7-1, 9-7-22 22-22-1 et. seq.		Alabama	New Statutes	22-2-1 through 22-2-25 Chapter 74	
Alaska	Alaska Statutes (1988)	45.05-040 (1988) 45.05.100 45.05.110 through 45.05.160 45.05.010 et. seq. 45.05.780 through 800 45.05.020 through 45.05.029	46.03.674 46.03.780 46.03.822 (1984) 46.05.028 (1988)	New York	McKinney's Consolidated Laws of New York (1988)	Public Health §1285-1289 §4801-4803 Environmental Conservation - Articles 17, 18, 21, 27, 33, 37, 38, 39, 45, 71	Environmental Conservation §27-1313 §71-1991
Arizona	Arizona Revised Statutes (1988)	45-101 through 45-1101	41-676	North Carolina	General Statutes of North Carolina (1988)	§143 Articles 21, 21A, 21B	§143-216.20
Arkansas	Arkansas Code Annotated (1988)	6-1-101 through 6-7-619 Supp. 6-7-601 and 6-7-619	6-4-103(a)	North Dakota	North Dakota Century Code (1988)	22-05-01 et. seq. 22-05-01 et. seq. 22-01-01 et. seq. 22-03-01 et. seq. 22-03-01 et. seq.	61-25-02, 67
California	West's Ann. Cal. Code (1988)	Health and Safety 39102 through 39300 §5385, §5775	Health and Safety 17600 and 17601 (1988) Health and Safety §5601, §6, 60	Ohio	Ohio Revised Code (1988)	3734.01-3734.09 3745.01-3745.13 3760.01-3760.09 3761.01-3761.09 3764.01-3764.09 3765.01-3765.09 3765.01-3765.09	3745.12 3745.13
Colorado	Colorado Revised Statutes (1988)	26-22-101 through 26-22-109 26-7-101 through 809 26-Jan 8-16 26-Jan 11-16 26-Jan 12-16 26-Jan 16-16	26-26-104 26-7-121, 127 26-6-809 26-6-815 26-16-104.1	Oklahoma	Oklahoma Statutes Annotated (1988)	62-1123-45-49 47-6235.1-6235.16 68-11-6201-6201.47 47-62271-62280 Title 67	62-1123-47 25-693 25-679 25-69
Connecticut	Connecticut General Statutes Annotated (1988)	22a	22b-64 22b-65	Oregon	Oregon Revised Statutes (1988)	465.025-465.032 465.035-465.038 465.039-465.039	465.030 465.033
Delaware	Delaware Code (1988)	7 DC 38000 et. seq. 20 DC 38000 to 38008		Pennsylvania	Pennsylvania Statutes Annotated (1988)	Title 25 Chapters 25A, 25C, 44 35-14201 et. seq.	Consol. Art. 1 §37 34-21201
Florida	Florida Statutes Annotated (1988)	Chapter 403	403.021 403.121 403.131 403.141 403.412	Rhode Island	General Laws of Rhode Island (1988)	16-20-1 through 16-20-11 25-10-1 through 25-10-1-20 25-10-10-1 through 10-11 25-24-8 et. seq. 25-24-8 through 25-24-20 25-24-1 through 25-24-16 42-17-6-1 through 42-17-6-6 25-21-1 through 25-21-16	Consol. Art. 1 §17 21-32 42-17-6-6
Georgia	Code of Georgia (1988)	13-6-1 through 13-6-24 13-6-1 through 13-6-427 13-6-1 through 13-6-142 13-6-1 through 13-6-32 13-12-1 through 13-12-20 13-12-1 et. seq. 13-14-1 et. seq.	13-14-4 13-6-61 through 63	South Carolina	Code of Laws of South Carolina (1988)	Title 45, Chapters 1, 2 45-25, 124 through 61-70, 270 61-70, 284 et. seq. 61-70, 285 et. seq. 61-70, 286 et. seq. 61-61 et. seq. 61-67 et. seq.	45-1-20 45-1-20
Hawaii	Hawaii Revised Statutes (1988)	Title 12, Chapters 171, 177 Title 18, Chapters 229 through 344	Title 16, 342-107 and Chapter 344	South Dakota	South Dakota Codified Laws (1988)	24A-1 24A-2 24A-3 24A-4 24A-5 24A-6 24A-7 24A-8 24A-9 24A-10 24A-11 24A-12	24A-12-1 through 12-17 24A-10-1
Idaho	Idaho Code (1988)	Title 26, Chapters 20, 26, 44, 55, 62	26-6211	Tennessee	Tennessee Code Annotated (1988)	49-13-101 through 1013 49-25-101 through 102 49-27-101 through 102 49-31-101 through 102 49-45-101 through 101	49-45-102 49-45-102 49-45-207
Illinois	Smith-Hurd State Annotated Statutes (1988)	Chapter 111 1/2 Paragraph 1021-1057	111 1/2 Paragraph 1024 (includes) 1012(a) 1042, 43	Texas	Texas Statutes and Codes (1988)	Agriculture §128.001 et. seq. Water §263.001 et. seq. §265.121 et. seq. §265.201 et. seq. Child Statutes Art. 6077-3a Art. 6077-4 Art. 6077-7, -7a, -7b, -7c	Water §263.124 §265.200(a) Domestic Law §265.121 through 121 Chapter 69 20-102
Indiana	Burns Indiana Statutes (1988)	Title 13, Article 1 and Article 7	16-6-6-7, 13-7-6-112 13-7-6-1, 13-7-12-3 13-7-6-10 13-7-6-6	Utah	Utah Code Annotated (1988)	25-11 et. seq. 25-12 et. seq. 25-13 et. seq. 25-14 et. seq. 25-14a et. seq. 25-14b et. seq. 25-14c et. seq. 25-14d et. seq. 25-14e et. seq.	25-11-6
Iowa	Iowa Code Annotated (1988)	Vol. 28 §485A §485B	485B, 207	Vermont	Vermont Statutes Annotated (1988)	T, 10 C 20 et. seq. T, 10 C 47 et. seq. T, 10 C 48 et. seq. T, 10 C 23 et. seq. T, 10 C 28 et. seq.	T, 10 §1291 T § 11323
Kansas	Kansas Statutes Annotated (1988)	Chapter 66 Articles 1, 27, 30, 32, 34, 34a, 46, 57	66-2423 66-3-480	Virginia	Code of Virginia (1988)	45-1-1200-1201 45-1-1202-1202 45-1-1400-1407 45-1-184.1	45-1-1405
Kentucky	Kentucky Statutes Annotated (1988)	Chapter 294 1/2-1A Chapter 294	294.277	Washington	Revised Code of Washington (1988)	70-100 C-200 70-100 C-210-220 43.21 C-210-210 70-100 et. seq. 70-100 §210-220 70-142 43.21 A-200 et. seq. §43A-010 et. seq. 80-48 et. seq.	70-100 C-210 70-100 §210 80-48-142
Louisiana	Louisiana Revised Statutes (1988)	LRS Title 32 Subtitle B	Louisiana Const. Art. 9 §11 32-3020 32-2271 32-3280	West Virginia	West Virginia Code (1988)	16-20 et. seq. 16-20 et. seq. 20-24 et. seq. 20-42 et. seq. 20-47 et. seq. 20-43 et. seq.	20-24-10b 20-2-6a
Maine	Maine Revised Statutes Annotated (1988)	Title 26 Chapters 13, 14, 16, 18, 17	26-11267	Wisconsin	Wisconsin Statutes Annotated (1988)	Chapter 144 except 144.20-144.34	144.76 144.208 142.23
Maryland	Annotated Code of Maryland (1988)	Environment Title 1-12	Environment §7-230, 231, 232	Wyoming	Wyoming Statutes Annotated (1988)	26-11-101 through 26-11-204 26-11-201 through 26-11-1020	26-11-201
Massachusetts	Massachusetts General Laws Annotated (1988)	Chapters 21A-4, 111	21A §7A 21-61 21-6, 50				
Michigan	Michigan Consolidated Laws Annotated (1988)	Section 269					
Minnesota	Minnesota Statutes Annotated (1988)	Chapters 116, 116-116a	§116B.20(2)(f) §116B.24 §116B.29 §116B.17				
Mississippi	Mississippi Code Annotated (1988)	17-17-1 through 17-17-126 49-17-1 through 49-17-47 49-17-401 49-17-432					
Missouri	Missouri Revised Statutes (1988)	§202 §643	§202 §30				
Montana	Montana Code Annotated (1988)	Title 79 Beginning -75-10-719	75-10-711 75-10-19				
Nebraska	Revised Statutes of Nebraska (1988)	81-1801 through 1814b	81-1820 through 1820				
Nevada	Nevada Revised Statutes (1988)	Chapters 444, 445, 450 41-640 through 670	450 385				
New Hampshire	New Hampshire Revised Statutes Annotated (1988)	Chapters 148A, C, D 147A through D 148 149	147 B, 10a 147 A, 9				
New Jersey	New Jersey Statutes Annotated (1988)	Title 66 Chapters 10, 26 Title 19 10, 6, 7, L, K	66-10-22 11g (water only)				

pertain to release of a hazardous substance causing injury, loss or destruction of a natural resource. From this general survey of state laws, the discussion focuses on specific states whose laws in this area are of particular note. Finally, recommendations are made for states to improve their laws and regulations in this area.

STATE ENVIRONMENTAL LAWS

All states have some form of law concerning the natural environment. Since the advent of federal laws on hazardous waste management and release of hazardous substances, the majority of states have passed laws similar to those passed by the U.S. Congress. Some states have simply passed the federal law as a state law, with little or no change in the substantive language. Other states have passed environmental laws that are, for the most part, original pieces of legislation. Still others have passed very little in the way of environmental legislation, perhaps relying on the federal laws and common law theories of recovery.

Table 1, column 3, provides a list of each state's environmental laws. To develop this list of state statute citations, certain criteria were utilized. Initially, a state's statutes were surveyed for laws pertaining to the release of hazardous substances in the environment, a la CERCLA/SARA. The next statutes of interest were those concerning management of hazardous wastes, a la RCRA. Then the state statutes were surveyed for other laws pertaining to environmental pollution, such as air and water statutes. Those statutes concerning radioactive material and waste were not included in the list of state environmental statutes in Table 1.

Column 4 of Table 1 is a list of those state statutes related to release of a hazardous substance causing injury, loss or destruction to natural resources. To develop this list of state statutes, certain criteria were utilized. Initially, the environmental law statutes of a state were reviewed to determine if there were any specific statutes concerning injury to natural resources. If no statutes could be found directly on point, then the state environmental laws were reviewed to determine if related statutes could be used as authority to bring a state claim for injury, loss or destruction of natural resources. An absence of either type of statute led to a review of general water pollution or similar type statutes whereby a claim for natural resource injury, loss or destruction could be made.

There are two caveats to reliance on the statutes listed in Column 4. The first is that these statutes are in many cases current only through the 1988 legislative session. Every attempt was made to secure laws as up-to-date as possible using the Advance Legislative Service, etc. At best, this list is current through July, 1989. The other caveat concerns legal interpretation of a state's statutes by the state attorney general or other legal representative. A state may rely on other types of damage, nuisance, fish and wildlife, agricultural, etc. statutes as a basis for making the same claim as the federal government would under the language of CERCLA/SARA §9607(a)(4)(C).¹⁰ With these caveats in mind, the next section discusses particular state statutes that have specifically addressed a hazardous substance release causing injury, destruction or loss to a natural resource.

SELECTED STATE NATURAL RESOURCE INJURY STATUTES

As discussed previously, a state can have laws similar to the federal laws, as long as the state law does not conflict with the purpose and intent of the like federal law. One distinct advantage for a state to have its own law on a certain subject, and not rely on federal law, has to do with the forum in which a case is litigated. In a number of situations, a state may find it more advantageous to present its case in a state court instead of a federal court. A state in this situation would have the opportunity to be heard by a judge who is very familiar with the intent of the state's laws.¹¹ Forum shopping is a practice actively engaged in by many litigants, and a state action to enforce a state law has a better chance of remaining in the state court.

It is to the state's advantage to draft its own laws when the subject matter holds a special interest for the state, is already highly regulated by other state laws and/or is of a unique and complex nature in which the state has previously invested time and money to gain a better understanding. State statutes that are carefully and specifically drafted to treat such technical subject matter usually will be given great

deference by a court of law.

State statutes that apply to release of a hazardous substance causing injury, destruction or loss of a natural resource fall into the definition of unique subject matter as discussed in the previous paragraph. Natural resources, as defined by federal and state laws, include almost everything living in the natural environment.¹² Most states have statutes concerning hazardous substances and/or pollution in general. All states have statutes concerning quality and regulation of fish, wildlife, air, water, soil, biota and other natural resources. Natural resources, as they exist, are of great interest to a state. Why then have more than half of our states not considered it worthwhile to pass laws that address injury, destruction or loss to a natural resource?

The following is a selection of states that utilize their statutes to address harm to a natural resource from release of a hazardous substance. For each state, a brief comment regarding the state's statutory scheme is included. There are states not discussed here that have statutory mechanisms for addressing injury to a natural resource. However, the states that were selected for inclusion have unique or comprehensive approaches to natural resource injury, destruction or loss.

California

In the California code, there are a number of sections concerning injury to and damages for natural resources. California has a trust fund/account set up to provide for the assessment and replacement of injured natural resources.¹³ California provides for punitive damages when the injury, loss or destruction to a natural resource occurred after Sept. 25, 1981.¹⁴ Due to the state's interest in marine natural resources, there is a provision specifically for release of a hazardous substance causing injury in this type of environment.¹⁵

Colorado

Colorado relies on CERCLA/SARA and other federal environmental laws, but also provides specific statutes where natural resource injury results in recovery of damages.¹⁶ Monies recovered for the CERCLA fund in Colorado, unlike the federal Hazardous Substance Response Fund, can be used to restore, replace, etc. natural resources.

Connecticut

Connecticut not only provides for liability to a person causing injury, destruction or loss of a natural resource, they also provide for imposition of civil penalties towards such action.¹⁷

Iowa

A statute directly on point that includes cost of damage assessment and punitive damages for willful release.¹⁸

Louisiana

Louisiana, like several states, has placed within its constitution a section concerning the public policy interest of protecting natural resources and the environment.¹⁹ Thus, natural resources could arguably be considered a constitutionally protected interest. Monies collected from a responsible party can be used for restoration of the natural resource.

Maine

Maine has an extensive liability statute on recovery of damages for injury, destruction or loss of a natural resource.²⁰ This statute also includes punitive damages.

Maryland

As with a number of states, Maryland provides a reference to natural resource injury when discussing removal or remedial actions.²¹ The state also provides for a State Hazardous Substance Control Fund and that expenditures from this fund can include natural resource injury, loss or destruction.²²

Massachusetts

Massachusetts has an extensive statute on liability for injury, destruction or loss of natural resources that paraphrases

CERCLA/SARA.³¹ Massachusetts also provides a definition of "damage to the environment."³²

Minnesota

Minnesota has one of the more extensive statutes on release of a hazardous substance causing injury, destruction or loss of natural resources.³³ The statute is modeled after CERCLA/SARA. The state also describes who is the trustee for natural resources.³⁴ There is an Environmental Response, Compensation, and Compliance Fund from which monies can be spent on natural resource injury, loss or destruction.³⁵

Montana

Montana's liability statute is to the point, but does not specifically refer to recovery of assessment costs.³⁶ The statute has a provision for punitive damages as well. Montana is also included as an example of many state statutes. Based on the language under the section providing for remedial action, Montana could bring an action for liability to injury, loss or destruction of the environment. The term environment is arguably analogous to natural resources.³⁷

North Carolina

North Carolina has an excellent, extensive statute on liability for injury, destruction or loss of natural resources.³⁸ The statute also discusses assessment of damages more extensively than most states. Punitive damages are available for intentional or negligent release.³⁹

Oregon

In addition to the language of federal law placed in their environmental statutes, Oregon also provides a price list for natural resource replacement.⁴⁰

Pennsylvania

Pennsylvania has an excellent series of provisions for protection of natural resources. The Pennsylvania constitution affirms that preservation of natural resources is an important public consideration.⁴¹ The state basically has modeled its laws concerning liability for injury, destruction or loss of natural resources after CERCLA/SARA.⁴² The state has a Hazardous Sites Cleanup Fund which provides for expenditures to restore, rehabilitate or acquire natural resources.⁴³ Pennsylvania also has a statute focusing on economic evaluation methods to arrive at damages for loss of fish or wildlife.⁴⁴ The language in this section, while not referring directly to hazardous substances, could arguably include a release of such in causation.

South Dakota

South Dakota laws are somewhat general as they relate to damages for injury, destruction or loss to natural resources, with a need for inference. Several sections of the South Dakota law provide very specific procedures for actions by the state to recover damages for injury, destruction or loss of natural resources.⁴⁵ The reference is not to release of a hazardous substance, but to pollution. However, in this context, these terms are analogous.

Washington

The Washington statute concerning liability for injury, loss or destruction to natural resources should be considered a model in this area of legislation.⁴⁶ The statute makes it very clear that restoration of the environment is the goal to be achieved and damages will be sought for the full amount. This statute shows unusual foresight in light of the recent natural resource damage assessment opinions previously discussed.⁴⁷ The Washington Department of Fisheries and Game is given the responsibility of determining the pre-harm condition of the natural resource.

CONCLUSIONS AND RECOMMENDATIONS

When the release of a hazardous substance occurs, concerns related to impacts on the public health and welfare are immediately addressed. Simultaneous with this release event, there may have been injury, loss or destruction of natural resources. The public is a vocal and persis-

tent advocate for remedy of potential health impacts resulting from the release. The natural resources that are harmed, however, cannot communicate the degree of present and potential injury that has occurred. Often, a significant period of time elapses before the effects of a release on natural resources are addressed.

The federal government has an interest in the protection of natural resources. But this interest is dedicated to a nationwide responsibility. Federal management of natural resources, and representation as trustee in matters affecting said resources, cannot begin to adequately protect localized resource related interests. It is, therefore, the responsibility of individual states to ensure their natural resources are being given the proper degree of protection.

For a state to provide adequate protection of natural resources when the release of a hazardous substance occurs does not require large capital expenditures and additional bureaucracy. Every state has the basic tools required to ensure protection of their natural resource interests. For example, each state has some form of a Department of Natural Resources or equivalent agency. This department, along with assistance from universities within the state, can provide the technical resources required to determine the impacts of a hazardous substance release on the natural environment. States also have an office of the attorney general. This office can provide the legal resources to hold those persons responsible for resultant harm from the release of a hazardous substance.

What many states do not have in place, however, is the comprehensive statutory language needed to adequately recover the monies for restoration of injured, lost or destroyed natural resources. While the specific language and approach of individual state's statutes will vary, said statutes should, at a minimum, address the following: who is the trustee and what is the level of response authority; how is the injury, destruction or loss to be assessed; liability for injury, loss or destruction of a natural resource to pre-release levels; punitive damages and/or criminal penalties for recalcitrant responsible parties; if the state has a hazardous substance response fund, provide access to the fund monies for restoration, replacement, etc. of natural resources.

Of the 15 states discussed in this paper for their statutory approach to protect natural resource interests, the following five should be considered noteworthy: Minnesota, North Carolina, Pennsylvania, South Dakota and Washington. These state statutes, along with the language of CERCLA/SARA, should be utilized to derive a series of statutes that will adequately protect the natural resources located within an individual state.

REFERENCES

1. 42 USC §9607(a)(4)(C) holds a person liable for "damages for injury to, destruction of, or loss of natural resources, including the reasonable costs of assessing such injury, destruction, or loss resulting from such a release, and . . ."
2. 42 USC §301(c)(1), (2). The President delegated the authority to promulgate natural resource damage assessment regulations to the U.S. Department of the Interior.
3. 43 CFR §11.10 through 11.93 (1987).
4. 42 USC §9651(c)(1), (2).
5. 53 F.R. 5166 (1988).
6. Type B Regulations - Ohio et. al. v. U.S. Department of the Interior, No. 86-1529 (D.C. Cir. 1989). Type A regulations - Colorado v. U.S. Department of the Interior, No. 87-1265 (D.C. Cir. 1989).
7. Id., note 6.
8. Colorado v. Idarado Mining Co., 707 F. Supp. 1227 (D.C. Colorado 1989).
9. Landreth, Lloyd W., Recovery for Natural Resource Damages on Superfund Sites, p. 605 n. 8, *Hazardous Materials Control Research Institute, 9th National Conference Proceedings*, 605-607 (November 1988).
10. The third caveat is that a statute may have been so obscured within a general area of law that it was never uncovered.
11. This is not to say that a federal district court residing in the state would not be any less competent in matters of state law.
12. For the CERCLA/SARA definition of natural resources see 42 USC §9601(16).
13. West's California Code, Health and Safety Code §25352 (1989).
14. Id at 25359, 25359.1.
15. Id at Harbors and Navigation Code §293 (1989).
16. Colorado Revised Statutes §25-16-104.7, 201 (1988).
17. Connecticut General Stat. Ann. §22a-6a, 6b (1989).

18. Iowa Code Annotated §455 B.392 (1989).
19. Louisiana Constit. Article IX, §1.
20. Maine Revised Stat. Ann. Title 38, §1367 (1988).
21. Ann. Code of Maryland. Environment §7-222 (1988).
22. Id at §7-220-221 (1988).
23. Massachusetts General Laws Ann. Chapter 21 E §5 (1989).
24. Id at Chapter 214 §7A (1989).
25. Minnesota Stat. Ann. §115B.04 (1989).
26. Id at 115B.17.
27. Id at 115B.20.
28. Montana Stat. Ann. §75-10-715 (1988).
29. Id at §75-10-711 (1988).
30. General Stat. of N. Carolina, Art. 21A §143-215.90 (1989).
31. Id at §143-215.91 (1989).
32. Oregon Revised Stat. Ann., Hazardous Waste and Materials, Chapter 466.890 (1988). While this statute is roughly on point, the prices for these natural resources are likely low compared to restoration value.
33. Purdon's Pennsylvania Stat. Ann. Constitution Art. 1 §27.
34. 34 Purdon's Pennsylvania Stat. Ann. §6020.702 (1989).
35. Id at 35 P.S. §6020.902 (1989).
36. Id at 34 P.S. §2161 (1989).
37. South Dakota Codified Laws, Chapter 34A-10, §34A-10-1 through 10-15 (1989).
38. Revised Code of Washington Annotated, Title 90, §90.48.142 (1989).
39. See note 6.

Institutional Controls of Waste Sites: The Groundwater Management Zone

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ABSTRACT

The management of waste sites which are contaminating groundwater typically involve source control or removal, and aquifer restoration. Generally this process relies on federal authority and involves the expenditure of massive amounts of money. All too often, these expenditures far exceed any damages or even potential damages they are intended to rectify or prevent. Further, they do not preclude inappropriate future occupation of the site and potential future exposure to contaminants.

Usually, the protection of human health and the environment can be accomplished just as adequately—and far less expensively—by using alternate unthreatened water supplies in combination with State and local authorities controlling well construction, water withdrawals and land use. In fact, such controls should be considered for application to any waste-related case of groundwater contamination regardless of other remedial activities.

The employment of state water controls and local land use restrictions to create groundwater management zones has been undertaken in Delaware as a means of protecting existing and future local residents from exposure to contaminated groundwater near waste sites. These same state and local authorities have been used to augment federal authority at Superfund sites as well as to manage groundwater contamination situations where federal authority was not thought to bear.

INTRODUCTION

Groundwater contamination has been documented at many sites of past waste disposal. It can be argued that groundwater contamination is the inevitable result of past waste disposal practices where little effort was employed to minimize water entrance to the waste and prevent leachate percolation to the subsurface. However, this groundwater contamination is virtually always a local problem for which local tailored solutions are the most efficient.

Sometimes the contamination from old waste sites is of such a toxic and persistent nature and of such considerable area extent that valuable aquifers and, in a relatively few cases, high capacity water supplies, are affected by the contaminants. Sometimes, but even less commonly, the groundwater contaminants discharge into streams at rates sufficient to degrade stream quality to the point that uses are impaired. However, the loss of irreplaceable groundwater supplies to contamination is rare and adverse impacts on major streams or significant segments of minor streams is even less frequent.

Nonetheless, the typical public and governmental response to the discovery of groundwater contamination at abandoned waste sites is to insist on cleanup. The cleanup process often involves the invocation of the federal Superfund program or its state equivalents. These processes entail a comprehensive investigation of the nature and extent

and existing and potential impacts of contamination, an assessment of alternatives, selection of a remedy (usually designed to achieve strict cleanup levels on-site), implementation of remedial action(s) and long-term operation, maintenance and monitoring. The cost for a single site in this process averages approximately \$20 million per site¹.

Fortunately, the majority of cases of groundwater contamination from old waste sites have limited the relatively minor adverse impact on water supplies and the environment. Ninety-five percent of Delaware is in the Atlantic Coastal Plain, much of which is blanketed by permeable unconsolidated sands and annual recharge averages 12 to 16 in./yr. Water supplies in the coastal plain are derived from water wells, so groundwater is both vital for the health and economy and is often very vulnerable to contamination. Even so, few of the Superfund sites have impacted major wells or even threatened aquifers capable of supporting large supply wells.

The typical effect of old waste sites is a contaminant plume of relatively limited area which extends downgradient to or towards nearby streams. Generally, however, the concentrations of many contaminants are effectively reduced below levels of detection and/or concern during transport through porous earth materials. In fact, natural attenuation of contaminants is sufficient in many areas to adequately treat groundwater before it reaches a water supply well or discharges to a stream. In several cases, nearby wells have been contaminated or are threatened by contamination to a degree which would render the water unsuitable for use without treatment.

Although volatile and semi-volatile organic compounds generally are present in the leachate of these waste sites in concentrations objectionable for public water supply, these compounds rarely are present in appreciable concentrations in groundwater downgradient of the sites and have little or no significant impact on local streams. The most common objectionable off-site contaminants in the groundwater are dissolved inorganics, iron and/or manganese. Although relatively mundane, these contaminants still render local groundwater unfit for use without treatment. Treatment costs for iron removal typically are greater than for removal of dissolved organics. Also, individual well water treatment systems usually exchange sodium for the dissolved iron, increasing the intake of a substance linked to high blood pressure.

In most cases, locally contaminated or threatened water wells can be replaced by deeper wells or by the extension of a public water system whose source is not threatened by the contaminants. The cost of providing alternative safe water supplies by use of treatment or replacement is typically only a fraction of the costs to remove or control the contaminant source and to decontaminate the aquifer to a quality suitable for use at the waste site boundary.

The only practical dilemma with a cost-effective remedy of providing safe replacement water supplies is the potential for future occupation

of the waste site or drilling of water wells in the contaminant plume. However, the incorporation of state authority over water development and local controls over land-use make it possible to prevent future exposure to the contaminants.

The use of both state and local authorities to prevent the exposure to contaminants is prudent regardless of whether an outright no-action alternative is followed or a very complicated and lengthy remedial alternative is selected. In either case, some form of controls to prevent water well development or inappropriate land-use are warranted. Restriction of land and water uses will prevent further exposure to contaminants both on-or off-site. Typically, remedial actions require many years to complete and even longer to achieve desired results.

APPLICABLE STATE WATER MANAGEMENT POLICIES

State water management policies vary considerably. However, good policy should support a practical, common sense approach to problem solving. Delaware's official Groundwater Management Policy states that "The geologic materials which comprise an aquifer possess a limited capacity to attenuate certain contaminants. This capacity should be considered in remedial actions for existing incidents of groundwater contamination...if (the abilities of earth materials to attenuate contaminants) are judged effective, then dependence on these properties may be a workable remedial strategy." It also states that "groundwater quality management should be integrated with the management of water supplies such that one activity does not contravene another."³

The state groundwater management plan takes the position that "Delaware's official water management policy allows consideration of the use of earth materials to attenuate contaminants in groundwater if (1) no environmental harm results and (2) water supply development is integrated with waste management so that wells do not draw water with objectionable concentrations of contaminants"... or further, "Based on the costs and limited success of groundwater recovery programs, an alternative to pumping and treating contaminated groundwater should be developed."⁴

Adequate protection - not cost - should be the primary consideration in any contamination management program. We should remember that the key role of government in managing water and wastes is to prevent the exposure of unacceptable levels of contaminants to people or the environment. In Delaware, this state goal is expressed as "to ensure sufficient groundwater quality for the protection of public health and for such beneficial uses as may be desired, including the preservation of significant ecological systems, now and in the future."⁵

This goal can be accomplished by requiring safe sources of water for users in areas of contamination and preventing the development of wells or activities near or on waste sources to prevent exposure to the contaminants. The basic concept for groundwater contamination management zones is not new⁷. In fact, the avoidance of contaminant plumes by provision of alternate water has been a traditional though unofficial response to cases of groundwater contamination. Besides effectively preventing exposure to contaminants, this approach usually is at least an order of magnitude less expensive than major waste source controls, groundwater decontamination and continuous extensive monitoring of groundwater quality.

The authorities to regulate water supply development and to restrict land use traditionally have been vested with state and local governments, respectively. In Delaware, the authority to regulate water supplies rests with DNREC and includes:

- Licensing of water well contractors
- Requiring permits to construct all wells
- Issuance of permits for well construction only to licensed water well contractors
- Requiring a separate water withdrawal permit for withdrawal rates greater than 50,000 gpd

The authority to regulate land-use exists at the county and municipal levels. These local authorities include land-use planning, zoning and building and occupancy permits. Additionally, local authorities can insert use restrictions into property deeds.

Delaware's groundwater management plan concludes by stating that

"regulatory controls, existing policy and economic practicality would allow natural attenuation of contaminants from existing waste sites in groundwater where 1) such attenuation would have no significant adverse impact on public water supply sources, potential water supply sources, the ecosystem, or aquatic life; and 2) uncontaminated water would be available to meet existing and future water supply needs." These conditions can be met in a number of instances⁴.

To bring existing state and local authorities are brought to bear on managing groundwater contamination by attenuation without contaminating any water supplies, a joint effort of several agencies is required. These include:

- Delineation of a contaminant attenuation/well restriction zone by the state's Department of Natural Resources and Environmental Control in cases where groundwater contaminants would have no significant impact on the environment at the point of discharge to the surface. Use of land-use controls by local governments to ensure that homes are not build and occupied in the restriction zones unless a safe, uncontaminated source of water is available to the occupants.
- A commitment by the party(ies) responsible for the contamination to provide a safe, uncontaminated water supply to those water users in the well restriction zone.

"Where these conditions are met and the controls previously outlined can be jointly arranged by the parties, groundwater attenuation/well restriction zones should be formally delineated to manage incidents of groundwater contamination."⁴

Groundwater management zones have been officially designated at several abandoned waste disposal sites in Delaware¹ including, recently, a Federal Superfund site. These designations have included the delineation of areas in which existing threatened wells must be replaced and no future threatened wells can be constructed (these include negotiations to include deed notices and deed restrictions) and the provision of alternate safe water supplies at the expense of the responsible party. These designations have been made at sites addressed entirely by the state's environmental regulatory authority and at a Superfund site by incorporation into the Record of Decision.

CASE 1: SUSSEX COUNTY LANDFILLS (BRIDGEVILLE LANDFILL)

During the 1970s the Sussex County government operated six landfills for the disposal of solid waste generated in the county. These landfills were unlined and were constructed in permeable sandy soils with shallow water tables. Monitoring wells installed at the landfills detected contamination of groundwater beneath and adjacent to each site. This contamination included low concentrations of hazardous substances and highly elevated dissolved solids and iron concentrations. These latter contaminants render the water immediately downgradient of the landfills unfit for water supply purposes. However, little adverse impact is observed or anticipated in streams to which the landfill contaminated groundwater is or will be discharging.

The contaminants from landfills which about streams are discharged with groundwater directly to the streams baseflow. There is little potential for these landfills (Omar, Stockley and Anderson's Crossroads) to contaminate groundwater supplies. The impact on surface water—though detectable—is not significantly adverse to biota or other possible uses of the streams. The other landfills (Bridgeville, Laurel and Angola) have groundwater flow paths extending up to several thousand feet to streams into which they discharge. The landfill-contaminated groundwater from these sites will have no detectable impact on the surface waters to which they eventually will discharge, but do threaten existing and possible future groundwater supplies.

Generally little groundwater development occurs downgradient of these landfills (which are in rural areas). However, a few wells do exist in the unconfined aquifer in areas threatened by contamination and additional future development is possible. A report documenting the groundwater conditions at these sites was required by the state. The county's report⁸ documented these conditions and recommended the establishment of Groundwater Management Zones (GMZs).

Subsequently, the State of Delaware and Sussex County executed

a Memorandum of Understanding¹ establishing the GMZs as a practical, cost-effective and sure way of resolving the threat of water contamination posed by the landfills. The GMZs consist of three concentric areas, drawn (on maps) for each of the landfill sites, wherein groundwater withdrawal rates and well designs are regulated. The GMZs are designated as follows:

- "No well zone:" all wells prohibited from the unconfined aquifer;
- "GMZ A:" wells screened in the unconfined aquifer to be pumped at a rate of 10 gpm are prohibited;
- "GMZ B:" wells screened in the unconfined aquifer to be pumped at a rate of more than 100 gpm are prohibited.

The principal points of this agreement provide that:

- Permit applications for wells to be located in the "no well zone" may be issued only after a joint review has been conducted by the DNREC and Sussex County. Where (1) a central public water supply is available well permits will be denied; or (2) public water will be available within five years of the request for water service, a well permit may be issued by DNREC and continued that it be abandoned once public water is available; or (3) public water is not provided, a method of supplying water safe from landfill contamination, such as a double-cased well screened in a confined aquifer, may be permitted by DNREC.
- Sussex County must replace all existing wells (with the exception of irrigation wells) located in the "no well zone" and screened in the unconfined aquifer with either a public water supply of acceptable quality or an alternative source such as double-cased well in a confined aquifer. A schedule for accomplishing this work prioritized according to threatened wells was required within 6 mo of the date of execution of the MOU. This well replacement schedule had to be such that existing wells will be free from contamination at all times. Existing irrigation wells in GMZs had to be investigated to determine the effects of such pumping, and the county and DNREC were to determine the best course of action to be taken.

For new wells that would, but for the landfill contamination or threat of contamination, be constructed within a "no well zone," Sussex County must pay the difference in cost between a water supply like the cost of a typical domestic well completed in the unconfined aquifer and one safe from landfill contamination, such as a double-cased well in a confined aquifer or an extension of an acceptable public water supply. This requirement did not include properties that are leased, transferred or subdivided after the notification or property restrictions are provided by Sussex County.

Sussex County had to create, within 6 mo of the execution of this MOU, a procedure that would indicate that a particular parcel is located within a GMZ when a proper title search is performed. Additionally, the county had to develop, within the same six month period, other mechanisms (deed restrictions, zoning requirements, etc.) that will alert potential buyers to the intent and content of this MOU.

The Bridgeville Landfill received mixed municipal, residential and industrial solid waste between 1968 and 1984. Wastes were buried in unlined trenches excavated in sandy loam soil to the top of the zone of saturation (approximately) 10 ft below ground surface). The landfill covers approximately 135 ac.

The unconfined (Columbia) aquifer is an unconsolidated, medium textured, predominantly quartz sand which was deposited by Quaternary streams. The aquifer has a saturated thickness in the vicinity of the Bridgeville landfill of approximately 120 ft and a transmissivity of about 83,000 gpd/ft.

No deeper aquifers have been explored locally because of the high productivity and generally excellent water quality of the unconfined aquifer. Regionally, deeper aquifers often contain water with objectionable concentrations of (naturally occurring) iron.

The water table beneath the Bridgeville landfill slopes toward the Nanticoke River as shown in Figure 1. The Nanticoke functions as the regional groundwater drain.

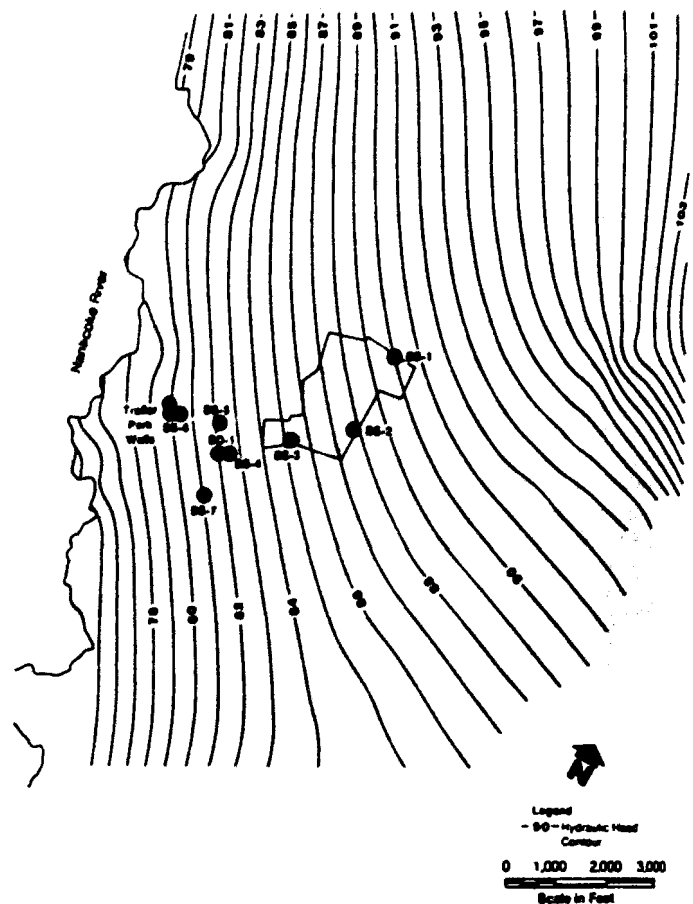


Figure 1
Calibrated Hydraulic Head Distribution for Bridgeville Landfill

Groundwater beneath and immediately downgradient of the Bridgeville landfill contains objectionably high concentrations of iron and has a putrescible odor. The maximum concentrations of priority pollutant volatile and semivolatile organics total less than 100 μL . This water is unsuitable for supply to the growing trailer park and individual residences downgradient of the landfill. However, it will not have any significant adverse (or likely, even detectable) impact on the Nanticoke River because of attenuation prior to reaching the river and dilution with the river water.

The GMZs for the Bridgeville Landfill are shown in Figure 2. The proposed source of safe alternate water supply for existing and future water users within the GMZ is a public wellfield located north of an outside the GMZ. A water transmission main will extend from this new wellfield to the threatened water users. Because of the number of threatened water users, the Bridgeville landfill is the number one priority of the Sussex County government. The new replacement public water system is scheduled for completion during 1990.

CASE 2: WILDCAT LANDFILL

The Wildcat Landfill was a privately owned and operated landfill which accepted both municipal and industrial wastes from 1962 until 1973. Following its inclusion on the NPL in 1982, an RI/FS² was conducted followed by two RODs in June and November, 1988. The remedial action selected for the landfill and the adjacent areas was detailed in the June, 1988 ROD. Besides the general requirements for alleviating problems at the landfill, the ROD specified the need for administrative and institutional controls both upon the landfill and in areas adjacent to the landfill which were susceptible to groundwater contamination originating from the landfill. Figure 3 shows the general features of the landfill flow.

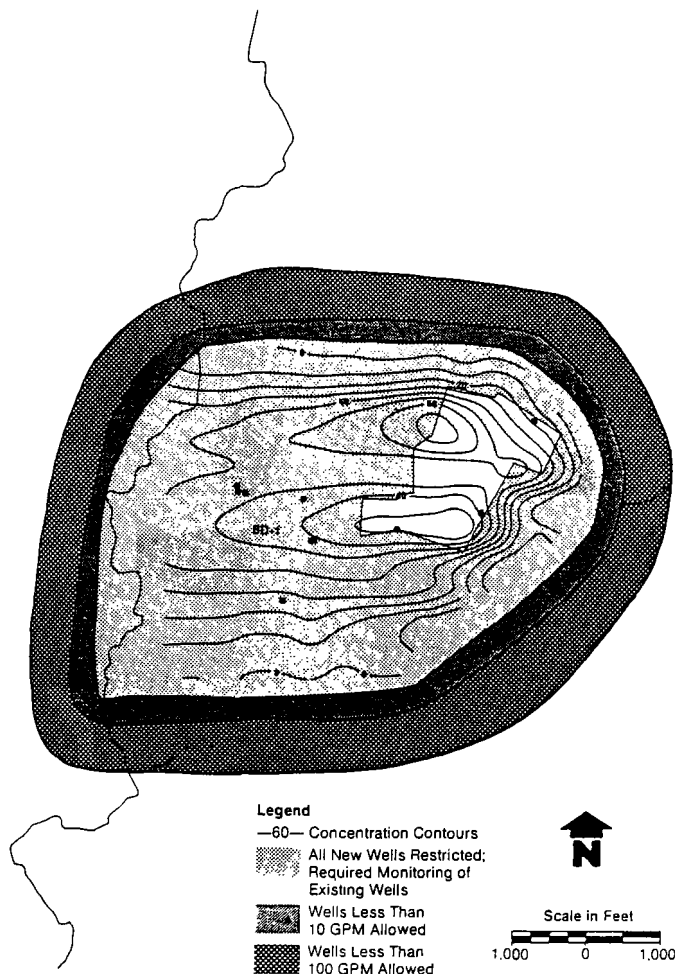


Figure 2
Groundwater Restriction Zone
for Bridgeville Landfill
(Weston, 1987)

Since the source of contamination, the landfill, was not to be removed, surficial aquifer which was affected by the off-site movement of contaminants was of very limited useable value and since the landfill discharges into nearly surface water bodies, administrative and institutional controls were deemed to be an appropriate and cost-effective approach to preventing human exposure from contaminated groundwater. Contaminated groundwater discharged directly into the St. Jones River and Tidbury Creek where contaminant levels would not likely exceed federal limits.

The administrative and institutional controls associated with the selected remedy included the following:

- Water well installation (except monitor wells) would not be permitted within the landfill boundary;
- Water wells within the shallow, unconfined aquifer in areas down-gradient and other nearby areas would not be permitted. Deep wells constructed in to the local confined aquifers may be permitted provided special conditions established the DNREC are met (e.g., double cased);
- Existing shallow wells within the GMZs are to be replaced by the responsible party with deep wells screened in a confined aquifer;
- Commercial and residential building on the landfill would not be permitted;
- Governmental agencies would work toward obtaining agreements from property owners to have restrictive language placed into deeds to prevent future building or other activities which could expose humans to landfill wastes or contaminants in the water.

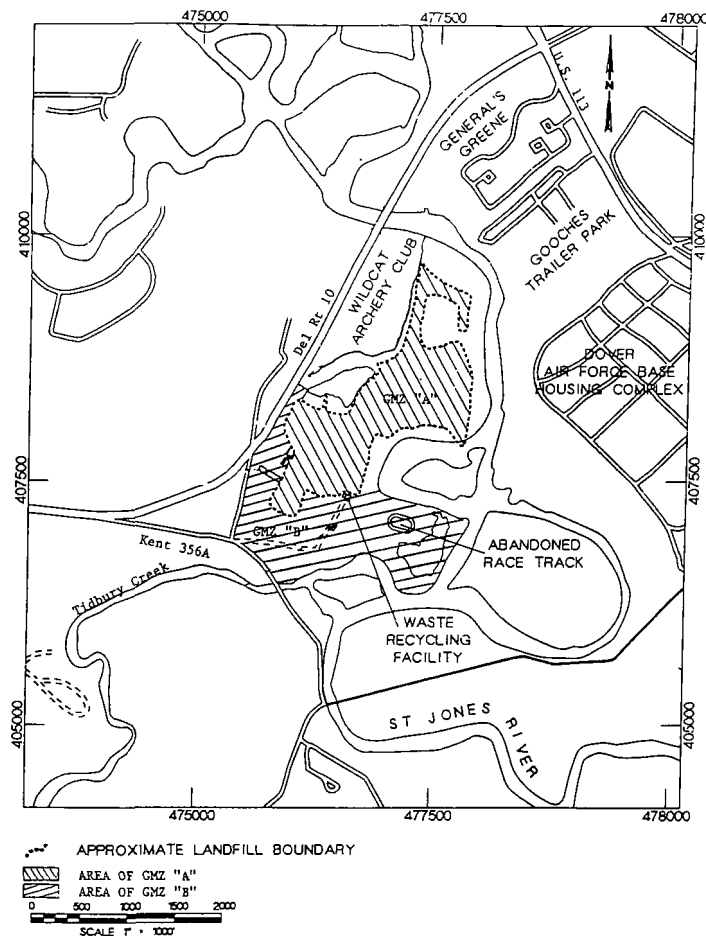


Figure 3
Groundwater Management Zone for the Wildcat Landfill
Superfund Site (After CH2M Hill, 1988)

Both DNREC and DPA recognized that some form of institutional control was necessary to prevent future exposure to the population in the future. Although the general guidelines for some form of control were mentioned in the ROD, it was left to DNREC to develop the specific mechanism for developing reliable controls. DNREC had recently concluded the agreement (Case 1) with Sussex County. In the case of the Wildcat Landfill, however, the landfill had been privately owned and operated.

To meet the requirements of the ROD, DNREC developed an internal mechanism for ensuring that water wells were not constructed within the restricted areas. A Memorandum of Agreement (MOA) was formalized between state agencies responsible for management of the Superfund program and for groundwater management programs. This agreement⁶ defined the groundwater management zones (GMZs) associated with the landfill and adjacent areas. Figure 3 illustrates the GMZs established in the agreement:

- GMZ "A": areas where no water wells are permitted, except for monitor wells
- GMZ "B": areas where no shallow water wells are permitted but where deep wells may be permitted following joint review of the permits by the DAWM and the DWR

A copy of this agreement was subsequently provided to U.S. EPA and included in the administrative record for the site.

Concurrent with the purely administrative nature of the MOA, DNREC and U.S. EPA negotiated with a PRP group to implement the

remedies selected in the RODs for the landfill and an adjacent pond. The PAP group for the Wildcat landfill included the property owner. Consequently, DNREC and U.S. EPA requested that the owner voluntarily include restrictive language into the property deed which, among other things, served notice to future property owners of the presence of landfill areas.

The MOA complimented the voluntary cooperation of the property owner in providing the restrictive language in placing "permanent" controls on preventing future exposure to contaminants both on the site and adjacent to the site.

CONCLUSIONS

The formal designation of groundwater management zones has been made at several abandoned waste disposal sites and one Superfund site in Delaware. These zones include portions of an aquifer in which contaminants will be allowed to attenuate, existing threatened water wells must be replaced new threatened water wells are prohibited and supply of water to existing and future occupants of the zones is provided from an unthreatened source by the responsible party.

These GMZs are a creative, practical, adequate, cost-effective alternative or supplement to a remedial alternative. However, as Delaware's Groundwater Management Plan cautions:

"Obviously not all contamination instances will allow for a groundwater attenuation/well restriction zone remedial management alternative. If, after transportation and attenuation in the subsurface, groundwater used for supply purposes or in the protection and propagation of aquatic organisms fails to meet the criteria for its designated use and no alternative water source is available, corrective actions may be required.

The choice between corrective action and a groundwater attenuation/well restriction zone option must be made on a case-by-case basis after careful consideration of the technical and administrative merits of each case. Clearly, the intent in both management options is the protection of human health and the environment."

DISCLAIMER

Any opinions expressed are those of the authors' and are not necessarily those of the State of Delaware Department of Natural Resources and Environmental Control.

REFERENCES

1. Appgar, M. A. and Cherry P.J., Jordan J.H. and S. N. Williams, "The Groundwater Management Zone - An Alternative to Costly Remediation," Groundwater Monitoring Review, 1988.
2. CHEM Hill Southeast, Inc. *Wildcat Landfill Remedial Investigative Report*, Vol. 1, 1988.
3. Delaware Department of Natural Resources and Environmental Control, "Groundwater Quality Management." From The Management of Water Resources in Delaware (officially adopted as DNREC policy). Prepared under the Direction of the Comprehensive Water Resources Management Committee, 1983, 100 pp.
4. Delaware Department of Natural Resources and Environmental Control. *State of Delaware Groundwater Management Plan*, 1987, 42 pp.
5. Delaware Department of Natural Resources and Environmental Control, "Memorandum of Understanding Between Sussex County and the Delaware Department of Natural Resources and Environmental Control," executed Aug. 9, 1988, 3 pp.
6. Delaware Department of Natural Resources and Environmental Control, "Memorandum of Agreement Between the Division of Air and Waste Management and the Division of Water Resources: Wildcat Landfill Groundwater Management Zones," 1989, 2 pp.
7. Landon, R. A., "Waste Disposal Zoning," Presented at the NWWA Annual Convention, Boston, MA, 1977.
8. Weston, Roy F., Inc., "Groundwater Management Investigations for Six Sussex County Landfills, Final Report prepared for Sussex County Delaware," December, 1987, 250 pp.
9. U.S. EPA, 40 *CFR* Part 300 "National Priorities List for Uncontrolled Hazardous Waste Sites - Final Update No. 5," *Federal Register* 54, (61), p. 13304, 1989.

Implementation of Permanent Remedies in New York State

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ABSTRACT

The use of destruction/treatment technologies at inactive hazardous waste sites has been underutilized primarily as a result of the cost of such technologies. SARA and RCRA, which restrict land burial, provide incentives to use treatment technologies in remedial programs. SARA clearly gives preference to treatment technologies "that, in whole or in part, will result in a permanent and significant decrease in the toxicity, mobility, or volume of hazardous substances, pollutants or contaminants," to the maximum extent practicable. The State of New York strongly supports this position. A New York State guidance document expected to be adopted in September of 1989 uses the same criteria to evaluate and analyze remedial alternatives, proposed in the revised NCP, dated Dec. 12, 1988; however, there are significant major differences between the proposed NCP and New York State's guidance document.

INTRODUCTION

The use of treatment technologies at Inactive Hazardous Waste Sites has been underutilized primarily as a result of the cost of such technologies. SARA and RCRA, which restrict land burial, provide incentives to use treatment technologies in remedial programs. SARA requires that preference be given to remedies that permanently reduce the toxicity, volume or mobility of the hazardous substances, pollutants or contaminants, and to remedies using alternative treatment technologies (SARA Section 121). In addition, the 1984 amendments to RCRA restricted land disposal of all listed hazardous wastes by 1991.

A New York State Department of Environmental Conservation (NYSDEC) guidance document which is expected to be adopted in September 1989 uses the same criteria to evaluate and analyze remedial alternatives proposed in the revised NCP, dated Dec. 21, 1988; however, there are significant differences between the proposed NCP and the guidance document. This document presents detailed guidelines for evaluation and selection of remedial alternatives for some on-going and all new RI/FS projects at Federal Superfund, State Superfund and PRP sites. NYSDEC would consider exempting an inactive hazardous waste site from this document if deemed appropriate. For example, if a remedial action for a site is readily apparent, it would not be beneficial in selecting remedies in accordance with this guidance document.

IMPLEMENTATION OF REMEDIAL ACTIONS

In order to eliminate the significant threat to public health and the environment, NYSDEC prefers to implement permanent

remedies in accordance with SARA's preference for treatment technologies, wherever practicable. When remedies such as conventional isolation and/or control technologies are selected, the ROD shall discuss why a remedial action resulting in a permanent and significant reduction of the toxicity, volume or mobility of hazardous wastes was not selected.

If a remedial action that leaves any hazardous wastes at the site is selected, such remedial action shall be reviewed no less than once each 5 yr after completion of the remedial action; this review will take place in addition to the regularly scheduled monitoring and operation and maintenance, even if the monitoring data indicate that the implemented remedy does not contravene any "cleanup criteria or standards." The objective of the review will be to evaluate if the implemented remedy protects human health and the environment and to identify any "permanent" remedy available for the site. In addition, if upon such review, it is determined that action is appropriate at such site, New York State shall take or require such action. Before taking or requiring any action, all interested parties including the responsible parties and the public shall be provided an opportunity to comment on New York State's decision.

Hierarchy of Remedial Technologies

The following provides the hierarchy of remedial technologies for hazardous waste disposal sites, from most desirable to least desirable. The Department shall consider only destruction or separation/treatment or solidification/chemical fixation of inorganic wastes as permanent remedies. However, solidification/chemical fixation of wastes containing "low" level organic constituents may be considered as a permanent remedy if justified.

Destruction

This type of remedy will irreversibly destroy or detoxify all or most of the hazardous wastes to "acceptable cleanup levels." The treated materials will have no residue containing unacceptable levels of hazardous wastes. This type of remedy will result in permanent reduction in the toxicity of all or most of the hazardous wastes to "acceptable cleanup level(s)."

Separation/Treatment

This type of remedial action will separate or concentrate the hazardous wastes from the wastes; this remedy would leave a treated waste stream with acceptable levels of hazardous wastes and a concentrated waste stream with high levels of contaminants—e.g., treatment of contaminated leachate by granulated activated carbon. This type of remedy will result in permanent and

significant reduction in volume of hazardous wastes. In these instances where the concentrated waste stream can be destroyed or detoxified, preference shall be given to this additional treatment.

Solidification/Chemical Fixation

This type of remedy will, for a site containing predominantly inorganic hazardous wastes, significantly reduce the mobility of inorganic hazardous wastes. This type of remedy may not significantly reduce the toxicity or volume of the inorganic hazardous wastes, but will significantly and permanently reduce the mobility and hence the availability of the inorganic hazardous wastes to environmental transport and uptake.

Control and Isolation Technologies

This type of remedial action will significantly reduce the mobility of the hazardous wastes, but will not significantly reduce the volume or toxicity of the hazardous wastes. It also includes construction of a physical barrier to control migration of leachate, contaminated groundwater and surface runoff, solidification/fixation of organic hazardous wastes and pumping and treatment of contaminated leachate/groundwater.

In evaluating treatment technologies, NYSDEC shall give or require that preference be given to technologies which have: (1) been successfully demonstrated on a full-scale or a pilot-scale under the Federal Superfund Innovative Technology Evaluation (SITE) Program; (2) been successfully demonstrated on a full-scale or pilot-scale at a Federal Superfund site, at a Federal facility, at a State Superfund site anywhere in the country or at a PRP site overseen by a State environmental agency or U.S. EPA; (3) a RCRA Part B permit; (4) a RCRA Research and Development permit; or (5) a documented history of successful treatment, such as a granulated activated carbon unit.

DEVELOPMENT OF REMEDIAL ALTERNATIVES

Alternatives typically are developed concurrently with the RI. This process should consist of five general steps briefly presented below:

- Develop remedial action objectives specifying the contaminants and media of interest and exposure pathways. The objectives developed are based on contaminant-specific cleanup criteria and ARARs.
- Develop general response actions for each medium of interest that may be taken to satisfy the remedial action objectives for the site or specific operable unit.
- Identify volumes or areas of media to which general response actions might be applied, taking into account the requirements for protectiveness as identified in the remedial action objectives and the chemical and geological characterization of the site or a specific operable unit.
- Identify and screen the technologies applicable to each medium of interest to eliminate those technologies that cannot be implemented technically at the site for that medium.
- Assemble the selected representative technologies into appropriate remedial alternatives.

Initial set of alternatives developed shall include appropriate remedial technologies that are representative of each of the four categories of remedial technologies as described previously.

PRELIMINARY SCREENING OF REMEDIAL ALTERNATIVES

The objective of remedial alternatives screening is to narrow the list of potential alternatives that will be evaluated in detail. Hence, alternatives will be evaluated more generally in this phase than during the detailed analysis. In some situations, the number of viable alternatives to address site problems may be limited such that screening may be unnecessary or minimized. During the

screening, the extent of remedial action (e.g., quantities of media to be affected), the sized and capacities of treatment units and other details of each alternative should be further defined, as necessary, to conduct screening evaluations.

Individual remedial technologies should be screened primarily on their ability to meet medium-specific remedial action objectives, their implementability and their short-term and long-term effectiveness. At this time, cost will not be used to screen remedial technologies or alternatives.

Effectiveness Evaluation

Each alternative should be evaluated as to the extent to which it will eliminate significant threats to public health and the environment through reductions in toxicity, mobility and volume of the hazardous wastes at the site. Both short-term and long-term effectiveness should be evaluated; short-term referring to the construction and implementation period, and long-term referring to the period after the remedial action is in place and effective.

The expected lifetime or duration of effectiveness should be identified for each alternative. The control and isolation technologies may fail if any of the following is expected to take place: (1) significant loss of the surface cover such as clay cap with a potential for exposure of waste material underneath the cap; (2) contamination of the groundwater by the leachate from the waste material; (3) contamination of the adjoining surface water by the leachate from the waste material or by the contaminated groundwater; or (4) structural failure of the control or isolation technology.

Table 1 should be used in evaluating the effectiveness of each alternative in protecting human health and the environment. If an alternative is scored less than 10 out of a maximum score of 25, the project manager may consider rejecting that remedial alternative from further consideration.

Table 1
Short-Term/Long-Term Effectiveness
(Maximum Score = 25)

Analysis factor	Basis for Evaluation During Preliminary Screening	Score
1. Protection of community during remedial actions	<ul style="list-style-type: none"> • Are there significant short-term risks to the community that must be addressed? (If answer is no, go to Factor 2.) <ul style="list-style-type: none"> Yes <input type="checkbox"/> 0 No <input type="checkbox"/> 4 • Can the short-term risk be easily controlled? <ul style="list-style-type: none"> Yes <input type="checkbox"/> 1 No <input type="checkbox"/> 0 • Does the mitigative effort to control short-term risk impact the community life-style? <ul style="list-style-type: none"> Yes <input type="checkbox"/> 0 No <input type="checkbox"/> 2 	
Subtotal (maximum = 4)		
2. Environmental impacts	<ul style="list-style-type: none"> • Are there significant short-term risks to the environment that must be addressed? (If answer is no, go to Factor 3.) <ul style="list-style-type: none"> Yes <input type="checkbox"/> 0 No <input type="checkbox"/> 4 • Are the available mitigative measures reliable to minimize potential impacts? <ul style="list-style-type: none"> Yes <input type="checkbox"/> 3 No <input type="checkbox"/> 0 	
Subtotal (maximum = 4)		
3. Time to implement the remedy.	<ul style="list-style-type: none"> • What is the required time to implement the remedy? <ul style="list-style-type: none"> ≤ 2yr. <input type="checkbox"/> 1 > 2yr. <input type="checkbox"/> 0 • Required duration of the mitigative effort to control short-term risk. <ul style="list-style-type: none"> ≤ 2yr. <input type="checkbox"/> 1 > 2yr. <input type="checkbox"/> 0 	
Subtotal (maximum = 2)		
4. Permanence of the remedial alternative.	<ul style="list-style-type: none"> • Will the remedy be classified as permanent in accordance with Section 2.1(a), (b), or (c). (If answer is yes, go to Factor 5.) <ul style="list-style-type: none"> Yes <input type="checkbox"/> 5 No <input type="checkbox"/> 0 	
Subtotal (maximum = 5)		

Implementability Evaluation

Implementability is a measure of both the technical and administrative feasibility of constructing, operating and maintaining a remedial action alternative. Technical feasibility refers to

(1) the ability to construct, reliably operate and meet technical specifications or criteria and (2) the availability of specific equipment and technical specialist to operate necessary process units. It also includes operation, maintenance, replacement and monitoring of technical components of an alternative, if required, into the future after the remedial action is complete. Administrative feasibility refers to compliance with applicable rules, regulations and statutes and the ability to obtain approvals from other offices and agencies, the availability of treatment, storage and disposal services and capacity.

Determination that an alternative is not technically feasible and not available for implementation will preclude it from further consideration unless steps can be taken to change the conditions responsible for the determination. Often, this type of fatal flaw would have been identified during technology development, and an alternative which is not feasible would not have been assembled. Remedial alternatives which will be difficult to implement administratively will not be eliminated from further consideration for this reason alone.

Implementability of each remedial alternative should be evaluated using Table 2. If an alternative does not score a minimum of eight out of a possible maximum score of 15, then the Project Manager has the option of screening out this alternative from further consideration.

Table 1 (continued)
Short-Term/Long-Term Effectiveness
(Maximum Score = 25)

Analysis Factor	Basis for Evaluation During Preliminary Screening	Score
5. Lifetime of remedial actions.	o Expected lifetime or duration of effectiveness of the remedy.	25-30yr. ____ 4 20-25yr. ____ 3 15-20yr. ____ 2 < 15yr. ____ 0
Subtotal (maximum = 4)		
6. Quantity and nature of waste or residual left at the site after remediation.	i) Quantity of untreated hazardous waste left at the site.	None ____ 3 < 25% ____ 2 25-50% ____ 1 > 50% ____ 0
	ii) Is there treated residual left at the site? (If answer is no, go to Factor 7.)	Yes ____ 0 No ____ 2
	iii) Is the treated residual toxic?	Yes ____ 0 No ____ 1
	iv) Is the treated residual mobile?	Yes ____ 0 No ____ 1
Subtotal (maximum = 5)		
7. Adequacy and reliability of controls.	i) Operation and maintenance required for a period of:	< 5yr. ____ 1 > 5yr. ____ 0
	ii) Are environmental controls required as a part of the remedy to handle potential problems? (If answer is no, go to "iv")	Yes ____ 0 No ____ 2
	iii) Degree of confidence that controls can adequately handle potential problems.	Moderate to very confident ____ 1 Somewhat to not confident ____ 0
	iv) Relative degree of long-term monitoring required (compare with other remedial alternatives evaluated in the Detailed Analysis).	Minimum ____ 2 Moderate ____ 1 Extensive ____ 0
Subtotal (maximum = 5)		
TOTAL (maximum = 25)		

IF THE TOTAL SCORE IS LESS THAN 10, PROJECT MANAGER MAY REJECT THE REMEDIAL ALTERNATIVE FROM FURTHER CONSIDERATION.

DETAILED ANALYSIS OF ALTERNATIVES

The detailed analysis of alternatives follows the development and preliminary screening of alternatives and precedes the actual selection of a remedy. During this phase, remedial alternatives are analyzed in detail and relevant information is presented to allow decision-makers to select a remedy. The evaluations conducted during the detailed analysis phase build on previous evaluations conducted during the development and preliminary screening of alternatives. This phase also incorporates any treatability study

data and additional site characterization information that may have been collected during the RI.

Table 2
Implementability.
(Maximum Score = 15)

Analysis Factor	Basis for Evaluation During Preliminary Screening	Score
1. Technical Feasibility		
a. Ability to construct technology.	i) Not difficult to construct. No uncertainties in construction.	____ 3
	ii) Somewhat difficult to construct. No uncertainties in construction.	____ 2
	iii) Very difficult to construct and/or significant uncertainties in construction.	____ 1
b. Reliability of technology.	i) Very reliable in meeting the specified process efficiencies or performance goals.	____ 3
	ii) Somewhat reliable in meeting the specified process efficiencies or performance goals.	____ 2
c. Schedule of delays due to technical problems.	i) Unlikely	____ 2
	ii) Somewhat likely	____ 1
d. Need of undertaking additional remedial action, if necessary.	i) No future remedial actions may be anticipated.	____ 2
	ii) Some future remedial actions may be necessary.	____ 1
Subtotal (maximum = 10)		
2. Administrative Feasibility		
a. Coordination with other agencies.	i) Minimal coordination is required.	____ 2
	ii) Required coordination is normal.	____ 1
	iii) Extensive coordination is required.	____ 0
Subtotal (maximum = 2)		
3. Availability of Services and Materials		
a. Availability of prospective technologies.	i) Are technologies under consideration generally commercially available for the site-specific application?	Yes ____ 1 No ____ 0
	ii) Will more than one vendor be available to provide a competitive bid?	Yes ____ 1 No ____ 0
b. Availability of necessary equipment and specialists.	i) Additional equipment and specialists may be available without significant delay.	Yes ____ 1 No ____ 0
Subtotal (maximum = 3)		
TOTAL (maximum = 15)		

IF THE TOTAL IS LESS THAN 8, PROJECT MANAGER MAY REJECT THE REMEDIAL ALTERNATIVE FROM FURTHER CONSIDERATION.

Detailed Analysis of Remedial Alternatives

During the detailed analysis, each alternative is assessed against the seven evaluation criteria. The seven evaluation criteria listed encompass technical, cost and institutional considerations and compliance with specific statutory requirements. The seven criteria and their relative weights are presented in Table 3. Each evaluation criterion has been further divided into specific factors to allow a thorough analysis of the alternatives.

Table 3
Criteria for Detailed Analysis of Remedial Alternatives.

Criteria	Weight
1. Short-term effectiveness	10
2. Long-term effectiveness and performance	15
3. Reduction of toxicity, mobility and volume	15
4. Implementability	15
5. Compliance with ARARs	10
6. Protection of human health and the environment	20
7. Cost	15
TOTAL	100

Short-Term Effectiveness (Relative Weight: 10)

This evaluation criterion assesses the effects of the alternatives on human health and the environment during implementation of the remedial action. The following factors of this criterion should be addressed for each alternative; (1) Protection of the community during remedial actions—This aspect of short-term effectiveness addresses any risk that results from implementation of the proposed remedial action, such as dust from excavation or air-quality impacts from the operation of an incinerator; (2) Environmental impacts—This factor addresses the potential adverse environmental impacts that may result from the implementation of an alternative and evaluates how effectively available mitigation measures would prevent or reduce the impacts; (3) Time until remedial response objectives are achieved—This factor includes an estimate of the time required to achieve protection for either the entire site or individual elements associated with specific site areas or threats; and (4) Protection of workers during remedial actions—This factor assesses threats that may be posed to workers and the effectiveness and reliability of protective measures that could be taken.

The score for this criterion should be assigned based on the analysis of factors (1), (2), (3) presented in Table 4. Analysis of the factor "protection of workers during remedial actions," should be used to design appropriate safety measures for on-site workers.

Table 4
Short-Term Effectiveness.
(Relative Weight = 10)

Analysis factor	Basis for Evaluation During Detailed Analysis	Weight
1. Protection of community during remedial actions.	o Are there significant short-term risks to the community that must be addressed? (If answer is no, go to factor 2.)	Yes ____ 0 No ____ 4
	o Can the risk be easily controlled?	Yes ____ 1 No ____ 0
	o Does the mitigative effort to control risk impact the community life-style?	Yes ____ 0 No ____ 2
	Subtotal (maximum = 4)	
2. Environmental impacts	o Are there significant short-term risks to the environment that must be addressed? (If answer is no, go to factor 3.)	Yes ____ 0 No ____ 4
	o Are the available mitigative measures reliable to minimize potential impacts?	Yes ____ 3 No ____ 0
	Subtotal (maximum = 4)	
3. Time to implement the remedy.	o What is the required time to implement the remedy?	< 2yr. ____ 1 5 2yr. ____ 0
	o Required duration of the mitigative effort to control short-term risk	< 2yr. ____ 1 5 2yr. ____ 0
	Subtotal (maximum = 2)	
	TOTAL (maximum = 10)	

Long-Term Effectiveness and Permanence (Relative Weight: 15)

This evaluation criterion addresses the results of a remedial action in terms of its permanence and the quantity/nature of waste or residual remaining at the site after response objectives have been met. The primary focus of this evaluation is the extent and effectiveness of the controls that may be required to manage the waste or residual remaining at the site and operating system necessary for the remedy to remain effective. The following components of the criterion should be addressed for each alternative: (1) Permanence of the remedial alternative; (2) Magnitude of remaining risk—The potential remaining risk may be expressed quantitatively such as by cancer risk levels, margins of safety over NOELs for non-carcinogenic effects or the volume or concentration of contaminants in waste, media or treatment residuals remaining at the site. The characteristics of the residuals that should be considered to the degree that they remain hazardous,

taking into account their toxicity, mobility and propensity to bio-accumulate; (3) Adequacy of controls—This factor assesses the adequacy and suitability of controls, if any, that are used to manage treatment residuals or untreated wastes that remain at the site. It may include an assessment of containment systems and institutional controls to determine if they are sufficient to ensure that any exposure to human and environmental receptors is within protective levels; and (4) Reliability of controls—This factor assesses the long-term reliability of management controls for providing continued protection from residuals. It includes the assessment of the potential need to replace components of the alternative, such as a cap, a slurry wall or a treatment system; the potential exposure pathway; and the risks posed should the remedial action need replacement. This factor should also include systems to warn of the failure of a remedial alternative, once in place.

Table 5 should be used during the analysis to assign a score for this criterion.

Table 5
Long-Term Effectiveness and Permanence.
(Relative Weight = 15)

Analysis factor	Basis for Evaluation During Detailed Analysis	Weight
1. Permanence of the remedial alternative	o Will the remedy be classified as permanent in accordance with Section 2.1(a), (b), or (c) (If answer is yes, go to factor 3.)	Yes ____ 5 No ____ 0
	Subtotal (maximum = 5)	
2. Lifetime of remedial actions	o Expected lifetime or duration of effectiveness of the remedy	25-30yr. ____ 4 20-25yr. ____ 3 15-20yr. ____ 2 < 15yr. ____ 0
	Subtotal (maximum = 4)	
3. Quantity and nature of waste or residual left at the site after remediation	i) Quantity of untreated hazardous waste left at the site.	None ____ 3 < 25% ____ 2 25-50% ____ 1 ≥ 50% ____ 0
	ii) Is there treated residual left at the site? (If answer is no, go to factor 4.)	Yes ____ 0 No ____ 2
	iii) Is the treated residual toxic?	Yes ____ 0 No ____ 1
	iv) Is the treated residual mobile?	Yes ____ 0 No ____ 1
	Subtotal (maximum = 5)	
4. Adequacy and reliability of controls	i) Operation and maintenance required for a period of	< 5yr. ____ 1 > 5yr. ____ 0
	ii) Are environmental controls required as a part of the remedy to handle potential problems? (If answer is no, go to "iv")	Yes ____ 0 No ____ 2
	iii) Degree of confidence that controls can adequately handle potential problems	Moderate to very confident ____ 1 Somewhat to not confident ____ 0
	iv) Relative degree of long-term monitoring required (compare with other remedial alternatives evaluated in the Detailed Analysis).	Minimal ____ 2 Moderate ____ 1 Extensive ____ 0
	Subtotal (maximum = 5)	
	TOTAL (maximum = 15)	

Reduction of Toxicity, Mobility and Volume (Relative Weight: 15)

This evaluation would focus on the following specific factors for a particular remedial alternative: (1) The amount of hazardous materials that will be destroyed or treated, including how the principal threat(s) will be addressed; (2) The degree of expected reduction in toxicity, mobility or volume measured as a percentage of reduction (or order of magnitude); (3) The degree to which the treatment will be irreversible; and (4) The type and quantity of treatment residuals that will remain following treatment.

Table 6 lists factors to be addressed during the analysis of toxicity, mobility or volume reduction.

Implementability (Relative Weight: 15)

Of the total weight of 15, the technical feasibility shall receive

a maximum score of 10 while administrative feasibility and availability of services and materials shall be assigned a combined maximum score of 5.

Table 6
Reduction of Toxicity, Mobility or Volume.
(Relative Weight = 15)

Analysis Factor	Basis for Evaluation During Detailed Analysis	Weight
1. Volume of hazardous waste reduced (Reduction in volume or toxicity).	i) Quantity of hazardous waste destroyed or treated.	100% _____ 10 80-99% _____ 8 60-80% _____ 6 40-60% _____ 4 20-40% _____ 2 < 20% _____ 0
	ii) Are there concentrated hazardous waste produced as a result of (i)? (If answer is no, go to Factor 2.)	Yes _____ 0 No _____ 2
	iii) How is the concentrated hazardous waste stream disposed?	On-site land disposal _____ 0 Off-site secure land disposal _____ 1 On-site or off-site destruction or treatment _____ 2
Subtotal (maximum = 12) (If subtotal = 12, go to 3)		
2. Reduction in mobility of hazardous waste.	i) <u>Method of Reduction</u>	- Reduced mobility by containment _____ 1 - Reduced mobility by alternative treatment technologies. _____ 3
	ii) <u>Quantity of Wastes Immobilized</u>	< 100% _____ 2 ≥ 60% _____ 1 < 60% _____ 0
Subtotal (maximum = 5)		
3. Irreversibility of the destruction or treatment of hazardous waste.	Completely irreversible	_____ 3
	Irreversible for most of the hazardous waste constituents.	_____ 2
	Irreversible for only some of the hazardous waste constituents	_____ 1
	Reversible for most of the hazardous waste constituents.	_____ 0
Subtotal (maximum = 3)		
TOTAL (maximum = 15)		

Technical feasibility: This criterion relates to the technical difficulties and unknowns associated with a technology. This was initially identified for specific technologies during the development and preliminary screening of alternatives and is addressed again in the detailed analysis for the alternative as a whole.

- **Reliability of technology**—This criterion focuses on the ability of a technology to meet specified process efficiencies or performance goals. The likelihood that technical problems will lead to schedule delays should be considered as well.
- **Ease of undertaking additional remedial action**—This criterion includes a discussion of what, if any, future remedial actions may need to be undertaken and how difficult it would be to implement such additional actions. This is particularly applicable for a FS addressing an interim action at a site where additional operable units may be analyzed at a later time.
- **Monitoring considerations**—This criterion addresses the ability to monitor the effectiveness of the remedy and includes an evaluation of the risks of exposure should monitoring be insufficient to detect a system failure.

Administrative feasibility: Activities needed to coordinate with other offices and agencies (e.g., obtaining permits for off-site activities or rights-of-way for construction) should be evaluated for the alternative.

Availability of services and materials: The following should be considered during the analysis: (1) Availability of adequate off-site treatment, storage capacity and disposal services; (2) Availability of necessary equipment, specialists and skilled operators and provisions to ensure any necessary additional resources; and

(3) Availability of services and materials, plus the potential for obtaining competitive bids, which may be particularly important for alternative remedial technologies.

Table 7 lists typical factors to be addressed during the analysis of the implementability criterion.

Table 7
Implementability.
(Relative Weight = 15)

Analysis Factor	Basis for Evaluation During Detailed Analysis	Weight
1. <u>Technical Feasibility</u>		
a. Ability to construct technology.	i) Not difficult to construct. No uncertainties in construction.	___ 3
	ii) Somewhat difficult to construct. No uncertainties in construction.	___ 2
	iii) Very difficult to construct and/or significant uncertainties in construction.	___ 1
b. Reliability of technology.	i) Very reliable in meeting the specified process efficiencies or performance goals.	___ 3
	ii) Somewhat reliable in meeting the specified process efficiencies or performance goals.	___ 2
c. Schedule of delays due to technical problems.	i) Unlikely	___ 2
	ii) Somewhat likely	___ 1
d. Need of undertaking additional remedial action, if necessary.	i) No future remedial actions may be anticipated.	___ 2
	ii) Some future remedial actions may be necessary.	___ 1
Subtotal (maximum = 10) Minimum Required Score = 7		
2. <u>Administrative Feasibility</u>		
a. Coordination with other agencies.	i) Minimal coordination is required.	___ 2
	ii) Required coordination is normal.	___ 1
	iii) Extensive coordination is required.	___ 0
Subtotal (maximum = 2)		
3. <u>Availability of Services and Materials</u>		
	i) Are technologies under consideration generally commercially available for the site-specific application?	Yes ___ 1 No ___ 0
	ii) Will more than one vendor be available to provide a competitive bid?	Yes ___ 1 No ___ 0
	iii) Additional equipment and specialists may be available without significant delay.	Yes ___ 1 No ___ 0
Subtotal (maximum = 3)		
TOTAL (maximum = 15)		

Compliance with ARARs (Relative Weight: 10)

This evaluation criterion is used to determine how each alternative complies with applicable or relevant and appropriate Federal and State requirements as defined in CERCLA Section 121. There are three general categories of ARARs: chemical-, location- and action-specific. ARARs for each category are identified in previous stages of the RI/FS process (e.g., chemical-specific ARARs should be preliminarily identified during scoping of the project). The detailed analysis should summarize which requirements are applicable or relevant and appropriate to an alternative and describe how the alternative meets these requirements. When an ARAR is not met, justification for use of one of the six waivers allowed under CERCLA and SARA should be discussed.

Other information in the form of advisories, criteria and guidance that are not ARARs may be available. Compliance with such guidance may be necessary to ensure protectiveness and may be appropriate for use in the evaluation of a specific alternative.

If an alternative complies with all ARARs, it should be assigned a full score of 10. If an alternative complies with none of the above-mentioned four specific aspects of the ARARs, it should receive a score of 0. Each component of the four specific aspects of the ARARs shall receive a maximum score of 2.5. If an alternative does not meet the ARARs and a waiver to the ARARs is not appropriate or justifiable, such an alternative will not be further

considered. Table 8 should be used to evaluate remedial alternatives.

Table 8
Compliance With ARARs.
(Relative Weight = 10)

Analysis Factor	Basis for Evaluation During Detailed Analysis	Yes	No	Weight
1. Compliance with chemical-specific ARARs.	Meets chemical specific ARARs such as groundwater standards	Yes	No	2 5 0
2. Compliance with action-specific ARARs.	Meets ARARs such as RCRA minimum technology standards	Yes	No	2 5 0
3. Compliance with location-specific ARARs.	Meets location-specific ARARs such as wild and scenic Rivers Act	Yes	No	2 5 0
4. Compliance with appropriate criteria, advisories and guidelines.	The alternative meets all relevant and appropriate Federal and State guidelines that are not promulgated	Yes	No	2 5 0
TOTAL (Maximum = 10)				

Protection of Human Health and the Environment **(Relative Weight: 20)**

This evaluation criterion provides a final check to assess whether each alternative meets the requirement that it is protective of human health and the environment. The overall assessment of protection is based on a composite of factors assessed under other evaluation criteria, especially long-term effectiveness and performance, short-term effectiveness and compliance with ARARs.

Evaluation of the overall protectiveness of an alternative during the RI/FS should focus on how a specific alternative achieves protection over time and how site risks are reduced. The analysis should indicate how each source of contamination is to be eliminated, reduced or controlled for each alternative.

Table 9 outlines pertinent questions to be answered to help the evaluator assign relative weighing scores to remedial alternatives.

Table 9
Protection of Human Health and the Environment.
(Relative Weight = 20)

Analysis factor	Basis for Evaluation During Detailed Analysis	Yes	No	Weight
1. Use of the site after remediation.	Unrestricted use of the land and water. (If answer is yes, go to the end of the Table.)	Yes	No	20 0
TOTAL (Maximum = 20)				
2. Human health and the environment exposure after the remediation	i) Is the exposure to contaminants via air route acceptable?	Yes	No	3 0
	ii) Is the exposure to contaminants via groundwater/surface water acceptable?	Yes	No	4 0
	iii) Is the exposure to contaminants via sediments/soils acceptable?	Yes	No	3 0
Subtotal (maximum = 10)				
3. Magnitude of residual public health risks after the remediation.	i) Health risk ≤ 1 in 1,000,000			5
	ii) Health risk ≤ 1 in 100,000			2
Subtotal (maximum = 5)				
4. Magnitude of residual environmental risks after the remediation.	i) Less than acceptable			5
	ii) Slightly greater than acceptable			3
	iii) Significant risk still exists			0
Subtotal (maximum = 5)				
TOTAL (maximum = 20)				

Cost (Relative Weight: 15)

The application of cost estimates to evaluation of alternatives should include capital costs, operation and maintenance costs,

future capital costs and costs of future land use. The U.S. EPA's guidance for conducting RI/FS under CERCLA⁴ may be referred to for detailed descriptions of cost elements such as capital costs, operation and maintenance costs and cost-sensitivity analysis.

Capital Costs. Capital costs consist of direct (construction) and indirect (non-construction and overhead) costs. Direct costs include expenditures for the equipment, labor and materials necessary to install remedial actions. Indirect costs include expenditures for engineering and other services that are not part of actual installation activities but are required to complete the installation of remedial alternatives.

Operation and Maintenance Costs. Annual costs are post-construction costs (such as operating labor costs, maintenance materials and labor costs) necessary to ensure the continued effectiveness of a remedial action.

Future Capital Costs: The costs of potential future remedial actions should be addressed and, if appropriate, should be included when there is a reasonable expectation that a major component of the remedial alternative will fail and require replacement to prevent significant exposure to contaminants. It is not expected that a detailed statistical analysis will be required to identify probable future costs. Rather, qualitative engineering judgment should be used, and the rationale should be well documented in the FS report.

Cost of Future Land Use. Any remedial action that leaves hazardous wastes at a site may affect future land use and perhaps groundwater use. Access or use of such sites will be restricted, resulting in loss of business activities, residential development and taxes to the local, state and federal governments. During the feasibility study, potential future land use of the site should be considered. Based on this potential land use, economic loss attributable to such use should be calculated and included as a cost of the remedial alternative. In addition, the continuing presence of an inactive hazardous waste site, even though remediated, may have a negative effect on surrounding property values. This loss in value should be considered as a cost of the remedial program developed for the site. Economic loss due to the future land use should be derived based on comparison with a neighboring community not affected by any hazardous waste sites.

Cost of future land use should be determined for sites only when such cost is deemed appropriate and significant. When cost of land surrounding an inactive hazardous waste site located in the urban/suburban area is determined to be significant in relation to the cost of a remedial alternative, then cost of future land use as described above should be determined for inclusion in the present worth analysis of the remedial alternative.

Accuracy of Cost Estimates. Site characterization and treatability investigation information should permit the user to refine cost estimates for remedial action alternatives. It is important to consider the accuracy of costs developed for alternatives in the FS. Typically, these study estimate costs made during the FS are expected to provide an accuracy of +50 to -30% should be identified as such in the FS.

Present Worth Analysis. A present worth analysis is used to evaluate expenditures that occur over different time periods by discounting all future costs to a common base year, usually the current year. This figure allows the cost of remedial action alternatives to be compared on the basis of a single figure representing the amount of money that, if invested in the base year and disbursed as needed, would be sufficient to cover all costs associated with the remedial action over its planned life.

In conducting the present worth analysis, assumptions must be made regarding the discount rate and the period of performance. NYDEC recommends that a discount rate equivalent to the 30-yr U.S. Treasury bond rate before taxes be used; this discount rate should take inflation into account. In general, the period of performance for costing purposes should not exceed 30 yr.

An alternative with the lowest present worth shall be assigned

the highest score of 15. Other alternatives shall be assigned the cost score inversely proportional to their present worth.

Presentation of Comparative Analysis of Alternatives

Once the alternatives have been individually assessed against the seven criteria, a comparative analysis should be conducted to evaluate the relative performance of each alternative in relation to each specific evaluation criterion. The purpose of this comparative analysis is to identify the advantages and disadvantages of each alternative relative to the others so that the key trade-offs to be evaluated by the decision-maker can be identified.

The first five criteria (short-term effectiveness; long-term effectiveness and permanence; reduction of toxicity, mobility and volume; implementability; and cost) will generally require more discussion than the remaining criteria because the key trade-offs or concerns among alternatives will most frequently relate to one or more of these five. The overall protectiveness and compliance with ARARs criteria will generally serve as threshold determinations in that they either will or will not be met.

The comparative analysis should include a narrative discussion describing the strengths and weaknesses of the alternatives relative to one another with respect to each criterion, and how reasonable variations of key uncertainties could change the expectations of their relative performance. If destruction and treatment technologies are being considered, their potential advantages in cost or performance and the degree of uncertainty in their expected performance (as compared with conventional/isolation technologies) should also be discussed.

The presentation of differences between alternatives can be measured either qualitatively or quantitatively, as appropriate, and should identify substantive differences (e.g., greater short-term effectiveness concerns, greater cost, etc.) between alternatives, differences in total scores, etc. Quantitative information that was used to assess the alternatives (e.g., specific cost estimates, time until response objectives would be obtained and levels of residual contamination) should be included in these discussions.

The Final Draft RI/FS or the Proposed Remedial Action Plan (PRAP) should present the remedial alternative recommended for the site and a clear rationale for the recommendation.

COMMUNITY ASSESSMENT

The community assessment incorporates public comment into the selection of a remedy. There are several points in the RI/FS process at which the public may have previously provided comments (e.g., first phase of the RI/FS). The Department will solicit public comments on the remedial alternatives and the recommended alternative in accordance with the New York State Inactive Hazardous Waste Site Citizen Participation Plan and statutory and regulatory requirements. A document titled, "New York State Inactive Hazardous Waste Site Citizen Participation Plan," dated Aug. 30, 1988, should be used as a guide to solicit the public comments on the remedial alternatives and the recommended alternative at New York State inactive hazardous waste sites. The public comments shall be considered. The remedy for the site will be selected and documented in accordance with the Organization and Delegation Memorandum #89-05 Policy-Records of Decision for Remediation of Class 2 Inactive Hazardous Waste Disposal Sites.

DIFFERENCES BETWEEN PROPOSED NCP AND NEW YORK STATE GUIDANCE DOCUMENT

The following are major differences between the proposed NCP and New York State guidance document in application of

SARA's preference for the selection of remedies that permanently reduce the toxicity, volume or mobility of the hazardous wastes.

The New York State guidance document identifies a hierarchy of preferred remedies toward meeting the State's goal of implementing remedial actions which would result in a permanent and significant decrease in the toxicity, mobility or volume of hazardous wastes. This hierarchy is consistent with the New York State policy in hazardous waste management, SARA and RCRA land disposal restrictions.

The guidance document does not consider cost of remedial alternatives in initial screening of the remedial alternatives. Effectiveness and implementability are the only criteria used to screen the remedial technologies.

The New York State guidance document assigns numerical weighting factors for criteria to ensure objectivity, uniformity and consistency in the initial screening and detailed analysis of remedial alternatives; this document also outlines guidelines to be used in assigning weighting factors for evaluation criteria.

In addition to capital cost and operation and maintenance cost, the present worth analysis of a remedial alternative includes: (1) cost of future capital cost when there is a reasonable expectation that a major component of a remedial alternative will fail, and (2) cost of future land use when such cost is deemed appropriate and significant.

The U.S. EPA has proposed to use the Office of Management and Budget's circular A-94 discount rate of 10% when determining the present value of remedial alternatives. If the discount rate is high, the cost of operation and maintenance in the future will appear low when evaluating costs, thus favoring remedies which have low initial capital costs. Permanent treatments and remedies often will have high initial capital costs but lower operating and maintenance costs in the future than less-permanent remedies which will need longer operation or continual oversight. Therefore, the use of a high discount rate may result in an unfair bias against permanent or treatment remedies.

The New York State guidance document recommends the use of 30-yr U.S. Treasury bond rates before taxes as the discount rate; this discount rate should also take inflation into account.

CONCLUSION

The New York State guidance document assigns weights to evaluation criteria to ensure objectivity, uniformity and consistency in initial screening and detailed analysis of remedial alternatives; this process would facilitate implementing permanent remedies. Deletion of the cost criterion in initial screening of remedial alternatives would help to carry permanent remedies over to the next phase of detailed analysis. Inclusion of the cost of future land use and a discount rate of a 30-yr U.S. Treasury bond rate (instead of 10%) would eliminate unfair bias against permanent remedies.

The draft guidance document was distributed to the public and other interested state and federal agencies for review and comment. The guidance document was revised to reflect public review and comments.

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REFERENCES

1. Comprehensive Environmental Response, Compensation, and Liability Act of 1980, Public Law 96-510, Dec. 1980.
2. Superfund Amendments and Reauthorization Act of 1986, Public Law 99-499, Oct. 17, 1986.
3. National Oil and Hazardous Substances Pollution Contingency Plan; Proposed Rule, *Federal Register*, 53 (245), pp. 51394-51520, Dec. 21, 1988.
4. Environmental Protection Agency, *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA*, EPA/540/G-89/004, Oct. 1988.
5. New York State Department of Environmental Conservation, *Technical and Administrative Guidance Memorandum for the Selection of Remedial Actions at Inactive Hazardous Waste Sites*, Sept. 1989.
6. New York State Department of Environmental Conservation, *New York State Inactive Hazardous Waste Site Citizen Participation Plan*, Aug. 30, 1988.

U.S. EPA'S Federal Facility Hazardous Waste Compliance Program

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ABSTRACT

Ensuring compliance by Federal facilities with hazardous waste requirements is a challenging task because of the number and size of Federal facilities, the types and sources of contamination involved and the potential for overlap of jurisdictional and/or statutory authority. Although Federal facilities must comply with RCRA and CERCLA requirements similar to private parties, there are some differences. For example, Federal agencies are delegated certain CERCLA response authorities by executive order. Also, under both RCRA and CERCLA, dispute resolution procedures differ.

RCRA-regulated activities occur at most Federal facilities that require CERCLA action, and the U.S. EPA is developing a mechanism for creating a coordinated response between statutory and jurisdictional authorities. For Federal facilities, the integration solution may be a site-specific three-party CERCLA interagency agreement with the state, the U.S. EPA and the Federal facility as parties. This paper provides a statutory overview of requirements that apply to Federal facilities. It outlines two issues that are unique to the executive branch and discusses RCRA/CERCLA integration.

INTRODUCTION

At the U.S. EPA, the Office of Waste Programs Enforcement (OWPE), within the Office of Solid Waste and Emergency Response, is responsible for ensuring compliance by Federal facilities with RCRA and CERCLA requirements. In 1987, OWPE established a Federal Facility Task Force to focus dedicated resources on achievement of Federal facility compliance. The task force now has a permanent role within OWPE and has been renamed the Federal Facilities Hazardous Waste Compliance Office (FFHWCO).

The primary goals of FFHWCO are to assist U.S. EPA regions to reach CERCLA cleanup agreements at NPL sites and ensure compliance with RCRA in a nationally consistent manner. FFHWCO develops guidance and policy for Federal facility compliance, assists in resolution of issues that arise in negotiations with Federal facilities, tracks ongoing negotiations and supports enforcement actions.

Over 1,100 Federal facilities that will require investigation and possible remediation under CERCLA have been identified. These facilities range in size from hundreds of acres to tens of thousands of acres, and many contain multiple contaminated areas.

Federal facilities that require investigation are those that manage hazardous waste or may have potential hazardous waste problems. The Departments of Defense (DOD), Interior (DOI) and Energy (DOE) account for 84% of the Federal sites that require investigation.

Hazardous waste contamination at Federal facilities may result from such activities as weapon manufacturing, testing, loading and packaging; aircraft and vehicle maintenance and repair; metal plating; and

producing, processing and recovering nuclear materials. Types of hazardous waste disposed of include explosives, solvents and cleaning agents, paints, heavy metals, pesticides, waste oil and various organics. At DOE facilities, disposal of high and low level radioactive and mixed hazardous and radioactive waste is a common problem. Past disposal practices at Federal facilities include disposal in unlined pits, drainage ditches, holding ponds, drying beds and landfills; discharge on the ground; and burning.

The number of Federal facilities to be investigated, their sizes, and the types and sources of contamination involved combine to create the challenge of ensuring compliance by Federal facilities with hazardous waste laws. This challenge is heightened by the potential at each site for overlapping jurisdiction both among federal programs and between states that are authorized for the RCRA base or HSWA programs (i.e., the 1984 RCRA amendments, called the Hazardous and Solid Waste Amendments) and the federal CERCLA or HSWA programs. There is also a potential overlap with other Federal laws, such as the Atomic Energy Act, and with other state and local hazardous waste-related authorities.

STATUTORY OVERVIEW

Federal facilities must comply with the requirements of RCRA and CERCLA. This section contains an overview of those requirements.

RCRA

Section 6001 of RCRA expressly subjects Federal facilities to RCRA provisions and implementing regulations, including requirements for permits, corrective action and reporting. Federal treatment, storage and disposal facilities that handle hazardous waste must have RCRA permits and must address hazardous waste releases.

There are approximately 336 Federal facilities that treat, store or dispose of hazardous waste. Eighty of these facilities are land disposal facilities and 256 are treatment and/or storage facilities. This total represents less than 7% of the universe of RCRA treatment, storage and disposal facilities in the country.

The U.S. EPA or an authorized state conducts an annual inspection at all RCRA-regulated Federal facilities, as required by section 3007(c). As of December, 1988, 46 Federal land disposal facilities were out of compliance. Compliance mechanisms are discussed in the section following this statutory overview.

CERCLA

CERCLA devotes a special section to Federal facilities, section 120, enacted in the 1986 Superfund amendments. Section 120 (a) states that Federal departments, agencies and instrumentalities are subject to CERCLA like non-governmental entities, including CERCLA's liability

provisions. Pertinent guidelines, rules, regulations and criteria apply in the same manner and to the same extent, with the exception of requirements on bonding, insurance and financial responsibility.

Section 120 establishes special requirements and timetables regarding Federal facilities. For example, section 120 (c) requires establishment by the U.S. EPA of a Federal Agency Hazardous Waste Compliance Docket that lists Federal facilities which manage hazardous waste or may have potential hazardous waste problems. The docket identifies the universe of Federal facilities to be evaluated for possible contamination by compiling information submitted under RCRA and CERCLA.

The docket is updated every 6 mo. and includes:

- Information on releases of reportable quantities of hazardous substances under section 102 of CERCLA
- Information submitted to obtain a permit under section 3005 of RCRA
- Information submitted under section 3010 of RCRA from generators, transporters, owners and operators involved with waste designated as hazardous under RCRA
- Information submitted for the inventory of Federal agency hazardous waste facilities that is compiled every 2 yr. under section 3016 of RCRA.

The docket is available for public inspection at U.S. EPA regional offices. Each regional docket contains the documents submitted under the reporting provisions described above, and any relevant correspondence, for each facility in that region. A complete national index is maintained at U.S. EPA headquarters. The docket was first published on Feb. 12, 1988 in the *Federal Register* 153 p 4280 with 1,095 facilities on the list. The first update was published on Nov. 16, 1988 (53 *Federal Register* 46364); this list contained 1,170 facilities.

Once a Federal facility is listed on the docket, the Federal facility must conduct a preliminary assessment (PA) and, if necessary, a site inspection (SI) within 18 mo. The statute requires the U.S. EPA to assure that PAs are conducted, while the authority to conduct PAs is delegated to Federal agencies by executive order 12580. As of August, 1988, 987 of the 1,095 facilities listed in the original docket submitted PA information to the U.S. EPA. The U.S. EPA currently is reviewing this information for completeness and to determine whether further action is required.

Following the PA, the U.S. EPA applies the hazard ranking system (HRS) and includes sites that score 28.50 or above on the NPL. Inclusion on the NPL does not mean Superfund monies are available for cleanup as is the case with non-Federal sites; section 111(e) (3) specifies that the Fund is not available for remedial actions at Federal facilities (except for providing alternative water supplies where groundwater contamination is outside the Federal facility boundaries and the Federal facility is not the only potentially responsible party involved). Still, NPL listing of Federal facilities serves the purpose of alerting the public and providing information concerning risks to public health or the environment from the site. In addition, NPL listing assists Federal agencies to set cleanup priorities. There are currently 41 Federal facilities listed on the NPL and 74 proposed for inclusion.

If a Federal facility is included on the NPL, section 120(e) of mandates that it begin an RI/FS, in consultation with the U.S. EPA and the state, within 6 mo. of listing. The U.S. EPA and the state must publish an enforceable timetable and deadlines for RI/FS completion, and the U.S. EPA must review the RI/FS when completed.

Section 120(e) also requires the Federal facility to enter into an inter-agency agreement (IAG) with the U.S. EPA for the remedial action within 180 days of the U.S. EPA's review of the RI/FS. An IAG is the vehicle for remedy selection. At a minimum, the IAG must include a review of cleanup alternatives considered and the remedy selected, a schedule for cleanup accomplishment and arrangements for operation and maintenance.

U.S. EPA policy, reflected in the model IAGs developed with DOD and DOE, is to enter into an IAG at the RI/FS stage. This procedure meets the requirements of an RI/FS start and a published timetable and deadlines and provides for early input by the U.S. EPA and the state to the RI/FS and remedy selection process. U.S. EPA policy is to have three-party IAGs with the state joining the U.S. EPA and the Federal

facility as an active partner and signatory. IAGs are enforceable by the parties to the agreement and by citizens and states using CERCLA Section 310 authority.

Section 120(e) requires cleanup to begin at a Federal facility no later than 15 mo. after RI/FS completion. In their annual budget submissions, Federal agencies must include a review of alternative funding that might be used to provide for cleanup costs. The annual budget submission also has to include a statement on the hazards posed to public health, welfare and the environment, and the consequences of failure to begin and complete remedial action. In addition, an annual report to Congress must be submitted by each Federal agency participating in the CERCLA program. This report must describe the Federal agency's progress in such areas as reaching IAGs and conducting RI/FSs and cleanups.

To facilitate the negotiation of site-specific IAGs, the U.S. EPA developed model IAGs with DOD and DOE in 1988. The models cover the following areas:

- Jurisdiction
- Purpose
- Statutory Compliance/RCRA-CERCLA Integration
- Consultation with U.S. EPA
- Dispute Resolution
- Enforceability
- Stipulated Penalties
- Extensions
- Force Majeure
- Funding

The models are captioned as CERCLA section 120 agreements and are designed to apply at NPL sites where CERCLA is the lead response authority. Compliance with substantive RCRA requirements as applicable, relevant or appropriate requirements (ARARs) is assured through section 121 of CERCLA and the model's statutory compliance section. For installations that include both NPL sites and RCRA units, language in the jurisdiction section that cites RCRA authorities may be used. Although these model agreements do not reflect state involvement (because it was impossible to have 50 state representatives at the negotiating table), it is the U.S. EPA's policy to integrate state participation into the IAG provisions at site-specific negotiations.

The consultation section establishes the procedures for U.S. EPA and state review of documents. Documents designated as primary, including discrete portions of RI/FS and remedial design and remedial action (RD/RA) activities, are subject to dispute resolution procedures. Documents designated as secondary are subject to review and comment. Secondary documents are feeders to primary documents and are subject to dispute resolution when incorporated into primary documents or when the corresponding primary document is issued.

The dispute resolution section provides the parties to the agreement with the ability to formally dispute issues associated with primary documents. This process assures that the work being conducted by the Federal facility is in compliance with the requirements of CERCLA, the NCP and applicable state law. The U.S. EPA administrator makes the final decision in disputes should the parties not resolve these disputes at lower levels. The U.S. EPA expects that in all but the most extraordinary situations, disputes will be resolved at the project manager or director level.

The dispute resolution section also includes a threshold for stopping work affected by a dispute. The threshold is crossed in the event of inadequate or defective work which is the U.S. EPA's or the state's opinion is likely to yield an adverse effect on human health or the environment or to have a substantial adverse effect on the remedy selection or implementation process.

The enforceability section preserves citizen suit rights under section 310 of CERCLA. States are "persons" under CERCLA and therefore can sue to enforce the IAG in Federal district court. The enforceability section specifically establishes that deadlines related to the RI/FS and terms and conditions of the IAG are enforceable, as is final dispute resolution, by any person pursuant to section 310. Also, all parties have the right to enforce IAG terms.

The stipulated penalties section allows the U.S. EPA to assess stipu-

lated penalties to be payable to the Hazardous Substances Response Trust Fund in the event of specified failures under the agreement. The amount assessed and the reasons for the assessment must be reported on a facility-specific basis by DOD or DOE in its annual report to Congress on progress under section 120.

The funding section requires DOD and DOE to seek sufficient funds for response and include estimates in their annual reports to Congress. The U.S. EPA reserves its rights against any other party if funding is not available.

Provisions describing the work to be accomplished at a specific site, the schedule for its accomplishment, and any individual state concerns, are negotiated on a site-specific basis. As of August, 1989, IAGs have been concluded for 21 Federal facilities covering 26 NPL sites.

Federal Agency Authority Under CERCLA

Executive order 12580, which delegates authorities contained in SARA, delegates Section 104 response authority to DOD and DOE for releases on or originating from their facilities. It requires that such response authority be exercised in accordance with section 120, which provides the U.S. EPA administrator with the final decision on remedy selection should the U.S. EPA and a Federal agency disagree. All Federal agencies are delegated section 104 response authority for non-emergencies at non-NPL sites where the release is on or originating from their facilities.

Executive order 12580 may have singled out DOD and DOE for additional response authority because both agencies established cleanup programs prior to the passage of SARA in 1986. DOD established its Installation Restoration Program (IRP) in 1975. Under IRP, each service operates a program whose goals are to identify and evaluate past waste disposal practices at DOD facilities. Studies and remediation are conducted as necessary. Section 211 of CERCLA governs management of the program. DOD funding for IRP in FY'89 is \$500 million.

DOE initiated an informal program in 1984 designed to identify, evaluate and remediate hazardous waste contamination at DOE facilities. DOE has not yet established a formal response program analogous to DOD's IRP.

ISSUES UNIQUE TO THE EXECUTIVE BRANCH

This section of our paper describes two issues that are unique to the executive branch. These issues are funding and dispute resolution.

Funding

Unlike the private sector, Federal agencies cannot use earnings to fund their hazardous waste cleanup responsibilities. Federal funding, including funding for cleanups by Federal facilities, is requested by the President and appropriated and overseen by Congress.

Clearly, Congress plays an essential role in Federal facility cleanups by appropriating sufficient funding for those cleanups. Compliance by Federal facilities with RCRA and CERCLA is subject to available appropriations, although the U.S. EPA's RCRA compliance agreements state that failure to obtain funding does not release the Federal facility from its obligations to comply with RCRA and the terms of the agreement.

Dispute Resolution

Federal agencies are created and supported by Congress and report to the President, who ultimately is accountable for agency missions. Federal agencies are immune from suit except to the extent that sovereign immunity is specifically waived in legislation by Congress.

In the view of the Department of Justice (DOJ), executive branch agencies may not sue each other; nor may one issue an administrative order to another without providing a prior opportunity to contest the order within the executive branch¹. Like lawsuits, unilateral order authority is viewed as inconsistent with the constitutional principles of unity and unitary responsibility within the executive branch². Executive branch disputes of a legal nature are properly resolved by the President or his delegate, in DOJ's opinion, because lawsuits and unilateral administrative orders interfere with the President's ability to manage the executive branch³.

RCRA

The DOJ has distinguished between section 3008(a) compliance orders and section 3008(h) corrective action orders in regard to the U.S. EPA's authority to issue RCRA orders to Federal facilities. In the DOJ analysis, the U.S. EPA may issue section 3008(h) corrective action orders but may not issue section 3008(a) compliance orders.

Section 3008(a) Orders

According to the DOJ, the U.S. EPA may not issue a section 3008(a) order to a Federal facility to address compliance violations because an order is not a "requirement" under Section 6001⁴. Section 6001 defines the obligation of Federal facilities to comply with RCRA.

Section 6001 states in part that Federal agencies dealing with solid waste:

... shall be subject to, and comply with, all Federal, State, interstate, and local requirements, both substantive and procedural (including any requirement for permits or reporting or any provisions for injunctive relief and such sanctions as may be imposed by a court to enforce such relief) . . . in the same manner, and to the same extent, as any person is subject to such requirements. . .

The DOJ found that the issue turned on whether a section 3008(a) order constitutes a substantive or procedural requirement, and cited RCRA's legislative history and case law to determine that section 3008(a) orders are not requirements; they are instead a means by which requirements are enforced⁵.

Instead of issuing section 3008(a) orders to address compliance at Federal facilities, the U.S. EPA will issue a Notice of Noncompliance (NON)⁶. A NON is similar to a section 3008(a) order in content and format; it details the violation, remedy and remedy implementation schedule.

After issuance of the NON, the U.S. EPA and the Federal facility negotiate a Federal Facility Compliance Agreement (FFCA)⁷. The FFCA is the document that resolves compliance violations by specifying the agreed-upon remedy, compliance schedule, reporting requirements and record-keeping requirements. Also included in a FFCA is dispute resolution language, which emphasizes resolution at lower levels, and an enforceability clause, which clarifies that the FFCA may be enforced under RCRA's section 7002 citizen suit provision.

To ensure that negotiation of FFCA's is concluded in a timely manner, the U.S. EPA has established an elevation process for resolution of issues⁸. The U.S. EPA's goal is to conclude FFCA negotiations within 120 days. At day 90, U.S. EPA regions evaluate the negotiations and determine whether agreement is likely within 120 days. In any case where agreement does not appear likely in that time-frame, the case is referred to U.S. EPA headquarters for resolution. Upon referral, the assistant administrator for the Office of Solid Waste and Emergency Response meets with an equivalent representative from the Federal agency involved. If the dispute is not resolved within 30 days, it is elevated for resolution to the U.S. EPA administrator and his Federal agency counterpart.

The DOJ's opinion that the U.S. EPA may not issue section 3008(a) orders to Federal facilities does not prohibit the U.S. EPA from issuing such orders to the contractor at a government-owned contractor-operated (GOCO) facility⁹. Contractors at GOCO facilities are subject to RCRA to the same extent as any non-Federal entity, including orders assessing penalties. Several courts have held that penalties may not be assessed against Federal facilities because, under section 6001, enforcement sanctions are distinct from requirements¹⁰. Although some Federal agencies indemnify their contractors, so that a fine assessed for environmental violations against the contractor ultimately is paid by the Federal agency, there is authority for the proposition that private contractors may not be afforded the privileges of the Federal government¹¹.

Section 3008(h) Orders

Section 3008(h) corrective action orders, as opposed to section 3008(a) compliance orders, are viewed by the DOJ as integral to the

permitting process, which Federal facilities are required to comply with under section 6001¹². Thus, the U.S. EPA may issue section 3008(h) corrective action orders to Federal facilities. Federal facilities that receive section 3008(h) orders may confer with the U.S. EPA on such orders and raise any issue that cannot be resolved at the regional level to the U.S. EPA administrator for final resolution¹³. The U.S. EPA may also issue section 3008(h) orders to the contractor at GOCO facilities.

CERCLA

The application of CERCLA authorities at Federal facilities is less subject to interpretation than the application of RCRA authorities. Section 120 requires Federal facilities to enter into IAGs for remedial action at NPL sites. IAGs are enforceable through CERCLA's section 310 citizen suit provision¹⁴. In addition, section 122(l) specifically authorizes imposition of civil penalties for failure or refusal to comply with a section 120 IAG.

The U.S. EPA may issue an order under section 104(e)(5)(A) to obtain access to a Federal facility or to collect information. The U.S. EPA may also issue a section 106 order to ensure compliance at a Federal facility where there is an imminent or substantial endangerment to public health, welfare or the environment due to an actual or threatened hazardous substance release from the facility. In either case, however, executive order 12580 requires that the U.S. EPA receive DOJ concurrence on the order. The U.S. EPA may use any of its administrative and judicial authorities under CERCLA against a contractor at a GOCO facility.

RCRA/CERCLA INTEGRATION ISSUES

RCRA commonly applies at a Federal facility that is subject to CERCLA. For example, a Federal facility that is listed or proposed on the NPL may also have interim status or a permitted unit under RCRA.

There are some unresolved issues about which statute should be used as the primary vehicle to ensure cleanup when both RCRA and CERCLA apply, and how the statutes may be used together. This is particularly so where a RCRA-regulated release is the cause of NPL listing, rather than a contributing factor. Neither statute is entirely clear on these issues.

Most states are authorized to run the RCRA base program, and several have gained authorization for HSWA authorities. Federal facilities have their own delegated authorities under CERCLA; DOD and DOE have response authority for all releases on or originating from their property. The U.S. EPA, states and Federal facilities share the ultimate goal of cleaning up Federal facilities, although there may be disagreement about which statute should control in a particular case.

The statutory overlap may be broader than RCRA and CERCLA. Another federal statute, such as the Atomic Energy Act, may apply in a given case. Also, state or local hazardous waste-related authorities, independent of RCRA or CERCLA, may apply to a particular facility.

Inherent in the statutory overlap is a jurisdictional overlap. The jurisdictional overlap may be between Federal programs, such as RCRA and CERCLA, or between state and Federal programs, such as an authorized state RCRA base program and the Federal CERCLA or HSWA programs.

Such overlaps contain a potential for slowing cleanup while disagreements over which statute to use are resolved and for inconsistent or duplicative cleanup activities if disagreements are not resolved. To speed cleanup and avoid inconsistency or duplication, the U.S. EPA is working to develop a mechanism to create a comprehensive, coordinated response at Federal facilities with a RCRA/CERCLA overlap. This mechanism

is a three-party IAG with the state, the U.S. EPA and the Federal facility as signatories.

A three-party IAG can address site-specific state concerns and maximize state involvement in the cleanup process. Regulatory or oversight authority for work conducted under an IAG can be allocated in a manner consistent with the concerns of the parties. Such an agreement could satisfy a Federal facility's corrective action responsibilities under RCRA as well as the public participation requirements of both RCRA and CERCLA; a RCRA permit could later incorporate requirements of the IAG, if appropriate.

A three-party IAG may be developed for either NPL or proposed NPL Federal facilities. A three-party IAG is also flexible enough to include a non-listed RCRA-regulated portion of a Federal facility where that makes sense from a technical standpoint, thus providing for a swifter comprehensive cleanup. An IAG allows the parties to include in a response action releases of CERCLA hazardous substances that are not regulated under RCRA (e.g., radionuclides).

The U.S. EPA is focusing on RCRA/CERCLA integration at Federal facilities through a variety of efforts including policy development and a work group of state and U.S. EPA regional representatives. The state representatives have taken the lead on developing language for a three-party IAG. While the U.S. EPA has expressed a strong preference for three-party IAGs, it will enter into two-party IAGs or issue 106 orders to the facility at Federal facility NPL sites where necessary to fulfill its statutory mandate.

CONCLUSION

The Federal facility hazardous waste compliance program is on track. The provisions of CERCLA section 120 are being implemented. With DOD and DOE agreement on model IAG language, the number of site-specific IAGs concluded is rising. Unique dispute resolution and enforcement procedures have been designed where deemed necessary by DOJ to ensure Federal facility compliance. To further enhance progress, the U.S. EPA is developing three-party IAGs as a mechanism to integrate RCRA and CERCLA at Federal facility sites.

REFERENCES

1. Statement of F. Henry Habicht II, Assistant Attorney General, Lands and Natural Resources Division, Department of Justice, before the Subcommittee on Oversight and Investigations, Committee on Energy and Commerce, House of Representatives, April 28, 1987, p.29.
2. Ibid.
3. Id.
4. Habicht statement, Appendix B.
5. Ibid.
6. Memorandum from J. Winston Porter, Assistant Administrator for Solid Waste and Emergency Response, to EPA Regional Administrators, "Enforcement Actions Under RCRA and CERCLA at Federal Facilities," January 25, 1988, p.3.
7. Porter memorandum, January 25, 1988, p.3.
8. Memorandum from J. Winston Porter, Assistant Administrator for Solid Waste and Emergency Response, to EPA Regional Administrators, "Elevation Process for Achieving Federal Facility Compliance Under RCRA," March 24, 1988.
9. Porter memorandum, January 25, 1988, p.4.
10. Habicht statement, Appendix B, pp. 6-9.
11. Inside EPA, "In Boon To Enforcement, Judge Bars DOE from Intervening for Contractor," December 18, 1987, p.5.
12. Porter memorandum, January 25, 1988, p.5.
13. Ibid.
14. Conference Report on Superfund Amendments Reauthorization Act of 1986, 99th Congress, 2d Session, Rept 99-962, p.242.

Community Assessment: A Planned Approach to Addressing Health and Environmental Concerns

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ABSTRACT

The U.S. EPA develops and implements plans for public participation at each site on the NPL. Public participation is required under SARA during the investigation and cleanup of Superfund sites. These provisions are included in SARA to ensure that residents in communities potentially affected by hazardous waste sites are informed of and have the opportunity to participate in site-related activities.

The core of each site-specific public participation program is a planning document called the Community Relations Plan (CRP). The CRP evaluates the community within the context of the site investigation and cleanup, and outlines the goals and activities to be undertaken by U.S. EPA to address the concerns and participation interests of the community. The CRP is developed through a process that the authors call community assessment.

Community assessment evaluates the potential economic, social and political impact of the site on the community and, conversely, the potential impact of the community on site remediation. Each community is distinct, frequently presenting several unique publics within the community structure. The publics which may include different levels of public officials, environmental activists, community groups, people residing in close proximity to the site or groups, such as the elderly, with special needs. The various groups within the community often have conflicting concerns and agendas.

Community assessment involves several activities, including identifying potentially affected or interested local residents and groups, making field trips to the affected community, conducting numerous in-person interviews and doing extensive file research. The result is an analysis that assists the U.S. EPA in addressing concerns, initiating a dialogue with the community and establishing credibility among community members.

The authors discuss a series of assessments they conducted in three Dane County, Wisconsin communities. The sites are located within a 15-mi region of the county in three different, but adjacent, communities in the Madison, Wisconsin, metropolitan area. Madison is the state capital and the home of a major midwestern university. The sites are all landfills in which similar types of hazardous wastes were disposed.

The authors will examine the community assessment process, its value as a tool in identifying potential community concerns and its use in anticipating potential community controversies and opposition in other areas of environmental planning.

INTRODUCTION

Several federal environmental programs address a growing public demand for knowledge about environmental risks and participation in decisions that will affect the health, welfare or the environment of their community. The Superfund community relations program is one such

program. The program involves a process of identifying potentially affected publics, defining their concerns and developing and implementing a comprehensive plan to address them.

The first step in this process is called community assessment. Community assessment identifies the extent and nature of community interest and concern about the site in the same way that a hazardous waste site assessment identifies the nature and extent of a potential contamination problem. Site assessments often involve qualitative and quantitative biological, physical and chemical analyses; community assessment includes qualitative political, social and economic analyses of a community in relation to a potential or existing hazardous waste problem. Each community assessment includes file research, library research, field interviews, analysis and report writing.

The product of the community assessment is a document called the Community Relations Plan (CRP). Among other things, the CRP proposes activities and actions to address the concerns and issues identified during community assessment.

Implementing the activities suggested in the CRP then becomes the ongoing basis of the site community relations program. Activities often include public and small group meetings, newsletters, library exhibits and public involvement programs.

One observation the authors have made over the course of working with numerous communities is that each community is unique. Even adjacent communities, sharing common schools and history, frequently react quite differently to Superfund, hazardous waste and environmental issues.

Three of the more interesting communities the authors encountered as a team were in Dane County, Wisconsin. Dane County is the home of Madison, the state capitol, the University of Wisconsin and several old hazardous waste sites. Three of these sites are included on the NPL: (1) the City Disposal Corporation Landfill site in Dunn Township, (2) the Hagen Farm site in Dunkirk Township (3) the Stoughton City Landfill in the City of Stoughton. Two additional sites, the Every Farm site in Dunkirk Township and the Madison Metropolitan Sewage System, were proposed for inclusion on the NPL but are not yet on the final list.

WHY COMMUNITY ASSESSMENT?

Community assessment serves a dual purpose. This phase of the community relations program primarily is designed to identify community concerns and understand their basis. However, the assessment also enables the U.S. EPA to become known by the community early in the site investigation and cleanup process. We were aware that making ourselves accessible to residents and officials would be crucial to the success of future community relations activities and the ultimate cleanup of the three sites. By letting people know at the beginning of the process who was accountable for the technical and community relations aspects

of each project, we hoped to win at least the cautious trust of Dunn, Dunkirk and Stoughton residents. Also, early intervention enabled the U.S. EPA to be proactive in addressing concerns, thus avoiding surprises and having to fight fires later in the process.

By the time the technical staff went into the field, both the community relations staff and technical project manager were knowledgeable about community concerns, potential controversies, information requirements and potentially sensitive issues. The U.S. EPA generally initiates formal contact with the community approximately 4 mo before the remedial investigation begins. Shortly thereafter, we start the community assessment.

Sometimes the U.S. EPA community relations coordinator becomes involved long before formal community assessment is started. In August, 1988, an Oneida Indian tribe contacted the U.S. EPA about some site related concerns shortly after the nearby Fort Howard Paper Company sludge lagoons site in Green Bay, Wisconsin was proposed for the NPL.

So, the U.S. EPA representatives traveled to Green Bay with officials from two other agencies to hold public meetings and meet with the Oneida Business Committee to explain the Superfund process.

When community assessment is not done, the potentially affected community may feel shut out of the cleanup process. This exclusion of interested parties may lead to increased uncertainty about the site and its associated risks. The credibility of the U.S. EPA may be severely decreased in the community. As a result, the community may become hostile toward the U.S. EPA. This was the case at one Superfund site in Indiana. While a well-planned program is now being developed and implemented, it may take a long time before a trusting relationship is established between the community and the U.S. EPA.

THE COMMUNITY ASSESSMENT PROCESS

Each community assessment began with extensive file research to understand as much about each site as possible. We reviewed technical reports and other documents to understand how the site was brought to the attention of the U.S. EPA, why it was placed on the NPL and to identify evidence of past community interest.

Technical information about the site's history was used in our later discussions with community officials and residents. In order to talk intelligently and to ask questions that addressed the basis of their concerns, we needed to have a good working knowledge of the nature and extent of the potential contamination problem.

While this background research was being done, the first telephone contacts with members of the communities were made. These community contracts were made while we established locations for the site information repositories, where site-related documents and information about the U.S. EPA and Superfund would be placed for public review. Establishing an information repository is one of the first community relations activities undertaken. The repository is an ideal location to place information that may be of interest to the community. Because the likely locations for the repositories include the local library and municipal hall, the repository establishment process provided an opportunity to meet one or more public officials and the local librarian. Conversations with these local officials frequently provide insight into the local political climate and general feelings about the U.S. EPA and Superfund.

Sue Pastor (U.S. EPA) contacted the Stoughton city clerk's office to set up the Hagen Farm repository because our information told us that Stoughton was the location of the NPL site. We learned that our information was not entirely accurate. We also learned three additional lessons from this one telephone call.

First, the city clerk refused to house the information repository, making it very clear that the NPL site was not located in Stoughton. The site was actually located in unincorporated Dunkirk Township which surrounds Stoughton on all sides and shares its schools, post office and Scandinavian ethnic culture. The clerk wanted us to be sure that there was no misunderstanding of the local geographic boundaries.

Lesson two was that Stoughton officials were very sensitive about the presence of a Superfund site within the city's corporate limits. Stoughton already was host to one Superfund site, the Stoughton City Landfill (which we had yet to start working on). The City of Stough-

ton was named as potentially responsible for the cleanup cost of the Stoughton City Landfill. The city wanted nothing to do with the Hagen Farm site.

The third lesson was that we needed to be very cautious to distinguish sites and communities and not to address them in our community assessment as a unit.

Through these preliminary contacts, Ms. Pastor also identified the local newspaper which covered all three communities and their respective governments. She learned that the Madison papers also covered that part of the county. She then contacted the local reporters. This contact provided her an opportunity to introduce herself as the U.S. EPA contact and learn more about the three communities as well.

During this early stage of community assessment, we tried to identify residents, officials and groups that might be interested in each site. Identifying the appropriate people to interview was critical in correctly characterizing communities' concerns and interests.

We identified potentially interested individuals through the background research using several valuable resources. Some of the most useful were: a plat map, a local telephone directory, a visitors' kit from the local Chamber of Commerce and the local health department.

The plat map of the area surrounding each site helped us identify specific residences or businesses located near the sites. We made a special effort to contact those individuals living near the site because they would be most directly affected by the site and its remediation.

The local telephone book, which served all three communities, helped us locate telephone numbers of people we identified. In addition, by thumbing through the yellow pages, we identified additional local community groups. The telephone book, as much as any other resource, also gave us a sense of the community's flavor and culture. It gave us an insight into the types of businesses, clubs, civic groups and services present in the community.

The Chamber of Commerce packet provided us with specific geographic, social and demographic facts about the community, including its major employer, the Uniroyal plant in Stoughton, population, community history and local services.

The local health department was an important contact at this stage. The health department is often the first official agency to hear health or environmental complaints from concerned residents. We were fortunate that these three sites were in contact with a county environmental health sanitarian knowledgeable about all three sites. He lived in Stoughton (in fact near the Uniroyal plant) and was able to supply us with a history of past community involvement and concerns and names of concerned residents for us to contact and interview.

Our research identified numerous parties to interview. As we telephoned the people on our list, we were often referred to neighbors and other interested residents. People were generally forthcoming and seemed to welcome our interest. The types of individuals we identified are shown in Table 1.

After the preliminary research and identification, we scheduled in-person interviews. We scheduled about 15 interviews in each community, trying to get a variety of perspectives. Some additional interviews were conducted over the telephone to accommodate those who were unavailable during the field trip. Good scheduling ensured that everyone who wished to had an opportunity to be interviewed and that appointments were not missed. We allowed 1 to 2 hr for each interview. We also left a half hour between meetings to find our way, over rural and unknown terrain, to the next appointment.

We limited the number of people present at each interview. We did this for several reasons. People tend to speak more openly and honestly about their concerns in a one-on-one situation. A local alderman, for example, might be more willing to disagree with the mayor if the mayor is not present. We also did not want to interview a large group of residents together at one meeting. The interview could easily turn into a public meeting, and the goal of information gathering could have been lost.

Based on the preliminary research, we developed an interview questionnaire to guide the interview and provide topics for discussion. The questions addressed site history, past community involvement, perceptions about the U.S. EPA, community culture, specific past and present

Table 1
Typical Local Contacts for Community Interviews

Local Officials:

Town Board Chairmen (Dunn and Dunkirk)
Mayor (Stoughton)
Town/City Clerk
Town Board members
Aldermen
Public Works Director

County Officials:

County Board Representative
County Environmental Health Sanitarian

State Officials:

state and district WDNR personnel
state Legislators from affected district
Wisconsin Division of Health personnel working on site health assessment

Groups:

League of Women Voters (Dane County and Stoughton Chapters)
Sierra Club
Audubon Society
Environment Wisconsin

Residents:

Long-time establishment residents
Newer term residents mostly from the University and working in Dane county
People living directly around the site

environmental concerns and the way in which the group or individual would like to be informed about, or involved with, the site remediation.

After returning home from the field trips, we reviewed and analyzed the many additional documents and newspaper clippings we obtained from local officials, residents, state files and the library. We also summarized our interview notes, identified common concerns and began to formulate how we might address them. The three communities were quite distinct and resulted in three different community relations approaches. Profiles of the communities based on the assessments are presented in Table 2.

Based on the field and other research, we compiled a comprehensive community relations plan for each site. Each CRP contained a site history, community profile, information about the local media, a history of past community involvement with the site and discussion of the concerns raised by residents, officials and other interested parties. Each CRP included a discussion of public participation goals for the community based on the concerns raised, and activities designed to achieve the public participation goals. While many of the activities outlined in the CRP are guided by CERCLA, others are designed to address specific and general environmental and health concerns expressed during the interviews.

DIFFERENT APPROACHES

In Stoughton, we addressed the city's interest in community relations by calling on it for logistical support in planning meetings and repositories. At the same time, we addressed the concerns of some of the residents by installing a groundwater and risk assessment exhibit in the water department foyer. We also addressed the special needs of the senior citizens we identified during our field work. We planned a special daytime public meeting at the development's clubhouse to accommodate the less mobile senior citizens. We developed written fact sheets to help residents understand Superfund, risk assessment and the nature of the work to be conducted at the site.

In Dunn, our research indicated that there was latent interest in the site. Our research was right. Nearly 100 people attended our first public meeting. People at the meeting wanted to be very involved and informed

Table 2
Community Profiles

Town of Dunn

- o Site closed for many years
- o Population: 5,000
- o Unincorporated Township
- o Madison, WI bedroom community
- o Environmental issues a strong concern
- o Politically active community
- o Town meeting well attended
- o Strong latent interest
- o Rely on private drinking water wells

Town of Dunkirk

- o Site closed for many years
- o Population: 1,800
- o Unincorporated township
- o Rural, farming community
- o Environmental issues not of great concern
- o Current interest in site is low
- o Rely on private drinking water wells

Stoughton

- o Site closed for several years
- o Incorporated municipality
- o Public water supply
- o City had suit pending against U.S. EPA to delete site from Superfund List
- o Site was being developed as a park
- o New senior citizen housing constructed adjacent to site
- o Very high level of interest in the site

about the cleanup program. After the meeting, the residents formed a citizens' committee to monitor activities. The U.S. EPA technical project manager has since attended several of those meetings.

In Dunkirk, as predicted, things have remained fairly quiet with only minimal expressed interest. Thirty people attended the public meeting. Another meeting will be held there this summer to keep interested residents up-to-date on site activities. But low interest has indicated no need for special activities.

During our Dane County community assessments we examined three communities, three sites and three worlds. Only by careful book and field research could we have anticipated and planned for these vast differences.

APPLICABILITY TO OTHER AREAS OF PLANNING

Community assessment is applicable whenever an issue may have an impact on the public health or environment of a community. One such issue is recycling, surely prominent in environmental planning. Community assessment might be used to identify the factors that will encourage individuals to recycle more materials. It also could identify the best avenues and vehicles for disseminating information about the recycling program. That information could then be used to increase participation in the recycling program.

Public health officials might use community assessments to identify and then act on local health concerns like AIDS, water pollution or environmental cancer risk. Programs geared to the nature and level of concern may then be more effectively developed.

Community assessment conducted before a chemical plant, incinerator or other locally unacceptable land use is planned and "imposed" on a community might help developers and planners choose host communities more carefully. Understanding the nature and extent of the community's concern may enable the developer to address legitimate concerns and work with the host community in planning the project.

Sometimes, no matter how well a community and its concerns are understood, conflict, controversy and opposition cannot be overcome. However, community assessment is a good first step in establishing a meaningful dialogue and a strong base for planning decisions.

Community Relations Programs: Improved Planning through Better Understanding of Communication Systems

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ABSTRACT

Thorough and situation-specific planning is often neglected during development of community relations programs. However, planning is critical to developing effective and ultimately successful community relations programs. Such planning involves several steps: setting goals and objectives, identifying community characteristics, understanding communication systems, determining target audiences and developing an evaluation scheme.

Although crucial to effective planning, the step "understanding communication systems" often is overlooked. This paper therefore not only emphasizes the importance of understanding communication systems, but also includes brief descriptions of each planning step.

Communication systems generally have seven components or aspects: objects (e.g., receivers, senders, communication media and messages), attributes of objects, relationships among objects, environments in which the system functions, balance, hierarchical organization and goal orientation. Each of these components or aspects is described as it pertains to community relations programs, and the main methods for obtaining information about each component or aspect are discussed.

INTRODUCTION

Implementation and operation of environmentally regulated projects often require the inclusion of programs to address community concerns.

For example, NEPA, CERCLA/SARA and RCRA projects often require community relations programs because these types of environmentally sensitive activities often attract public attention and invoke the interest, curiosity, concern and at times outrage of local communities. Whether community relations programs are required by law or not, they are strongly recommended as a means to mitigate negative community reaction as well as to foster community support.

The value of community relations programs often is underestimated. Consequently, thorough and situation-specific planning for such programs is frequently neglected during project development. A major benefit of such planning is eventual accomplishment of program goals and objectives. Also of benefit are improved corporate or agency images and increased credibility within the community. On the other hand, poorly planned and communicated community relations programs may damage one's image and one's credibility. Because community perceptions often extend beyond the bounds of a single project, they can influence the outcome of future, unrelated projects.

Future community relations programs will benefit from the experience gained during current program planning and implementation. Although planning effective communication strategies is initially energy-intensive and time-consuming, the effort pays off in the long run. Planning and implementing community relations programs becomes increasingly cost-effective as execution becomes more efficient with practice. For example,

experience assists organizations to respond more quickly and effectively, and with less preparation, in the event of unanticipated events or when time is not available for thorough advance planning. Furthermore, the costs associated with preparing community relations programs are small relative to the overall costs of the associated projects. Because most environmentally sensitive projects require public support to be successful, well-planned community relations programs can greatly influence their outcome.

Communities and their communication systems are complex and need to be characterized and understood before community relations activities are initiated. The planning so essential to success includes the following steps: setting goals and objectives, identifying community characteristics, understanding communication systems, determining target audiences and developing an evaluation scheme. Although the step "understanding communication systems" is particularly important, it frequently is overlooked by program planners and guidance documents. This paper therefore not only briefly discusses each planning step, but also describes communication systems and their components in more detail, thereby providing understanding of their functions and interrelationships.

COMMUNITY RELATIONS PROGRAM PLANNING STEPS

Planning provides the basis for a coordinated effort by providing program direction, reducing the effects of unexpected changes, minimizing waste and redundancy, and facilitating control over communication and information exchange. Community relations program planning steps include the following major activities: (1) setting goals and objectives, (2) identifying community characteristics, (3) understanding communication systems, (4) determining target audiences and (5) developing an evaluation scheme.

Setting Goals and Objectives

Community relations program goals and objectives underpin the planning process by indicating the purpose of the program in terms of expected accomplishments and desired outcomes. They should provide direction, yet be flexible enough to accommodate new information and necessary revision. Nevertheless, the desired outcomes of the program should be specifically stated so that each step has clear criteria for measuring program effectiveness. A program typically has multiple goals and objectives. Typical goals are to disseminate information to special interest groups, heighten the awareness of uninformed publics, gain project support from local government officials or agencies, resolve specific issues with local business groups or solicit the participation of affected community members.

Identifying Community Characteristics

Once the program goals and objectives have been set, planners should then learn about the community. Identifying community characteristics is essential to determining target audiences and to understanding the communication systems so that community relations messages can be meaningful. Numerous variables affect program development and outcome. Measuring these variables and analyzing their respective significance provides a community profile that is very valuable in determining community subgroups and target audiences, identifying communication systems, choosing appropriate communication channels and formulating messages. Table 1 lists the variables most important to community relations programs.

Table 1
Variables to Consider When Identifying Community Characteristics

Variable	Comment
Media attention, coverage, and opinion	Public visibility (supportive or adversarial)
Risk perception	Relative to actual risk
Actual hazard or risk	Relative to perception of risk
Saliency of issue or proposed activity	Importance of issue relative to other community issues
Degree of polarization within the community	Alignment of community opinion or support
Past public interest, involvement, or position	Expected level of activity
Demographics and social structure	Race, age, marital status, and income
Community leaders with public influence	Special interest groups, media personalities, elected officials, union representatives, educational and religious leaders, and neighborhood associations
Geographical proximity	"NIMBY" ^a response
Community concerns and environment	Competing or complimentary issues
Project duration	Long- or short-term effects
Benefits and costs to community	Municipal revenues and property values
Recipients of benefits and costs	Equitable distribution thereof
Required regulatory oversight	Compliance enforcement
Voluntary or involuntary participation	Amount of control over involvement and assumed risks
Public participation	Timing and significance of input; token involvement or real decision-making opportunities
Alternatives	Identify and consider technological and geographical options
Urgency of issue or activity	Immediate (e.g., spill response) or planned (e.g., treatment facility construction)
Image and credibility of players	Perceived sincerity and community respect
Communications system	Channels of communication and flow of information

^aNot in my backyard.

Understanding Communication Systems

Once acquainted with a community's characteristics, planners should move on to understanding its communication systems. They should assess how members of the public find out about environmental problems and how they learn new community information. This step usually is limited to identifying interested citizens, responsible government officials affected organizations and community subgroups. However, simply identifying these entities and compiling a list of contacts is insufficient for effective community relations program planning. Rather, the communication systems within which the community relations program must function should be identified. Not only identifying, but also learning about these systems, constitutes a more comprehensive approach to developing contacts.

A communication system—also called a communication network—comprises the multiple communication links between people, agencies and businesses. A communication system can be thought of as a network of individuals linked by information exchange through mass media or interpersonal communications. Any individual will likely participate in several communication systems. He or she will tend to participate in networks involving individuals who share interests and espouse similar values.

Community relations programs are less effective when the communication links are incorrectly identified or inadequately understood. For example, using inappropriate methods to inform community members about an environmentally sensitive project or to solicit public involvement will lead to costly errors and inefficiencies.

The following discussion provides a framework for understanding how information flows through a community and techniques for identifying communication links. Understanding communication system components promotes improved community relations program planning and selection of the most appropriate communication channels for conveying program information.

Communication System Components

Every communication system has several components. Although the components are common to all systems, their characteristics will vary according to specific circumstances (e.g., CERCLA/SARA remedial response or NEPA EIS preparation). However, component types should be identified first and then the major community-relations-specific aspects of these components should be described. Communication systems all have seven major components: objects, attributes of objects, relationships among objects, environments in which the system functions, balance, hierarchical organization and goal orientation.

Objects are the elements of communication systems. In the case of community relations communication systems, the three main objects are the senders, the receivers and the communications media and messages. For example, receivers could be the community groups and subgroups to which a message is directed.

Attributes are the qualities or properties of the system's objects. Table 2 lists selected attributes for the three main objects mentioned above. Example attributes of a communicated message include how it is designed and delivered. Attributes also include the characteristics of the people or organizations that communicate, such as their beliefs and value orientations and their previous exposures to similar environmental issues (e.g., an agency's attitude toward planning and conducting a community relations program).

Table 2
Attributes of Objects within a Communication System

Object	Attribute
Communication sender	Knowledge of community concerns Attitude toward involvement Previous public involvement Attitude toward communication receivers Environmental knowledge Personal proximity to issue Risk perception Position in community (e.g., opinion leader or environmental group president) Previous exposure to problem
Communication medium and message	Length Channel (e.g., personal or interpersonal) Type (e.g., brochure or newspaper) Timing and frequency of information dissemination Amount of information Amount of coverage Credibility of information Suitability of language (e.g., technical or regulatory jargon)
Communication receiver	Environmental knowledge or awareness Diversity of demographic characteristics Previous public involvement Previous exposure to problem and attitude regarding problem Personal proximity to issue Risk perception Position in community Community group membership Effect of message (e.g., is the message actually understood?)

Relationships among objects are how the objects interrelate and affect each other. A change in one part of a system causes change in another part. Moreover, relationships and their effects may be direct or indirect

and are usually multidirectional. In other words, information moves from senders to receivers, but also vice versa. Objects are discrete units; however, when they are combined with other objects, and as a result of the relationships between those objects, they become a communication system.

Aspects of relationships to consider during community relations program planning include frequency and credibility of communications, past community involvement and number of communication sources providing either similar or different information. Another aspect to consider is the system's openness with respect to other systems (e.g., whether Native American or boat marina communication systems are being accessed in addition to those of environmental groups).

Each system *functions within an environment* and is therefore affected by this environment. Furthermore, the type of environment will likely influence system relationships. For instance, open systems (i.e., those that are strongly linked to other communication systems) can be effective in reaching community subgroups.

A *balanced* communication system not only produces outputs, but also receives inputs. For example, if an agency gives information to community members, then the agency should be prepared to receive information. Community members receiving information will react and send other information to other parts of the system, as well as back to the sender. The response information may be communicated in a different form, such as anger, involvement or awareness. Therefore, to maintain balance, each system must adapt and change. As a result, the goals and objectives set early in the planning process may have to be changed.

Hierarchical organization implies that objects combine to form subsystems within the larger system. A subsystem might include the communications network of an agency or a firm with environmental interests.

All communication systems are *goal oriented*. Planners should set goals for the communication system, but recognize that there are multiple pathways to achieving those goals. The goals set should reflect the goals and objectives set in the initial planning step, as described previously. Like the overall program goals and objectives, the communication system goals may change as a result of system components having different or conflicting goals. Likewise, the pathways to achieving these goals also may change.

Techniques for Identifying and Describing Communication System Components

Once the communication system components for a particular community relations situation have been identified, three techniques generally are used to describe the components more specifically: conduct surveys; search and review documents; and use available expertise. Each technique has certain strengths and weaknesses. The level and type of information obtained by each, as well as the time required to implement each, also vary. In some cases, it may be appropriate to use combinations of these techniques.

Conducting surveys entails formal questioning of community members about their communication systems. This technique is the most comprehensive, but also the most time-consuming. In addition, it requires the most expertise. Three types of surveys are used: (1) mail, (2) telephone and (3) face-to-face.

All three survey approaches should be carefully considered before selecting the most appropriate one for a given situation. For example, mail surveys are easier to send out, but may produce lower response rates than telephone surveys. Telephone and face-to-face surveys require trained interviewers and time to conduct the interviews. In some cases, using more than one type of survey may be appropriate. For example, it may be most effective to interview influential community members (e.g., opinion leaders) by telephone and mail questionnaires to a random sample of community members.

Design and implementation of the survey also require careful consideration. Questions should be carefully worded so that they solicit the desired information. Furthermore, to ensure representative results and absence of bias, survey participants should be selected through an

appropriate sampling scheme. A survey specialist can be very helpful in this regard.

Searching and reviewing documents entails examining materials that contain hints about the communication links within the community. For example, telephone books and newspapers may help identify groups interested in the issue (e.g., yacht club members for a water quality issue or the Sons of the American Revolution for an excavation site containing historical artifacts). Other useful documents might include listings from the local Chamber of Commerce and government contact lists. (Suggestions for compiling contact lists are found in Table 3.)

Table 3
Contacts for Helping to Determine Communication Systems

Contact Type	Example
Elected federal, state, and local government officials	Senators, congressional representatives, governors, mayors, and council members
Environmental health and safety agencies	U.S. EPA regional offices and branches; state environmental protection agencies or departments of natural resources and conservation; city, county, or township environmental commissions; local advisory commissions and planning boards; and health department sanitary engineers
Environmental organizations	Local Sierra Club chapter
Service groups and neighborhood associations	Local bridge clubs, Kiwanis Club, and League of Women Voters
Press and media representatives	Television, radio, and newspaper staff
Special-interest citizen groups	Boating, hunting, and other recreation-oriented groups

Searching and reviewing documents is less time-consuming than conducting surveys and requires less specialized expertise. It facilitates identification of communication system objects, but it does not facilitate understanding of other system components (e.g., attributes, relationships and hierarchies). Nevertheless, assembling contact lists and identifying system objects provide the basis for preliminary diagramming of community relations-specific communication systems.

Using available expertise entails relying on experience gained from previous community relations program planning and implementation efforts and informal contacts with potentially influential community members such as government officials and service club leaders. Some of the contacts may be asked some of the same questions asked in a survey. However, one must be careful about the representativeness of the answers when only a handful of community members have been contacted.

Although this final technique may be the least time-consuming, it also is the least systematic of the three. Furthermore, it is limited to gathering information on system objects.

Determining the Target Audiences

After identifying community characteristics and understanding community communication systems, planners should proceed with determining the community relations program target audiences. The affected community is composed of many subgroups. A subgroup may be an individual, individuals with shared concerns or formal organizations. Participating subgroups are those whose members have expressed interest in being involved, have a record of participation or have special interests (e.g., homeowners concerned with the effect of the project on property values or local Sierra Club or League of Women Voters chapters). Nonparticipating subgroups generally account for a greater number of (but not necessarily the most influential) people and often are referred to as the "general public."

The community relations program goals and objectives for each community subgroup may be different. For instance, an objective for non-

participating community subgroups might be to increase their awareness of the issues by distributing general fact sheets. An objective for participating subgroups might be to educate them through project-specific cost/benefit analyses.

Each community subgroup is a discrete audience with its unique set of attributes and community characteristics (Table 1). To be effective, community relations program planners must recognize the existence of multiple target audiences and tailor the communications accordingly.

Developing an Evaluation Scheme

Mechanisms for community relations program evaluation should be formalized during the planning process so that evaluations can be conducted during program implementation as well as following completion. Moreover, program evaluation before full-scale implementation provides intermediate feedback, which allows decisions made in the previous planning steps to be appropriately modified to increase overall program effectiveness. For example, proposed messages and communication methods or formats could be pilot-tested to determine their appropriateness and effectiveness.

Early recognition and correction of ineffective messages and communication methods greatly increase program efficiency by minimizing production, administration and distribution activities. The effectiveness of community relations programs can and should be evaluated against measurable criteria developed during the setting of program goals and objectives both during and after program implementation. Evaluation results can then be used to modify inadequate program components. Post-program evaluations lead to better understanding of accomplishments and outcomes and provide the basis for the success of future community relations programs.

CONCLUSION

There are several benefits to completing the planning phases of com-

munity relations programs in a timely and thorough manner. Planning enables quicker and better responses to unanticipated changes. It also increases the level of experience, which is useful for future program development, and it can enhance the image and credibility of involved agencies and corporations. Such factors can influence the success of both current and future programs.

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REFERENCES

1. Babbie, E., *Survey Research Methods*, Wadsworth Publishing Co., Belmont, CA, 1973.
2. E. Bruce Harrison Company, Inc., *Environmental Communication and Public Relations Handbook*, Government Institutes, Inc., Rockville, MD, 1988.
3. Fazio, J. R. and Gilbert, D., *Public Relations and Communication for Natural Resource Managers*, Kendall-Hunt, Dubuque, IA, 1983.
4. Hanchey, J. R., *Public Involvement in the Corps of Engineers Planning Process*, IWR Research Report 75-R4, U.S. Army Engineer Institute for Water Resources, Fort Belvoir, VA, 1975.
5. ICF, Inc., *Community Relations in Superfund: A Handbook*, U.S. EPA Report No. EPA/540/G-88/002, U.S. EPA, Washington, DC, June 1988.
6. Littlejohn, S. W., *Theories of Human Communication*, Wadsworth Publishing Co., Belmont, CA, 1983.
7. McDonough, M. H., "Audience Analysis Techniques," in *Supplements to a Guide to Cultural and Environmental Interpretation*, prepared for Office, Chief of Engineers, U.S. Army, Washington, DC, by Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1984.
8. Robbins, S. P., *Management: Concepts and Practices*, Prentice-Hall, Englewood Cliffs, NJ, 1984.

Treatment of Coal Tar Contaminated Soil and Lagoon Closure

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ABSTRACT

During 1984 and 1985, Chemical Waste Management's ENRAC division removed 1,000,000 gal of coal tar from an open 1 acre lagoon. Two thirds of the coal tar was treated on-site to make a supplemental fuel blending component. The final one third of the coal tar was treated using an in situ stabilization process. The stabilized material was then disposed of in a hazardous waste landfill. After satisfying the cleanup requirements of the state regulatory agency, the coal tar lagoon underwent final closure.

Over 1500 coal gasification "town gas" sites left over from plants that operated in the United States between 1850 and 1950 have been located. Coal tar waste from these plants was accumulated in open lagoons. Many of these lagoons have since been filled in with debris and covered with soil. The following treatment technologies are evaluated for remediating coal tar contaminated soils at former town gas sites:

1. Bioremediation
2. Thermal Desorption
3. Organic Solvent Extraction
4. Surfactant Soil Washing

INTRODUCTION

For 100 yr, until the mid 1940s, "town gas" produced by coal gasification was a major source of energy for many cities throughout the United States. Town gas was formed by carbonizing coal.

Coal was heated in a reactor to drive off volatile compounds that became part of the town gas. At the same time, the heated coal was reacted with steam to produce "water gas", which also was mixed with the town gas.

In the town gas manufacturing process, 6 to 9 gal of waste by-product coal tar were produced for each ton of coal fed. The yield of coal tar from carbonization is approximately linearly related to the amount of volatile components in the coal¹. A typical plant using 50 tons of coal a day, over a 100 yr lifetime, produced 10 to 16 million gallons of coal tar², which usually was placed in trenches or lagoons on-site. Many of these trenches and lagoons have since been filled with debris and covered over to meet pressing real estate demands.

It is estimated there are 1500 to 2000 of these town gas sites potentially in need of remediation across the country³. Some of these sites are currently part of the Federal Superfund program.

COAL TAR CHARACTERIZATION

Coal tar made from the carbonization of anthracite, lignite or bituminous coal will have varying chemical compositions and physical properties depending on the constituents of the original coal. The total amount of volatile material in the coal has an impact on the amount

of coal tar produced when coal is carbonized. Composition also varies depending on whether benzene/toluene/xylene (BTX), creosote or pitch components were recovered from the tar. BTX often was recovered as a solvent or as a liquid fuel component. Creosote was recovered and used as a wood treating agent. Pitch was in demand as a sealing agent for roofs.

If no auxiliary recovery of the BTX, creosote, or pitch components took place, the typical composition of the resultant coal tar is illustrated in Table 1.

Table 1
Composition of Coal Tar⁴

Benzene	15%
Toluene	3%
Xylene	1%
Light Oil	4%
Naphthalene Oil	8%
Heavy Creosote Oil	9%
Anthracene Oil	13%
Soft Pitch	16%
Medium Pitch	14%
Hard Pitch	17%

PROJECT COAL TAR STRATIFICATION

Chemical Waste Management's (CWM) Environmental Remedial Action division (ENRAC) gained "hands on" experience in remediating a coal tar contaminated site between 1984 and 1985. During the project, ENRAC removed 1,000,000 gal of coal tar from a 1-ac lagoon. ENRAC found that the coal tar tended to stratify into several layers after settling for over 40 yr. Each layer exhibited unique physical and chemical characteristics^{4,5}. At room temperature, separate liquid, semi-solid and solid phases appeared. A description of each coal tar phase in the lagoon from the project is found in Table 2.

COAL TAR REMEDIATION PROJECT

At room temperature, a composite blend of coal tar phases is a sticky, tacky semi-solid material. However, significant changes in physical properties occur with variations in temperature. At higher temperatures the viscosity drops dramatically, causing the semi-solid material to liquify. Table 3 illustrates this relationship between temperature and viscosity for the coal tar found in the Illinois lagoon⁶.

Table 2
Phases Coal Tar Lagoon

<u>PHASE</u>	<u>DESCRIPTION</u>	<u>COMPONENTS</u>
I	Light Oil (LO)	BTX, Light Oil
II	Viscous-Rubbery (VR)	Naphthalene Oil, Anthracene Oil, Creosote Oil
III	Hard and Crumbly (HC)	All Pitches, and any Coal Solids (including coke)
IV	Contaminated Soils (CS)	All Phases of Tar

Table 3
Viscosity of Coal Tar vs. Temperature for Coal Tar⁶

<u>Temp (°F)</u>	<u>Viscosity (Poise)</u>
72	3400
120	435
160	85
200	16

Note: Coal tar becomes pumpable at 25 poise (roughly 185°F)

These changes in viscosity were exploited during the remediation of the site. ENRAC found that coal tar can be excavated when cold and pumped when heated. Because the coal tar in the project had separated into three separate organic phases plus a contaminated soils phase, individual materials handling strategies were developed for each phase. The strategies are described in the next four sections of the paper.

Light Oil Phase Strategy

In 1984, the light oil phase of the lagoon was removed using a high speed, open impeller submersible pump suspended from an overhead crane. Because coal tar is black, the surface of the lagoon absorbed significant heat energy from the sun during the summer to liquify the light oil. Eventually, enough of this energy was absorbed to cause a "sweet spot" to develop. This is an area where the sun had heated the light oil sufficiently that it flowed and could be pumped. The pump was continually moved to other new "sweet spots," until all of the pumpable light oil phase was removed from the top of the lagoon.

The light oil was pumped directly from the lagoon into liquid tankers. The tankers were heated using internal steam coils until shipment of the contents to a liquid fuels blending facility. The fuels blender blended waste solvents with the coal tar light oil prior to disposal as a liquid supplemental fuel in a blast furnace, cement kiln or industrial furnace.

Viscous Rubbery Phase Strategy

After the coal tar light oil was pumped off, the submersible pump began to pick up the heavier viscous/rubbery coal tar phase. Pumping operations slowed down. In addition to encountering a more viscous coal tar phase, ambient temperatures had decreased (the fall months), which made additional pumping almost impossible without auxiliary heating. Coal tar remediation was shut down during the winter of 1984-1985.

The following spring, 1985, ENRAC began the remediation of the viscous rubbery (VR) phase. A small pit was excavated adjacent to the lagoon. Then a box pattern 20 ft x 20 ft x 10 ft heat exchanger made of 2-in. pipe was placed into the pit. A hot glycol/water solution was circulated inside the 2-in. pipe. The glycol/water solution was heated by a steam package boiler system. The temperature of the coal tar in the pit was kept below 190°F, minimizing fugitive emissions of BTX during heating.

The heat exchanger had a large heat transfer area, which was needed to promote both convective and conductive heat transfer (coal tar has a low thermal conductivity). Once the semi-solid material is liquified, convective rather than just conductive heat transfer will occur.

The VR phase material was placed in the heat exchanger pit using a clam shell and heated until it became fluid. The material was then

pumped, using a submersible pump, into steam-heated tankers for shipment to the liquid fuels blenders as a liquid supplemental fuel component.

Hard and Crumbly Phase Strategy

Hard and crumbly material was stabilized in situ using proprietary blends of cement and lime kiln dust, then exhumed and transported to a hazardous waste landfill. This stabilization was done because it was the most practical option available at the time. No option for disposal as a solid supplemental fuel was available in 1984 or 1985. After May, 1990, untreated disposal of the hard and crumbly phase in a hazardous waste landfill will not be permitted, due to the HSWA land-ban hammers.

Contaminated Soils Phase Strategy

According to the 1985 closure plan, the contaminated soils below the hard and crumbly phase were stabilized and mixed with clean soil backfill and left on-site. Today, because of the HSWA land-ban hammers, further treatment to remove coal tar residuals is required. Strategies to remove coal tar residuals from contaminated soil are discussed in the next section.

In the past, the methods described above for the 1984-1985 project were sufficient to accomplish the remediation of an open coal tar lagoon. Today, with stricter environmental regulation of fugitive air emissions and land ban regulations, these remediation strategies will have to be modified. CWM's Research and Development Group is actively pursuing new and innovative technologies for dealing with each phase of the coal tar lagoon remediation problem.

FUTURE COAL TAR REMEDIATION PROCEDURE

Supplemental Fuels Recovery

CWM is developing a devolatilization/detackification process to convert a VR-HC mix into a solid supplemental fuel, which can be utilized as a coal substitute. The unit being developed will combine VR, HC and a blend of proprietary inorganic/organic detackifying agents and mix them in a totally enclosed, indirect, heated paddle mixer to produce a coal-like solid supplemental fuel. The devolatilization step in this process removes BTX, thus rendering the fuel non-hazardous.

VR and HC components having a fuel value of 5000 Btu/lb or more can be recovered and used as a solid supplemental fuel in industrial processes. The 5000 Btu/lb criterion is set because 5,000 Btu/lb is required to sustain combustion. Burning material of less than this value for fuel is considered sham recycling. If a compound has less than this fuel value and it is burned as fuel, technically it is being incinerated, because additional fuel must be added to sustain combustion.

It is the opinion of the authors of this paper that any facility that engages in this practice of sham recycling should be regulated as an incinerator. Generators should be very selective from a liability standpoint when choosing a fuels blender and energy recovery facility.

Solvent Extraction

Laboratory studies show that solvent extraction effectively removes coal tar from contaminated soil and rocks. CWM has tested solvents such as propane, pentane, Freon, methanol, trichloroethylene, and triethylamine (TEA).

Solvent extraction processes are designed to remove contaminants from contaminated soil by extraction into the solvent phase. The solvent is then recovered and reused. Solvent recovery is necessary because of its cost and fugitive emission control. The residual solvent in the soil is driven off thermally and recovered.

Solvent extraction may be expensive because of the costs associated with the hazard of using large volumes of solvent, the need to control fugitive VOC emissions, and material handling difficulties that may occur with the use of flammable organic solvents.

Since most of the town gas sites in need of remediation are in highly populated urban areas, the use of large volumes of organic solvent may be undesirable. The safety and toxicological risks of this technology must be carefully considered before choosing this option.

Soils Washing

In soils washing systems, surfactant/water solutions are mixed with the contaminated soil/rock in an agitated vessel. After sufficient agitation, the contaminant/aqueous solution is removed from the soil by filtration. CWM has developed a proprietary soils washing process, in which water and surfactant can be recovered without distillation and be re-used in the process. Benefits of soil washing include: the biodegradation properties of the surfactants used; the absence of solvents; and the non-thermal nature of the process.

Soils washing may be difficult, however, because of the need to emulsify the coal tar for good removal from soil. Hard pitch materials are harder to emulsify than the light oil phase of the coal tar. Soils washing will work for coal tar contaminated soil if the right situations exist. Adequate testing of bench-scale systems and stringent economic analysis must be completed before selecting this option.

Incineration

When a site has a significant amount of contaminated soil/debris that occurs after a lagoon has been filled in or covered, incineration may be the only practical remedial alternative. When using on-site incineration, all phases of the material can be disposed of collectively. Incineration, in some cases, may be required by the regulatory agencies.

CWM has developed PYROX, a transportable rotary kiln incineration system designed to handle these types of materials. The PYROX unit has a horizontal, rotary kiln, primary combustion chamber into which the contaminated soils are fed. The vertical, secondary combustion chamber takes gases from the primary chamber and exposes them to a temperature of 2200°F. Exit gases are scrubbed with a dry scrubber to remove HCl and particulates prior to discharge.

Incineration can treat all phases of coal tar effectively. However, it is the most expensive treatment technology discussed in this paper.

CONCLUSION

In most cases, more than one technology should be applied during town gas remediation projects. Certain technologies will work well for certain phases of the contaminated material, but one technology will not necessarily be the best solution for the whole cleanup. Careful testing of these technologies in the laboratory must be performed before committing to a full-scale project.

Table 4
Viability of Contaminated Soil Remedies

	Applicability/Effectiveness
Bioremediation	Potentially Viable for Low Contaminant Concentration - May not achieve needed levels of clean-up.
Thermal Desorption	Not Viable - Thermal Desorption will not effectively remove high boiling point PNAs from soil.
Solvent Extraction	Viable - Works well to remove coal tar. Hazards of use of large volumes of organic solvents must be considered.
Soils Washing	Potentially Viable - Must do treatability studies. Still under development.
Incineration	Very Viable - Will treat all phases of coal tar and contaminated soil.

Supplemental fuels are a cost-effective disposal outlet for all of the coal tar phases having a high heating value. The viability of contaminated soil remediation must be closely examined. Table 4 summarizes the viability of various soil remedies discussed in this paper.

When the final third HSWA land-ban treatment standards are enacted in May of 1990, most coal tar will be listed as characteristically hazardous because of CCW levels of BTX organics. This base will mean that untreated land disposal of coal tar waste will be prohibited. Because this waste is a final third waste, if no treatment standards have been established by May of 1990, land disposal of this waste, treated or untreated, will be prohibited regardless of what treatment technology is viable.

Until standards for the treatment and disposal of coal tar are set, Table 5 summarizes the recommended disposal options.

Table 5
Recommended Strategy for Coal Tar Lagoons Remediation

Coal Tar Fraction	Recommended Strategy
Light Oil:	Recovery as liquid supplemental fuel blending component. No auxiliary heating is required. Control of VOC emissions is necessary.
Viscous/Rubbery:	Development of solid supplemental fuel utilizing detackification and devolatilization process. Control of VOC emissions is necessary.
Hard and Crumbly:	(Same as above for viscous rubbery)
Contaminated Soil:	1. Incineration 2. Soils Washing 3. Solvent Extraction 4. Bioremediation

As each coal tar segment is encountered, the appropriate remedial remedy changes. This paper is intended to aid in the development of a management strategy for the selection of feasible remedies at town gas sites. This paper can be viewed as a road map for the remedy of town gas sites. By dividing the remedy of town gas sites into different phases, this coal tar problem can be conquered.

REFERENCES

1. Droegkamp, R. E., Schussler, M., Lambert, J. B. and Taylor, D. F., "Tar and Pitch" in *Encyclopedia of Chemical Technology*, Kirk and Othmer, Vol. 22, 3rd Ed., John Wiley and Sons, New York, NY, pp. 564-600, 1983.
2. Laformara, J.P. et. al., "Coal Tar: Pollutants of the Past Threaten the Future", *Proc. of the 1982 Hazardous Materials Spills Conference*, Milwaukee, WI, 1982.
3. Fochtman, E. G. and Cartwright R. T., "Closing a Coal Tar Lagoon," American Institute of Chemical Engineers Annual Meeting, New York, NY, Nov., 1987.
4. Kent, J. A., *Riegel's Handbook of Industrial Chemistry*, 7th ed, Van Nostrand Reinhold Publishing, New York, NY, 1974.
5. Austin, G. T., *Shreve's Chemical Process Industries*, 5th ed, McGraw-Hill Book Company, New York, NY, 1984.
6. Fochtman, E. G., and Cartwright R. T., "Closing a Coal Tar Lagoon," American Institute of Chemical Engineers Annual Meeting, New York, New York, Nov., 1987.
7. Swanson, C., "X*TRAX Low Temperature Transportable Treatment Process for Organic Contaminated Solids," *Proc. of the 1989 HazMat Central Conference*, Rosemont, IL, Mar. 15, 1989.

Owner, Contractor, Government Relationships

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INTRODUCTION

Superfund site cleanups are becoming more complex and involved, particularly with regard to the relationship between the remediators (Owner, Contractors) and the Regulators (Governments).

The relationship between the Owner and cleanup Contractor is basically contractual and governed by the principles of construction contract law. However, the relationship between the Owner/Contractor and the "Governments" can be relatively complex. Some of the governmental entities that can be involved are Federal (U.S. EPA), State (pollution control authority - usually both regional and headquarters staffs), local County and City authorities [police department, health department, fire department, building department, planning department, legal department, community relations department, engineering department and utility departments (water, sewer, storm drainage, streets), etc.] In addition, quasi-state authorities such as regional wastewater treatment authorities and regional air quality authorities often are involved in the cleanup.

Each of the governmental entity listed above has power to regulate construction activity within the "scope of their authority." The local authority's power usually is exercised by the granting of permits. Often the "scopes of authority" of the various governmental units overlap or are unclear. In this situation, the effect on the remediators can be either conflicting permit requirements imposed by different authorities or inaction on the part of the permitting authorities (each claiming another agency is responsible for some action). In addition, the Governments responsible for oversight of the cleanup (U.S. EPA or state pollution control agency) often delegate review authority for portions of the cleanup activity to other state and local agencies (i.e., regional wastewater treatment authority, regional air quality authority, etc.).

Potentially superimposed over this governmental review activity is "community action group" oversight. The formation and use of such community action groups was encouraged by SARA; Federal funding is available for their activity.

The purpose of this portion of the seminar is to apprise Owners/Contractors of the general regulatory scheme imposed on hazardous waste cleanup activities and some of the potential pitfalls they may face. Experience with the Western Processing Superfund site cleanup located in Kent, Washington, one of the largest site remediations (more than \$80 million) currently in progress, will be described relative to Owner/Contractor requirements imposed by the local government.

REGULATORY SCHEME

In most site remediations currently in progress, either the Federal government (U.S. EPA) or the State government (pollution control authority) is the lead agency. The state would be a lead agency if the remediation were conducted under a State "Superfund" program, or

site cleanup responsibility was delegated to the State by the Federal government. Lead agency status usually is decided internally between the Federal and State agencies. Thus, from the standpoint of the site remediation Owner/Contractor, the lead regulatory agency is clearly defined, and the set of rules/regulations governing the technical aspect of the cleanup is known. What is less clear in a site remediation is the status of the local governments (County or City). The balance of this paper will deal with the legal powers of the local governments and how the exercise of this power can be perceived by the local government.

Under the United States governmental system, all power emanates from "the people." The people delegated certain specific powers to the Federal government. The legislative powers, which are enumerated in the U.S. Constitution (Article 1), include spending, foreign affairs, war powers, immigration, taxation and commerce. The Constitution also grants implied powers (Article 1, Section 8) which allows Congress to regulate outside the enumerated areas so long as the result furthers an enumerated power (necessary and proper clause). Powers not delegated to the Federal government are specifically reserved to the states or the people under the 10th Amendment.

State constitutions likewise define the relationship between "the people" and state government for sharing of non-Federally delegated powers. Each state is somewhat different in terms of specific power allocation. However, certain non-Federal powers traditionally have been reserved "to the people" (i.e., local governments). These areas of power, as perceived by most local governments, include land use planning, police protection, fire protection, building code enforcement, local transportation, utility services, parks and recreation and community health services. Thus, the local governments expect that if a Federal or State site remediation activity impacts one of the above areas traditionally regulated by the local governments, the local governments will have control over that activity. Whether a local government does, in fact, have control, and the extent of that control, can be the subject of protracted legal and political maneuvering. The Owner/Contractor should be aware of the potential for an intergovernmental power struggle, particularly in areas traditionally regulated by local governments.

In addition to the power allocation issues, it makes good public relations sense for the Owner/Contractor to keep the local governments involved in the cleanup process to the maximum practical extent. Local governments tend to feel that they are the true grass roots representatives of the people, and thus usually are concerned about the health risks, timing and community impacts of the remediation effort. Oversight groups of private citizens, whose activities may be funded under SARA, may be established for each remediation site. In general, these groups either include members of local government or report to local government. Also, their opinions often are considered newsworthy by the press.

WESTERN PROCESSING SUPERFUND SITE

The Western Processing Superfund site is located in Kent, Washington, about 20 mi south of Seattle, Washington. The area is heavily industrialized, primarily with firms serving the aerospace industry.

Western Processing was operational during the 1960s and 70s, providing chemical reclamation and recycling for materials generated by over 400 public and private customers. Waste materials included animal by-products, metal finishing solutions, oils, paints, solvents, cyanide and battery acid. Due to spills and other releases, the materials over time contaminated the soil and groundwater beneath the site and Mill Creek which runs through the site. In 1983, the site was forced by the EPA to close.

The site is underlain with an alluvial aquifer that extends to a depth of approximately 150 ft. The aquifer is bisected by a 10) to 15-ft-thick semi-permeable stratum located at a depth of approximately 45 to 60 ft. The upper portion of the aquifer is referred to as shallow groundwater, and the lower portion is referred to as the regional aquifer. The shallow groundwater and soil beneath the site are contaminated with over 90 contaminants including lead, zinc, cadmium, phenol, toluene, methylene chloride, oxyzolidinone, trichloroethylene and other solvents. The regional groundwater is largely uncontaminated.

The largest single contributor of waste to the site was the Boeing Company. Boeing organized the negotiations between the Regulators and approximately 200 PRPs. A consent decree was entered in U.S. District Court in August, 1984, initiating Phase I of the remediation.

Phase I consisted of surface cleanup. Approximately 2,400 truck-loads of various wastes were removed for off-site treatment and disposal. Approximately 7,400 gal of dioxin-contaminated liquid were treated using the potassium polyethylene glycol process. This process destroys dioxin in a low-temperature, low-pressure reaction with no air or water emissions.

Phase II of the remediation process began in April, 1987, and dealt with subsurface cleanup. Approximately 22,000 yd³ of specific waste were hauled off-site for disposal at Arlington, Oregon, a U.S. EPA-approved hazardous waste landfill. A slurry wall was installed around the 16-ac site, extending down into the semi-permeable stratum (± 50 ft). A vacuum groundwater extraction system using 206 wells was installed along with an infiltration system. The groundwater extraction system discharges to a treatment system consisting of a stripping tower with a Calgon CADRE fume incinerator for volatile removal, and liquid phase phenol oxidation/heavy metal precipitation. Precipitated heavy metal sludge is dewatered in a plate and frame press and hauled to the Arlington, Oregon disposal site.

The general operational scheme is to pump, treat and re-infiltrate the groundwater in order to remove the heavy metal contamination. The pump- and treat-system has to operate for at least 5 to 7 yr and may have to be operated for as long as 30 yr to achieve the desired cleanup level.

GOVERNMENTAL ISSUES

The Federal and State Regulators (U.S. EPA and Washington State Department of Ecology) have dealt primarily with enforcement of the Consent Decree. The City of Kent, which was not a party to the Consent Decree, desired to be involved in the remediation process since it impacted their community and governmental services. Kent passed an ordinance requiring remediation contractors to pay an annual permit fee in order to fund the City's involvement in the remediation process. In April, 1987, Kent retained R. W. Beck and Associates, a Seattle-based consulting engineering firm, to provide technical oversight of the remediation process.

In addition to reporting to Kent on remediation progress, Beck assisted the Owner/Contractor and Regulators in dealing with a number of local

issues. The following is a summary of some key local issues and suggestions for dealing with such issues on other sites.

Land-use planning

A key assumption of the risk assessment associated with establishing the level of cleanup centered on the future use of the Western Processing site and surrounding property. Cleanup levels were predicated on the property retaining an industrial classification (i.e., residential type exposure not anticipated). The local planning agency should thus be involved in reviewing any assumptions regarding future land use relative to risk assessments.

Police protection

Site security is always a key issue in hazardous waste site remediation. If the Owner/Contractor expects the local police force to enforce trespass law and the local city attorney to prosecute trespassers, then the applicable law must be followed closely. It would be desirable to get in writing from the city attorney's office the exact steps needed to post the property for trespass enforcement.

Fire protection

Special training and equipment may be required for personnel expected to combat a fire on a hazardous waste remediation site. Frequent communication on potential problems and availability of supplies such as foaming agents, etc., is a must. Evacuation plans and air toxic control measures for the surrounding area also should be coordinated with the local fire department.

Utility services

At Western Processing, plans are to use up to 60 gpm (86,000 gpd) of potable water for infiltration flushing. Added to this are potable water requirements for equipment seals and cooling water. The Western Processing site remediation is one of the largest users of potable water in the city.

Code enforcement

The city enforces the Uniform Building Code, Uniform Plumbing Code and Uniform Fire Code. All construction should comply with these codes in order to reduce Owner/Contractor liability for negligent construction.

Local transportation

Since a hazardous waste site may be in limbo for 30 yr or longer, it can have a major impact on planning for local streets and arterials. Consideration should be given to future transportation plans when designing a remediation system.

Parks/Recreation

A major recreational facility called the Interurban Trail extends along the east side of the Western Processing site. This trail had to be closed for over 2 yr because of remediation activity. Consideration had to be given for alternative safe routing for people using the trail. Failure to adequately consider safe rerouting could substantially increase the liability of the Owner/Contractor for injury suffered by trail users.

CONCLUSION

The relationships among the site owner(s), remediation contractor(s) and Federal/State regulators are fairly well defined. The relationships of the above parties to local governments are less well defined.

Activities normally regulated at the local level include land-use planning, police protection, fire protection, utility services, code enforcement, local transportation and parks/recreation. Owners and Contractors should comply with local regulatory agency requirements to improve public relations and to minimize legal liability for asserted negligent conduct.

Evaluation of Procedures For Claims Presentation and Resolution

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ABSTRACT

The objective of this paper is to explore those procedures which can be taken by a construction manager to minimize the number of claims which result from contractual changes and to enhance their resolution. This objective is achieved through a discussion of mitigative actions that can be taken during both the pre-bid and the post-bit periods.

Pre-bid actions include: (1) developing clear and concise bid documents, (2) including contractual provisions that clearly define each party's responsibilities relating to change, (3) establishing a contracting strategy and (4) clarifying ambiguities.

Post-bid actions include: (1) assigning experienced contract administrators and inspectors to the construction management team, (2) establishing procedures for documentation of events, (3) educating team members on instruction procedures and claims elements and (4) avoiding arbitration and litigation whenever possible.

Adherence to these procedures will be material assistance in reducing the number of claims and in achieving their resolution in an efficient, equitable and cost-effective manner.

INTRODUCTION

Like death and taxes, two things that can be said with certainty about a construction project are: (1) changes will be made during the course of construction, and (2) the construction manager and the contractor will seldom initially agree on the effect the changes have upon the project. The objective of this paper is to provide a description of procedures which can be implemented by a construction manager to minimize the number of claims which result from contractual changes and to enhance their resolution.

Failure to properly address all aspects of the claims procedure will result in unnecessary performance and construction management costs. This oversight can also lead to the development of an antagonistic relationship between the construction manager and the contractor which increases the likelihood of disputes. Mitigative actions can be divided into pre-bid categories.

Requisite pre-bid actions include: (1) developing bid documents that precisely define the work to be performed and the expected site conditions, (2) including contractual provisions which clearly define each party's responsibilities relating to change, (3) establishing a contracting strategy and (4) clarifying ambiguities during pre-bid meetings and in formal responses to questions received during the bidding period.

Post-bid actions include: (1) assigning experienced contract administrators and inspectors to the construction management team, (2) establishing procedures to identify, document and track changes from inception through the issuance of change orders, (3) educating all members of the construction management team on pricing procedures, the elements of contractor costs and the necessity for documenting all

instructions to the contractor and (4) avoiding arbitration and litigation for claims settlement whenever possible.

DEFINITIONS

Prior to beginning this discussion of the procedures required for an effective claims control program, the following definitions are offered to avoid confusion.

Change:

A change is any modification to the guidance provided within the contract documents. Therefore, changes encompass modifications to specifications, drawings and other written or oral guidance. They may be generated as a result of design modifications, field orders, excusable delays, actions of the construction manager or other contractors, and differing site conditions.

Claim:

A claim is a written assertion by one of the contractual parties seeking as a legal right the payment of money, an extension of performance time, an adjustment of contract terms or other relief under the terms of the contract.

Change Order:

A change order is the formal instrument for establishing agreement between the parties to alter the contract price and/or performance time. It is the contractor's responsibility to notify the construction manager if an event occurs which he believes justified an increase in contract price or an extension in contract time. Conversely, the construction manager must initiate deductive claims.

The following discussion of claims procedures is directed specifically toward a construction management function for commercial contracting. However, most of these procedures are equally applicable to a governmental contract. Although changes will affect both cost-reimbursable and fixed-price contracts, the impact is far more severe on a fixed-price basis. Consequently, this discussion specifically addresses that type of contract.

PRE-BID ACTIONS

Completeness of Bid Documents.

Disagreement over the interpretation of contractual terms and conditions and the scope of work is a major cause of contract claims, disputes and litigation. A concerted effort should be made during the preparation of the contract bid documents to ensure uniformity, compatibility and clarity of construction requirements and to accurately define site conditions. The construction manager will be compensated many times over for this effort by reductions in expenditures related to claims and disputes and by reductions in performance costs. Achieving

completeness and clarity requires the early freezing of design and the performance of rigorous constructibility reviews during the design effort.

Many claims can be prevented by establishing a detailed definition of the work scope and an accurate description of the payment bid schedule items. Precise definition of contractor interface is particularly important when multiple contractors will be involved. Including a detailed description of payment items in the bid documents is a convenient and effective method of avoiding claims.

Contractual Provisions to Regulate Changes

Contractual provisions for change control procedures include both general provisions and special conditions, both of which are mandatory for the orderly resolution of claims. A properly formulated contract should, at a minimum, include provisions for the following:

- Changes in the work
- Changes in the contract price
- Changes in the contract time
- Decisions and disputes resolution
- Construction management responsibilities
- Differing site conditions
- Reference points
- Subcontractor Rejection
- Laws and regulations
- Related work at site
- Field Orders
- Defective work
- Suspension of work
- Contract termination
- Quantity variations and unit price adjustments
- Force account labor, equipment and mark-up rates
- Excusable delays

The most important change provisions are those which assure the construction manager's right to order changes, prescribe equitable contractor compensation and require the contractor to implement the change without undue disruption to project progress. Establishing the joint ownership of float is also a critical contractual requirement.

Contracting Strategy

There are two fundamental contract classifications: (1) fixed-price, for which the contractor has primary cost responsibility and (2) cost-reimbursable, for which the construction manager's client shares in the cost responsibility. The selection of the appropriate contract type requires an assessment of cost, time and quality priorities.

Fixed-price contracts provide the means for maximum cost control but require the longest period of project performance time since drawings and specifications must be completed prior to bid solicitation. The use of a series of fixed-price contracts can reduce the total project time by permitting construction to proceed on some initial work packages concurrently with the design of subsequent work packages. However, use of multiple fixed-price contracts requires a more definitive work scope and closer coordination of contractor operations. This method also creates the potential for increased claims resulting from the simultaneous use of work areas by contractors and the interdependency of various contractors' work activities.

Clarification of Ambiguities

Invitations to bid should include a request for the submittal of written questions from the contractors at the pre-bid meeting. In addition to providing answers to these questions, the construction manager should review his requirements for progress meetings, administrative submittals, project control, quality control, health and safety, site security and schedule compliance. Minutes of this meeting should be recorded and issued as a solicitation addendum. Substantive questions received during the bidding period also should be recorded and issued with their answers as a contract addendum. Efforts to assure a mutual understanding of contract language and intent will substantially reduce claims.

POST-BID ACTIONS

Experienced Staff

The experience of the administrative staff and inspection force is of particular importance in minimizing claims and in achieving prompt resolution and settlement. Staff personnel must be thoroughly familiar with construction procedures and be aware of the manner in which a change can impact the contractor's cost. Without this understanding, administrators will not appreciate the full effect of their actions upon the contractor's costs.

Change Documentation

The establishment of a procedure for documenting changes and potential claims is essential to the orderly settlement of the claims. Without suitable documentation, the construction manager will be at a disadvantage in assessing the validity of the contractor's contentions.

Accurate project records should be maintained so that the day-to-day work history can be recreated if necessary. Effective documentation can be achieved by maintaining daily construction reports and a project photograph log, performing time studies and establishing a correspondence control system which prescribes procedures for logging, serializing and filing correspondence and other written data.

Of particular importance to claims resolution is the maintenance of a separate file for each incident that may result in a claim. A case file should be established for each contractor with each incident assigned a serial case file number. All pertinent information relevant to a specific incident should be retained in the applicable case file. A confidential case file log, similar to the example provided as Appendix A, should be maintained to provide effective control of the required responses to each incident.

Every effort should be made to promptly settle claims while the facts and circumstances are current. Failure to quickly resolve claims will generally result in a more costly settlement. A construction management policy of pricing and resolving claims prior to the commencement of work, whenever possible, must be rigorously followed. Retroactive pricing is undesirable since it promotes force-account pricing and increases administrative control costs. However, where situations make it impractical to preprice the change or where operational conditions require the immediate execution of the change, a work directive may be issued on a cost-reimbursable basis. This decision should be based solely upon the nature of the uncertainties at the time the change must be executed.

When work is performed on a force-account basis, the scope of work must be clearly defined and daily records of the work effort maintained. Appendix B provides an example of the type of form that should be employed. These reports will provide invoice support for periodic payment by documenting daily agreement on labor, equipment and supply costs expended while executing the change.

Agreement between the parties must be formalized in a change order which includes the elements should in Appendix C. Forward-priced change orders will be executed prior to the commencement of the work. A formal change order would also be executed at the conclusion of force-account work to document costs and to modify the contract price.

A final procedural requirement is the maintenance of a change order log for each contract that contains the basic information shown in Appendix D.

Educating the Construction Management Team

The members of the construction management team must be thoroughly indoctrinated on the procedures necessary for suitable claims documentation and control. The objective of forward pricing and the necessity for only formal directives for field changes must be stressed. Inadvertent directives to the contractor must be prevented, since such instructions can result in costly and unnecessary claims.

All members of the construction management team should be reminded of the various manners in which a change can affect a contractor. A change may have both a direct and a consequential impact upon cost and/or performance time. In addition, the timing of the change can be critical. A change issued prior to the commencement of con-

A change issued during construction may result in a cost increase directly attributable to some combination of the following:

- Consequential impacts of a change may include the cost increases caused by the following:

- Change of work to unfavorable construction seasons
- Miscellaneous - bond and insurance
 - small tools and consumables
 - revisions to as-built drawings
 - extra cleanup costs
 - materials handling and disposal
 - materials expediting
 - increased warranty reserve
 - escalation

Avoidance of Arbitration and Litigation

Arbitration and litigation are methods of resolving disputes which customarily occur long after project completion. These remedies are costly for both parties, require the expenditure of considerable resources and necessitate the resurrection of past events, often by individuals unfamiliar with the circumstances of the claims. It is in the interests of

CASE FILE SUMMARY

DESCRIPTION: _____

[illegible]

Applying the procedures that have been addressed will not eliminate changes and resultant claims. However, these actions will be of material assistance in reducing the number of claims and in achieving their resolution in an efficient, equitable and cost-effective manner.

BIBLIOGRAPHY

1. Arnavaas, D.P., Ginsbury, G. J., Simchak, M.S. and Pachter, J.S., *Managing Contract Changes*. National Contract Management Association, McLean VA, 1987.
2. The Business Roundtable. *Contractual Arrangements*, Construction Industry Cost Effectiveness Project Report A-7, 1982.
3. *Concepts and Methods of Schedule Compression*, Publication 6-7. The Construction Industry Institute, Austin, TX, 1989.
4. *Contractor Planning for Fixed-Price Construction*, Publication 6-4. The Construction Industry Institute, Austin, TX, 1987.
5. *The Impact of Changes on Construction Cost and Schedule*. The Construction Industry Institute, Austin, TX, 1987.
6. *Impact of Various Construction Contract Types and Clauses on Project Performance*, Publication 5-1. The Construction Industry Institute, Austin, TX, 1986
7. National Contract Management Association. *Claims, Disputes & Appeals*, APPL-1. Active Procurement Program Library.
8. *Project Control for Construction*, Publication 6-5. The Construction Industry Institute, 1987.
9. *Work Packaging or Project Control*, Publication 6-6. The Construction Industry Institute, Austin, TX, 1989.

Appendix C

Appendix B

Project Description _____ C.O. No. _____
Contract No. _____ Description _____
Contract Name _____ Sheet _____ of _____

Scope of Change

Applicable Drawings and Specifications

Method of Payment

Schedule of Adjustment

All other terms and conditions of the contract remain unchanged

Original Contract Price	\$
Prior Change Ordered	\$
This Changed Order	\$ _____
Current Contract Price	\$

650 CONSTRUCTION MANAGEMENT

CONTRACT CHANGE ORDER SUMMARY

CONTRACTOR: _____

CONTRACT NO: _____

UPDATE DATE: _____ Sht _____ of _____

[illegible]

Transportation and Disposal of Denver Radium Superfund Site Waste

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ABSTRACT

The Bureau of Reclamation (Reclamation) and Department of Energy (DOE), both under contract to the U.S. EPA, have embarked on a monumental task involving the excavation and disposal of an estimated 385,000 tons of radium-contaminated soil and debris in the metropolitan-Denver, Colorado area. The efforts are divided into two separate contract areas and are expected to continue well into 1992. DOE will handle the excavation and site restoration, and Reclamation will provide the transportation and disposal of the waste.

The area of contamination has been designated as the Denver Radium Superfund Site (DRSS). The contamination is believed to have come from the residues from radium processing in Denver in the early 1900s.

Radium processing began in the United States about 1914. The National Radium Institute (NRI) was located in Denver at about that time. It extracted radium from Carnotite, a radium-bearing material available in Colorado.

The NRI refined the process for extracting radium and subsequently closed about 1916 after successfully producing 8.5g of radium from approximately 1,500 tons of ore. During this period, other radium processing operators also were active in Denver.

The primary hazards of radium process residues known today are that it produces radon gas as it degenerates, and if radioactive particles become airborne, enter the lungs or are ingested, they may cause cancer.

The legacy of the NRI and the rest of the Denver radium industry is present today in the form of tailings and unprocessed ore which, since the 1920s, have been spread and used as fill under and around buildings, as foundation material, parking lots, road base and otherwise mishandled.

As called for in the Interagency Agreement between the U.S. EPA and the Bureau of Reclamation, Reclamation has provided the transportation and disposal of the process residue (waste material). The contractor performing the work for Reclamation is Chem-Nuclear Systems, Inc., of Columbia, South Carolina. The DOE contractors are excavating the material and loading it into Chem-Nuclear's containers for transportation to the disposal facility.

Most of the material (approximately 85%) will be shipped in railroad gondola cars. The remaining 15% will be loaded into sealed 20-ton containers which are trucked to the rail yard and placed onto railroad flat cars for shipment. All material will be disposed of in Utah at a facility operated by Envirocare of Utah, Inc., under a subcontract to Chem-Nuclear.

The waste is considered Naturally Occurring Radioactive Material (NORM) of Low Specific Activity. The primary radioactive contaminants are Radium-226 (Ra^{226}) and Thorium-230 (Th^{230}).

Weights for payment and record purposes will be made on state-

certified scales. Scheduling and coordination, as well as recordkeeping, are important aspects of the work and are essential in working with the many agencies and entities involved in the DRSS effort.

INTRODUCTION

This paper discusses the Bureau of Reclamation's approach to accomplishing the transportation and disposal aspects of the Denver Radium Superfund Site (DRSS) work. Some background information is presented to provide a better understanding of the overall project.

When Madam Curie discovered radium in 1898, she set in motion a chain of events which left an unwanted legacy for following generations. By the early 1900s, radium was touted for its medicinal properties and ability to destroy or inhibit cell growth, and it became widely used as a treatment for cancer. As a result, the demand for radium skyrocketed, starting the radium boom of the early 1900s.

Prior to 1914, there was little or no domestic production of radium. Rather, radium-bearing ore was shipped from the United States to Europe where it was refined. About 1914, it became evident that processing in the United States would be advantageous. The U.S. Bureau of Mines entered into a cooperative agreement with a private corporation, the National Radium Institute (NRI). According to the agreement, the Institute was to develop and operate a radium processing plant in the United States. The demand for radium grew, and new sources for radium were sought. Carnotite, a radium-bearing material, was identified in Colorado about that time, and it seemed appropriate to locate the NRI in Denver. Carnotite provided the ore from which radium was extracted by several processors in Denver from 1914 to about 1920.

The Denver radium industry remained strong until around 1920 when very rich deposits of radium-bearing ore were discovered in the Belgian Congo. The Denver producers could not compete, and the Denver radium industry closed almost overnight.

The health-related implications of radium processing were not known or considered a problem in those days. Although much of the radium was recovered, process residues containing radioactive materials were discarded.

In 1979, the U.S. EPA discovered a reference to the NRI in a 1916 United States Bureau of Mines report. Subsequent research revealed the presence of many sites in the Denver-metropolitan area containing material requiring remedial measures. One of these sites was the Robinson Brick Company, the location of the original NRI. This site contains approximately 88,000 tons of contaminated material. Studies were subsequently conducted to identify the potential hazards on all of the known sites.

There are 44 properties that have low levels of radioactive contamination that could potentially endanger public health or the environment.

The DRSS was placed on the NPL in 1983. Due to the enormity and complexity of the DRSS, the U.S. EPA determined that response actions

could be conducted in groups or operable units, and 11 operable units were established. Nine of the 11 operable units are being serviced by Reclamation's transportation and disposal contractor.

The work falls under the jurisdiction of the U.S. EPA Region VIII, which is headquartered in Denver. The U.S. EPA's agreement with DOE is to provide the final studies and site investigations and to develop appropriate specifications for the excavation of the contaminated material and restoration of each of the sites to as near the original condition as possible. This is a difficult task, because each property where contaminated material is located is unique. The task involves open areas in some cases; in others it involves removal of buildings and improvements for later replacement after contaminated material is removed.

Strong efforts are made during all site work to keep existing active businesses in operation. The logistics of this present a significant challenge to DOE and UNC Geotech, the firm with which DOE has contracted to provide the engineering and construction oversight for the remedial action work.

The work involved for each operable unit is covered by its own construction subcontracts. At least two operable units have undergone excavation and stockpiling of material since 1988. Separate contracts have been awarded for the loading of this stockpiled material, which amounts to about 65,000 tons.

INTERAGENCY AGREEMENT

While the investigation and studies were underway and the U.S. EPA, DOE and UNC Geotech were involved in determining the quantities and full extent of the excavation/restoration portions of the work, the U.S. EPA asked Reclamation to provide remedial action assistance in the transportation and disposal phases of the work. The Interagency Agreement (IAG), signed in September, 1988, provides for Reclamation to finalize a solicitation including statement of work and to obtain a contractor to perform all aspects of work involved in the transportation and disposal of material at an appropriate, properly licensed, permitted disposal site. Reclamation is providing the Contract Administration and Construction Management for the work, which is expected to continue into mid-1992. Superfund money is made available to Reclamation as needed during the performance of the work.

Most of the overall coordination with interested and affected parties such as the owners and local, state and federal governments is handled by U.S. EPA personnel. Matters involving cost recovery, obtaining State of Colorado participation in funding and working with various entities to assist in identifying and obtaining permits and licenses are handled primarily by the U.S. EPA.

The matter involving cost sharing is important as it pertains to maintaining a timely schedule of work, because remedial work could not start on operable units until all agreements were finalized. Schedules were directly tied to signing these agreements.

QUANTITIES AND LOCATIONS OF WASTE MATERIAL

Since Reclamation involvement started in 1988, the estimated total amount of material to be transported has risen from 140,000 tons to the present estimate of 385,000 tons. This increased amount of contaminated material is due to better information further defining limits of contamination at each site. Determining the depths and lateral extent in some cases is quite difficult. Access to some sites is limited, buildings remain in place and the sheer magnitude of the project all make accurate computation of quantities difficult.

Of the nine operable units involved in Reclamation's transportation and disposal work, the estimate of material from the smallest unit or property within a unit is 160 tons. The largest operable unit contains approximately 158,000 tons. Transportation and disposal service must be provided to a wide variety of areas from a restaurant franchise to a large scrap metal processing facility covering several city blocks.

CONTRACT INFORMATION

For the transportation and disposal work, Reclamation chose a "requirements-type" contract. "Delivery Orders" will be made against the contract as the work progresses.

A solicitation for bids was issued in November, 1988. The technical

qualifications of the firm receiving the award were of paramount importance. Price was also of great importance. Interested firms were asked to submit separate proposals, one for technical evaluation, and one for price evaluation; the technical proposals carried 60% of the total available points and the price 40%.

Technical proposals from the firms were evaluated by a committee of professionals, performing each review without discussion among themselves. Following the independent review and scoring, the committee met to discuss the proposals. Consensus scores were arrived at for each item rated as it compared to the preestablished evaluation standard.

After best and final proposals were submitted and evaluated in the same manner as the initial proposals, a contract was awarded to Chem-Nuclear Systems, Inc., of Columbia, South Carolina, a subsidiary of Chemical Waste Management, Inc. Chem-Nuclear has been in business since 1969 is highly qualified in the radiological waste disposal field and has an excellent transportation safety record for this type of material. The contract value is expected to be about \$70 million if the final quantity of material is near the 385,000 tons presently estimated. Because it is a per ton price, the contract value will change depending on the final quantities involved.

The major subcontracts involved under Chem-Nuclear's contract include trucking and the disposal facility. The disposal facility is Enviro-care of Utah, Inc., a facility located approximately 80 mi west of Salt Lake City, Utah.

The base contract is set up to provide for transporting and disposing of material from time of mobilization through Sept. 30, 1989. Option years will include in sequence the fiscal years (Oct. 1 through Sept. 30) of each year until Sept 30, 1992. Chem-Nuclear's proposal contained somewhat different prices to perform the work for each succeeding year. The Government will place orders against the contract based on the quantities to be hauled and the prices submitted by the contractor for each calendar period of performance.

The quantities estimated by UNC Geotech are "in-place" volume. Through experience, a conversion factor of 1.6 tons/yd³ was established and applied to this project. The total estimated volume of material is 258,000 yd³. Applying the conversion factor, this yields to the 385,000-ton estimate for total material. The contract was awarded May 15, 1989, with the first Delivery Order issued June 13, 1989, for \$9.7 million, covering transporting and disposing of 57,500 tons of material.

When the contract was awarded, it was anticipated that up to approximately 20% of the material might be hauled by Sept. 30, 1989. Due to delays in the work for a variety of reasons, this figure will be significantly less than originally estimated. The option years were expected to include approximately 155,000 tons in 1990, 110,000 tons in 1991, and 40,000 tons in 1992. These amounts, too, may change due to the late start in 1989. Actual shipping of material started in mid-August 1989.

The 20-ton containers are top-loaded, containing top and end covers with waterproof gaskets to prevent dust from escaping. These containers have been impact-tested by Chem-Nuclear and the railroads to ensure continued integrity during accident conditions.

The Remedial Action contractor (UNC Geotech and its excavation subcontractors) will load all containers, mainly using front-end loaders. In the case of loading gondola cars from existing stockpiles, large units capable of loading large quantities of material in a short time will be used. Some areas do not contain stockpiles and will be loaded at the same time they are excavated. This is a slower process using smaller loading equipment. Some material will be excavated from inside buildings after floors are removed; this process is understandably slow and better suited to the use of the smaller 20-ton containers.

Loaded rail cars are decontaminated by UNC Geotech as they leave the operable unit. Gondolas are then switched and start their journey to the disposal facility by Burlington-Northern tracks to Speer, Wyoming, where they are switched to Union Pacific to continue to Enviro-care's disposal facility. The disposal facility has direct rail service and has easy truck access from U.S. Interstate Highway 80. The cars wait on a siding until test results allowing disposal are received.

Material from operable units not served by rail is loaded into the

20-ton containers. Chem-Nuclear has provided a transportation terminal in Denver, located at 1960 A 31st Street, where empty containers are stored and released as needed to operable units for loading. After loading, the vehicle and container will be decontaminated by UNC Geotech and will travel back to the transportation terminal for weighing. The container then proceeds to the railroad's intermodal yard for loading on flatcars for the trip to Salt Lake City, Utah. It is then picked up by truck and transported to a holding area at Envirocare to wait for test results allowing disposal.

Truckers must meet stringent qualification requirements. Vehicles are inspected daily. City routes have been established to avoid residential and school areas, and all routes meet the approval of local Transportation Engineering Departments.

Security is provided at the transportation terminal 24 hr/day. The station is manned and is enclosed by a chain-link fence. No loaded containers will be held at the station. They will only pass through for weighing and recordkeeping purposes.

All containers must be weighed using state-certified scales manned by state-certified weighmasters. The weights will be used for payment purposes; they also will provide a factual record of how much material originated at each operable unit. For gondola cars, rail scales capable of weighing cars as they travel slowly over the scale area are used.

A sign is located on each container and gondola car, showing that it is dedicated to the transportation of Denver Radium waste and must not be loaded with any other materials. The sign given shows a long-distance, toll free number to contact for information or notification in case of problems.

The bid schedule contains only four pay items. The most significant pay item is the per-ton, all-inclusive price for transporting and disposing of waste. Other items include holding loaded containers while waiting for waste certification test results, moving empty containers from one unit to another to accommodate loading schedule changes and returning loaded containers to the unit where loaded in the event the material falls outside of the waste classification limits of the solicitation.

DESCRIPTION OF THE MATERIAL TO BE HANDLED

The waste is considered Naturally Occurring Radioactive Material (NORM) of Low Specific Activity. It is not considered "radioactive" under the Department of Transportation's (DOT) definition in 49 CFR 173, but the contract requires that certain portions of those regulations be followed in transporting waste. Much of the material looks like ordinary soil, and the debris is mainly building materials, pavement chunks, tree stumps and similar items.

The primary radioactive contaminants include Radium-226 (Ra^{226}) - approximately 100 picocuries per gram (pCi/g), with very limited amounts, possibly 2 yd³, containing up to 65,000 pCi/g. There is also Thorium-230 (Th^{230}) - approximately 100 pCi/g with very limited amounts, possibly 2 yd³ containing up to 167,000 pCi/g.

Minimal amounts of asbestos-contaminated debris will be present at times. Waste may also contain trace amounts of other non-radioactive contaminants; however, it is not expected that the waste will be classified by characteristics or listed as hazardous waste under RCRA and 40 CFR Part 261. It is doubtful the waste will contain PCBs in concentrations of 50 ppm or more.

SAMPLING AND TESTING

The sampling and testing program set up and conducted by the U.S. EPA, DOE and UNC Geotech for waste certification provides needed information concerning the character and composition of the waste. Representative sampling will be done at the time of loading; thus, a determination can be made concerning the average concentrations of Ra^{226} and Th^{230} in the waste and to otherwise determine if the waste is acceptable to the disposal facility.

TRANSPORTING THE WASTE

Chem-Nuclear plans to transport at least 85% of the material in 100-ton railroad gondola cars and the other 15% in smaller containers mainly of 20-ton capacity. The sampling and testing procedures will accommodate these containers. Samples will be analyzed by the

Opposed Crystal System (OCS) gamma-ray spectrometer. The radium concentration determined by the OCS will be used to confirm that the average radium concentration does not exceed the maximum allowed by the disposal facility. Th^{230} testing and numerous other tests are to be performed as appropriate. Split samples will be provided to the disposal facility for comparative testing upon their request. As test results become available, containers will be released for disposal.

Since the first Delivery Order, Chem-Nuclear has been working intensely, improving old railroad spur tracks and installing new ones at two major operable units. This construction not only involves coordination among the railroads, owners and others, but also involves coordination with UNC Geotech to ensure that the transportation phase remains compatible with the loading operations. Railroads need to provide the necessary switches, track and schedule availability of gondola cars.

Operable units where rail service is not available, or where it is not feasible to construct spur track into the areas, will be served by trucked roll-on, roll-off, 20-ton containers.

All containers must meet DOT requirements for shipping radioactive waste. They must be closed, tight containers set aside for exclusive use for Denver Radium Superfund Site wastes. If the material is such that it will stick to the gondola floor, the gondola car floor will be lined with 6-mil polyethylene sheets. All cars will be filled, and steel clad foam covers will cover the entire car's top. The covers weigh approximately 1,200 lb and are lifted on and off by a small forklift. Disposable Trak-Pak covers were used on some initial shipments until the steel-clad foam covers were available.

DISPOSAL FACILITY

Envirocare of Utah, Inc., was chosen by Chem-Nuclear as the only operating NORM waste disposal facility in the country that can receive radium waste in bulk form. It has been used to receive material from several sources including at least 2.5 million yd³ of mine tailings. It became fully licensed in Feb. 1988. After years of comprehensive studies, this disposal site was selected by DOE and the State of Utah as the best of 29 potential sites in Utah. The facility is designed to handle over 20 million tons of contaminated material.

The facility lies above a substantial clay layer which provides a good bottom seal for the cells. The percolation rate through the layer is extremely low. The facility is far from surface water or potable groundwater. The DRSS cell will be excavated several feet down from the ground surface in an area approximately 600-ft wide by 800-ft long. It will be filled layer by layer with waste until all waste under the contract has been deposited in the cell.

Rail cars as they arrive will be held on Envirocare's railspur siding, capable of holding more than 250 railcars at one time, until official clearance to dispose of the material is received. The cars then proceed to the area where the covers are removed, and onto a rollover machine where each car is secured in the machine and turned over about 150° to dump its contents onto a concrete pad beneath the machine. The polyethylene liner, placed into the cars containing waste that may stick to the gondola floor, facilitates dumping of these loads. Cycle time is about 6 min/car.

The waste is then loaded into dump trucks with a front loader for the 4,000-ft trip to the cell. The dumped loads are spread into approximate 12-in. lifts, moistened if necessary to facilitate compaction and control dust, and rolled with a standard roller to at least 90% of laboratory maximum dry density using the standard Proctor Method ASTM D-698. When debris is present, it will be distributed so that adequate space is provided for proper placing and compacting.

Dust suppression is an important safety consideration for this material. If dust is present during the unloading, hauling and depositing process, appropriate respiratory protection must be worn by the workers.

The 20-ton containers trucked to the facility will be held in storage until the waste material is cleared for disposal. Material from the containers will then be dumped directly into the cell for spreading and compaction.

All containers are decontaminated using a high-pressure washer prior to being released for return to Denver. Only the outsides need be decon-

taminated, since the containers will be covered for the return trip and reused for Denver waste. At the end of the job, the entire container, inside and out, must be cleaned as necessary for the container to be released for nonrestricted use.

The completed cell will be topped with a 7-ft layer of compacted clay to provide a radon barrier. A 6-in. layer of gravel bedding topped with 18 in. of cobbles will provide the top and side slope erosion protection. A drainage ditch and Operation and Maintenance road will surround the cell. The disposal area is designed to be relatively maintenance free for up to 1,000 yr.

The facility can accept waste 12 mo a year. The average precipitation is only 5 in./yr so downtime due to heavy rains and snow is minimal.

Long-term assurances by trust agreement are provided for the continued maintenance of the facility. The facility is appropriately licensed in accordance with the requirements of 40 CFR 192(a), is fully approved by the State of Utah and is under its constant monitoring and inspection. Disposal activities at the site are in accordance with CERCLA, Section 121(d)(3). Groundwater and air monitoring measures are thorough.

PERSONNEL PROTECTION

The work is little different in many respects than other work involving heavy equipment. The use of heavy equipment coupled with the special hazards associated with radioactive materials and possible other contaminants, makes safety considerations of great importance. The contract requires Chem-Nuclear to abide by all applicable regulations, the most notable being OSHA, 29 CFR 1926/1910. In addition to these regulations, Reclamation's *Construction Safety Standards* must be followed. These standards closely parallel the OSHA regulations so do not significantly impact the contractor. The contractor submitted an all-inclusive safety program specific to the work before transportation and disposal work began.

In addition to the typical personnel protective measures, any person working on the Operable Units must have attended a 40-hr Personnel Protection and Safety course as required by SARA and must have had a recent (within the last 12 mo) physical examination meeting the SARA and OSHA requirements including a baseline analysis for heavy metals.

The site workers must be certified to use respiratory protective devices. When these devices are needed on the job, they are provided by UNC Geotech. Prior to work on the operable units, all employees also are required to attend an additional 4-hr training session conducted by that firm. This training is specific to the operable units and covers more in-depth information on handling radioactive materials of the type expected to be encountered here.

External thermoluminescent dosimeters (TLDs) must be worn by all site workers. UNC Geotech provides the TLD service, and the dosimeters should never leave the site. They are picked up when a worker enters the restricted area and are left at the guard shack when he leaves.

The usual gear worn by workers (such as hardhats, foot gear, safety glasses and hearing protection) is provided by Chem-Nuclear for its employees.

All areas within the DRSS that contain radioactive contamination or other identified potentially hazardous materials are considered to be restricted for the purposes of access control. Only trained personnel are allowed in the area. No eating, drinking, smoking or chewing of any substance is permitted. Even chewing on a toothpick or applying lip balm are not allowed. Everyone must sign in and out on the access log. A monitoring device (frisker) must be used each time anyone leaves the area. The monitoring equipment is provided, maintained and calibrated by UNC Geotech.

Once vehicles, tools or equipment enter the site, they may not be removed until certified clean by UNC Geotech. Workers leaving restricted areas must be monitored for contamination and must decontaminate their work clothes and/or wash their faces and hands, if necessary.

PERMITS AND LICENSES

Chem-Nuclear obtained all local, state and federal permits and

licenses required from each governmental body having jurisdiction over the transportation of the waste by virtue of the waste originating, passing through or ending in their jurisdictional region.

PUBLIC RELATIONS

Public relations aspects of the work are highly important. When the subject of radioactive waste comes up, the public perception is that it is highly dangerous material. In the case of the Denver Radium Superfund Site material, the contamination averages approximately 10% of the value to be considered radioactive by DOT guidelines.

Meetings with various groups helped dispel fears and were very important to the timely completion of the work. Contacts have been made with local groups in the vicinity of the transfer station and also with the cities and communities along the Colorado, Wyoming and Utah material transportation routes. Fears subside to a great extent when presented with the facts concerning the nature of the material and when details of the Emergency Preparedness Plan are discussed.

SCHEDULING AND COORDINATION

The solicitation contained a master schedule for the work. This schedule was intended to present only an indication of the sequence and duration of the work expected for the operable units involved. Weekly scheduling/coordination meetings are conducted involving the U.S. EPA, UNC Geotech, Chem-Nuclear and Reclamation. These meetings are very helpful in discussing progress in mobilization and preparatory work and are a valuable tool as the work progresses in providing a coordinated schedule whereby Chem-Nuclear will be aware of where and how many containers will be needed for the next week. Containers are to be supplied to best accommodate the schedule of the loadout contractors.

Because the project is still in the early stages, DOE is still advertising and awarding contracts for loading the waste. Chem-Nuclear is hauling from only three operable units. As more of DOE's contracts get underway, more operable units will be ready for waste transportation, and scheduling of containers will become much more difficult.

Because waste may be hauled from as many as six operable units at one time, so a long-range, 30- to 60-day forecast schedule is necessary so there is some advance planning opportunity. In the early stages of the job, funding for additional operable unit work was caught up in the lack of agreement between the State of Colorado and the U.S. EPA on the State's 10% contribution. This problem hampered the preparation of a meaningful long-range schedule.

With the many entities involved, the scheduling/coordination meetings are essential. They provide an opportunity for the group to discuss current problems and share ideas and information to help foresee future problems.

The transportation and disposal work is expected to have peaks during the better construction seasons and to slow significantly in winter months. This is a natural tendency. Any effort to level out the hauling schedule to eliminate the peaks makes scheduling much easier. Chem-Nuclear must provide an adequate number of containers to handle the peak periods and still provide for transportation time and holding periods. In slack times, the containers may be idle.

RECORDS AND REPORTS

Record-keeping in connection with Superfund work is very important. Chem-Nuclear is required to report weekly on the tonnage handled during the week from each operable unit. The report must contain the shipment/container number, the date the container was sampled for testing, the date it was released for shipment, the date it was actually shipped and the date it was unloaded at the disposal site.

Records must include the containers that are returned to an operable unit for any reason, including being overweight or because they contain mixed waste. Chem-Nuclear must also supply copies of documentation such as manifests. The location of each shipment/container at the end of the week, whether in transit, in staging, or if disposal is completed, must also be included. There is an annual report requirement that summarizes the activities for the year. A Health and Safety Weekly report noting reportable occurrences for the period also is

required. A final report is to be prepared when all work is completed.

CONCLUSION

The Bureau of Reclamation has utilized its knowledge of construction contracting to provide the support needed by the U.S. EPA in accomplishing the transportation and disposal phases of the Denver Radium Superfund Site work.

Reclamation's contractor, Chem-Nuclear, is successfully servicing DOE's remedial action contractors by providing the types of containers, in the required quantities for loading. The transportation and disposal work is proceeding without significant problems.

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REFERENCES

1. U.S. EPA Final Draft, Remedial Investigation - Denver Radium Superfund Site 51-81010, Apr. 30, 1986.
2. U.S. EPA "Fact Sheets."
3. Solicitation No. 8-SP-81-15150, Transportation and Disposal Services—Denver Radium Superfund Site, Denver, Colorado.

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BES Environmental Specialist Inc.
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Larksville, PA 18651 717/779-5316

Emergency and remedial construction services for industry and government in site restoration; characterization, excavation, transportation and disposal of liquid, drummed and bulk wastes; secure landfill and lagoon construction/closures; facilities decontamination and demolition; dewatering; storage tank testing, removal and remediation; site assessment, and complete sampling services.

BNA Communications Inc.
9439 Key West Ave.
Rockville, MD 20850 301/948-0540

BNA Communications Inc. will display brochures in the literature center on our video training programs: *Handling Hazardous Waste*; *Spills Happen: A Training Program for Small Spill Response*, and eight new safety training videos for hazardous waste operations covered under SARA 1910.120.

Baker/TSA, Inc.
Airport Office Park, Bldg. 3, 420 Rouser Rd.
Coraopolis, PA 15108 412/269-6000

Perform remedial investigation/feasibility studies, site assessments, hydrogeologic studies, RCRA monitoring; implement remedial actions at hazardous waste management sites; provide preliminary/final engineering design and construction/closure management at solid/hazardous waste sites, risk assessments, regulatory reviews, economic analyses, market studies, and permitting; provide asbestos and tank management services.

Bates Video Production
1033 O St., Suite 546
Lincoln, NE 68508 401/476-7951

Bates Video Production has experience developing projects dealing with the complex and politically sensitive issue of waste. We know how to communicate the technical aspects of waste disposal; we can help make the complicated, simple. If you're considering using video as a communications, informational, educational tool, we'd like to help.

Bio-recovery Systems, Inc.
4200 South Research Dr.
Las Cruces, NM 88003 505/646-5888

Bio-recovery Systems, Inc. is a rapidly growing company engaged in recovery of toxic, heavy metals from industrial wastewaters, contaminated groundwaters, Superfund sites and mining process streams. The Las Cruces, NM, firm provides an economical, proprietary technology for removing and recovering metallic hazardous wastes to meet pollution effluent limits.

Booz Allen & Hamilton
4330 East-West Highway
Bethesda, MD 20814 301/951-2690

Booz, Allen & Hamilton, Inc. is a leading technology and management consulting firm that has earned an outstanding reputation in environmental services through years of direct involvement developing and implementing key programs for government and industry world-wide. The firm has worked with the Superfund and RCRA programs since their inception and offers comprehensive mission and program-related expertise. Technology and management services include: risk management; audits and technical evaluations; regulatory enforcement and policy support; records management; information systems development, and program planning, implementation and evaluation.

Breg-Oil Sponge
300 Lafayette Blvd.
Fredericksburg, VA 22401 703/373-3482

Absorbents for emergency response, leak and spill control, and industrial maintenance: • Basic Sponge: absorbs water, oil, inks, and non-aggressive fluids • Oil Only Sponge: absorbs oil and repels water both indoors or outdoors • Chem-Sponge: absorbs any fluid—acids, caustics, solvents, without guesswork. Available as rubes, pillows, booms, mats and rolls.

Brown and Caldwell
P.O. Box 8045
Walnut Creek, CA 94596-1220 415/937-9010

A full-service firm, Brown and Caldwell has experience in site assessments; remedial investiga-

tions, feasibility and treatability studies; analytical programs; waste minimization; UST management programs; design of remediations, including soil and groundwater treatment; permitting; construction supervision, and solid waste management. The firm has offices nationwide, including three certified analytical laboratories.

The Bureau of National Affairs, Inc.
1231 25th St., N.W., 3-414
Washington, DC 20037 202/452-4229

BNA publishes regulatory, legal and working guides providing the latest information concerning the manufacture, transportation, safe handling and disposal of hazardous materials.

C-E Environmental
261 Commercial St.
Portland, ME 04112 207/775-5400

Environmental consulting, monitoring and chemical analysis; hazardous waste site investigations, remedial design, construction and clean-up; thermal and non-thermal waste treatment systems.

CECOS International
P.O. Box 3151
Houston, TX 77253 713/584-8850

CECOS International, Inc., a full-service company headquartered in Houston, Texas, and with facilities throughout the country, is primarily involved in the recycling, reclamation, remediation, treatment, transportation and disposal of chemical and hazardous waste.

CH2M HILL, Inc.
P.O. Box 4400
Reston, VA 22090 703/471-1441

CH2M HILL provides waste management services—including design, construction, investigation, and planning—to industry and government. We are the largest environmental engineering firm in the United States, with 4,000 employees in 57 offices worldwide. Over a third of our business is managing hazardous, radioactive, and solid waste.

The CHEMTOX® System
Div. of Resource Consultants, Inc.
P.O. Box 1848
Brentwood, TN 37024-1848 615/373-5040

Software programs and services designed to save time and control costs. Extensively tested over a variety of industries, government agencies, in more than a dozen countries. The CHEMTOX® System can make right-to-know, safety jobs, SARA reporting, and manifest tracking easier and more productive.

CompuChem Laboratories, Inc.
3308 Chapel Hill/Nelson Highway
Research Triangle Park
NC 27709 1/800/833-5097

CompuChem Laboratories, Inc., a full service organic and inorganic CLP laboratory, specializes in CERCLA, RCRA, Priority Pollutant, Dioxin and Waste Characterization Analysis. In 1990, CompuChem will expand its analytical services to include:

- Mixed Waste Analysis
 - Air Analysis
 - Low Level Radiological Analysis
- CompuChem's Environmental Site Profile (ESP), a proprietary data management system,

provides on-line access to test results which can be downloaded to personal computers. For forensic quality data and expedited turn-around times, visit the staff of CompuChem Laboratories.

Calgon Carbon Corporation
P.O. Box 717
Pittsburgh, PA 15230 412/787-6700

Calgon Carbon Corporation supplies activated carbon products, systems and services, and air strippers to remove soluble and volatile organic chemical compounds from contaminated groundwater, surfacewater or wastewater.

Camp Dresser & McKee Inc. (CDM)
One Cambridge Center
Cambridge, MA 02142 617/621-8100

Camp Dresser & McKee Inc. (CDM) provides environmental engineering and consulting services to government and industry for the management of hazardous and solid wastes, water resources, wastewater, and environmental facilities. Hazardous waste services include remedial design and construction; treatment facility design and operation; environmental assessments; RCRA permitting; and groundwater modeling and restoration.

Capsule Environmental Engineering, Inc.
1970 Oakcrest Ave., Suite 215
St. Paul, MN 55113 612/636-2644

An environmental management firm that specializes in the adaptation of waste reduction technology as the primary method of meeting present and future environmental regulations. While working with clients on waste reduction, Capsule provides engineering services in the areas of environmental assessments, regulatory compliance, management of site cleanups and education programs.

CarbonAir Services, Inc.
1624 5th St. South
Hopkins, MN 55343 612/935-1844

CarbonAir Services, Inc. is a major manufacturer of airstripping and carbon adsorption equipment for use in the decontamination of water and air.

Carnow, Conibear & Associates
333 W. Wacker Dr., #1400
Chicago, IL 60606 312/782-4486

Carnow, Conibear & Associates is a full service occupational and environmental health consultant firm offering the following services:

- Asbestos Surveys
- AIHA Supervisor Laboratory
- Environmental Audits
- Medical Surveillance
- Hazard Material Training
- Community Right-to-Know Programs
- Health Risk Assessment
- Hazard Communication Programs
- Health Care Network for Occupational Health Programs

Center for Hazardous Waste Management
10 West 35th St.
Chicago, IL 60616 312/567-4250

Sponsored by Illinois Institute of Technology and IIT Research Institute, the Center assists clients by performing research, developing im-

proved techniques, conducting seminars, and providing quality assurance for waste management programs. Recent activities include a technical, legal and policy study for the coalition on Superfund, and licensing an in-situ soil decontamination technique.

Chemical Waste Management, Inc.
3001 Butterfield Rd.
Oak Brook, IL 60521 312/218-1500

Chemical Waste Management, Inc. provides a complete range of hazardous waste management services. These include reduction, remediation, treatment, recycling, transportation and disposal.

Chen-Northern, Inc.
96 South Zuni St.
Denver, CO 80223 303/744-7105

Chen-Northern, Inc., is a full-service consulting firm offering services in solid and hazardous waste management, environmental engineering, geotechnical engineering, asbestos consulting services, tank testing services, geology, hydrology, hydrogeology, materials engineering and testing, construction quality control, construction contract administration, and management. The firm has complete in-house subsurface exploration capabilities including drilling and soil-gas investigation services. Headquartered in Denver, Chen-Northern maintains 18 offices throughout the Western United States.

Christensen Mining Products
4446 West 1730 South
Salt Lake City, UT 84130 801/974-5544

Christensen Mining Products booth features diamond core and drill bits, core barrels and their new casing advancer (which allows full-hole drilling) and center section removal via wireline for spot coring. We also display our environmental and mud products.

Chromanetics Scientific Products
709 N. Black Horse Pike
Williamstown, NJ 08094 609/728-6316

Chromanetics, known as the "One Stop" Shopping Service for environmental laboratory and field products, offers its new 500-page environmental products catalog to conference attendees. There are seven unique sections to the catalog, which describe specialty scientific glassware, a complete line of chromatography products, chemicals/reagents, plasticware, general labware, instruments (GC, IR, UV, AA, Furnace, etc.), lab furniture/hoods/refrigerators and field sampling and safety products, including HNU PI 101 sales and rentals.

Claytro Environmental Consultants
22345 Roethel Dr.
Novi, MI 48050 313/344-1777

Services include: Environmental Engineering Services • Environmental Risk Assessment and Corrective Action Strategy • Point Source and Ambient Air Quality Studies • Regulatory Agency Liaison • Underground Storage Tank Testing and Management • Hazardous Waste Disposal, Storage, Handling, and Training Programs • Geological and Hydrogeological Evaluation • Chemical Emergency Response Programs • Comprehensive Surveys, Audits, and Program Development • State and Federal Permit Application Preparation and Negotiation

Groundwater and Wastewater Studies • Fugitive Emission Inventories and Odor Studies.

Columbia Scientific Industries Corporation
Box 203190
Austin, TX 78720 512/258-5191

Portable x-ray analyzers for in-situ monitoring of inorganic contaminants. Directly measures elements in soil or in samples collected from the site. Elements range from Al-u includes RCRA elements such as Cr, Mn, Fe, Ni, Cu, Zr, Se, As, Pb, Ag, Cd & Hg. Sensitivity from ppm to 100%.

Consolidated Rail Corporation
Room 919—One Liberty Place
Philadelphia, PA 19103-7399 215/851-7281

Conrail is one of the largest freight railroad systems in the Northeast-Midwest quarter of the United States, operating over a network of approximately 13,100 route miles. Conrail is a licensed and registered transporter of hazardous waste and sixty percent of all Superfund sites are located within its territory. Conrail works closely with connecting rail carriers, trucking, and equipment companies to offer reliable service.

Corroon & Black Environmental Insurance Services
6510 Grand Teton Plaza, Suite 102
Madison, WI 53719 608/833-2887

Environmental Insurance Specialists: Corroon & Black is one of America's largest insurance brokers. C&B has developed specialized insurance and surety programs for many engineering & construction groups. Among the specialized programs is an insurance program for remedial action contractors, engineers and asbestos abatement contractors. It includes pollution legal liability, general liability, Contractors Pollution liability, engineers professional liability, engineers pollution liability, automobile and property coverages.

Cosa Instrument Corporation
55 Oak St.
Norwood, NJ 07648 201/767-6600

Cosa products include the TOX-10 Total Organic Halogen Analyzer and the TSX-10 Total Sulfur Chlorine Analyzer.

DartAmerica
61 Railroad St., P.O. Box 89
Canfield, OH 44406 216/533-9841

A group of companies dedicated to the transportation of hazardous waste and general commodities in 48 states utilizing dumps, roll-offs, vans, flatbeds, pneumatic and liquid tank equipment, and LTL van service.

DataChem Laboratories
960 W. LeVoy Dr.
Salt Lake City, UT 84123 801/266-7700

DataChem Laboratories, Inc. is one of the nation's largest and most experienced providers of comprehensive laboratory analytical services. These services assist clients in objectively evaluating environmental/hazardous waste issues and industrial hygiene/safety concerns. During its 16 year history, the company has established a national reputation for delivering accurate test results on a cost-effective basis for both the private and government sectors.

Davis Pugmill, Inc.
P.O. Box 60
Columbia, TN 38402-0060 615/388-0626

Twin-Shaft Twin-Drive pugmill and complete plants. The feeding system can consist of belt type feeder bins to specially designed screw type bins or a combination of bins. Complete electronic weighing and ratio controlled packages are available for precise measurement of added material and chemicals. Modular and portable units are available.

Donohue & Associates, Inc.
4738 N. 40th St.
Sheboygan, WI 53081 414/458-8711

Donohue is an ARCS contractor with a nationwide staff of over 1,000 and a 1989 ENR RANKING of 64. Our environmental scientists and engineers are specialists in waste management, disposal and cleanup. Donohue's hazardous waste services include RCRA investigations and compliance monitoring, RI/FS studies, and engineering of remedial cleanup actions.

Du Pont
1007 Market St., EAD, NA-228
Wilmington, DE 19898 302/774-7248

Dunn Geoscience Corporation
12 Metro Park Rd.
Albany, NY 12205 518/458-1313

Full Service Environmental Consultants: Complete staff of hydrogeologists, geologists, environmental scientists and engineers, toxicologists, and regulatory experts provides a range of services including RI/FS and RCRA Corrective Actions, Remedial Design and Construction Management, Toxicology/Public Health Assessments, Hazardous Waste Planning and Management, Hydrogeologic Services and Property Transfer Environmental Site Assessments.

Ebasco Environmental, A Division of Ebasco Services Incorporated
2 World Trade Center
New York, NY 10048-0752 212/839-2744

Ebasco Environmental, a division of Ebasco Services Incorporated, is a leader in environmental preservation, having remediated wastes safely and economically for more than 30 years. In addition to waste remediation services, we offer complete environmental services including permitting, siting studies, risk assessments, remedial investigations/feasibility studies and environmental impact reports.

ECOFLO, Inc.
8520-M Corridor Rd.
Savage, MD 20763 301/498-4550

ECOFLO provides answers to client-specific waste management needs from our extensive offering of services, including:

1. Waste characterization
2. Collection, transportation and treatment/disposal of most wastes
3. Lab pack services
4. Remediation and clean-up services
5. Waste minimization advice

ECOFLO serves the mid-Atlantic region from offices in Maryland and North Carolina.

ECOVA Corporation
3820 159th Ave., NE
Redmond, WA 98052 206/883-1900

Hazardous waste management technologies and services for *onsite* remediation. ECOVA geologists, hydrogeologists, microbiologists, chemists, engineers, and field support staff perform site assessments; sampling and analysis; underground storage tank management; treatability studies; pilot-scale demonstrations; and full-scale remediation using biological, chemical, physical, and mobile incineration technologies. In situ processes are available.

Eimco Process Equipment Company
P.O. Box 300
Salt Lake City, UT 84110 801/526-2000

Eimco provides biological reactor for soil reclamation processes. Inclined plate clarifiers, belt-press filters and other equipment for treating wastes are available.

ELANCO Product Company
Lilly Corporate Center
Indianapolis, IN 46285 317/276-2299

Typar® Biobarrier™ is a long-lasting root prevention system, which combines a fabric and a time-released herbicide. Biobarrier will block roots that attempt to penetrate closure caps over waste burial sites without harming the plants, trees or other vegetation. Biobarrier is flexible and easy to install.

ENR
1221 Avenue of the Americas
New York, NY 10020 212/512-3131

ENR is a weekly magazine reporting business and technical news on many types of construction projects worldwide to over 400,000 readers. The market includes design (architectural and engineering) and contracting companies serving industrial and commercial forms and government agencies. Areas of coverage are buildings, infrastructure, finance and environmental cleanup.

ENRECO, Inc.
P.O. Box 9838
Amarillo, TX 79105 806/379-6424

ENRECO is a technology company established in 1982 to manage solid, liquid and gaseous wastes. Our primary area of expertise, waste stabilization, has been used successfully on over 200 projects. Recent developments include specialized chemical separation techniques to isolate a variety of organic contaminants from the waste matrix.

ENSCO, Inc.
333 Executive Court
Little Rock, AR 72205 501/223-4160

ENSCO is a premier hazardous waste management company featuring transportation and incineration of RCRA and PCB wastes. ENSCO provides integrated hazardous waste management services to private industry, public utilities and governmental entities.

ERCE Environmental & Energy Services Co.
3211 Germantown Rd. Germantown Rd.
Fairfax, VA 22030 703/246-0539

ERCE is a professional and technical services company that offers environmental, infrastruc-

ture and energy consulting and engineering services to industrial and commercial companies, electric utilities and governmental agencies. Design services are supported by four accredited analytical laboratories strategically located throughout the U.S. ERCE maintains over 20 offices in the U.S.

The ERM Group
855 Springdale Dr.
Exton, PA 19341

800/544-5117

The ERM Group, a full-service environmental consulting firm with more than 50 offices worldwide, provides the following services: site remediation; hydrogeology; hazardous/solid waste management; management consulting; industrial/municipal water and wastewater treatment; underground tank management; environmental science; air pollution control; computer services; construction management; and health, safety and toxicology.

Eagle-Picher Environmental Services

36 B.J. Tunnell East
Miami, OK 74354

918/540-1507

Supplier of high quality glass and plastic ware washed according to EPA Protocols. All containers available with sampling label and each box custody sealed to insure sample container cleanliness. Specify full QA or Wash Only. Analytical quality control is performed in our full-service EPA Contract Laboratory Program. A variety of styles and sizes of containers are available and are distributed on an exclusive basis by Baxter Scientific Products.

Earth Resources Corporation (ERC)

P.O. Box 616961
Orlando, FL 32861

407/295-8848

Earth Resources Corporation (ERC) is a full-service hazardous materials management firm specializing in the containment, treatment, and removal of all types of hazardous materials. ERC has a highly trained professional and technical staff experienced in the design and implementation of innovative solutions to today's waste problems. ERC's capabilities include but are not limited to soil, groundwater, facilities, containerized wastes and pressurized gas cylinders.

The Earth Technology Corporation

100 W. Broadway, Suite 5000
Long Beach, CA 90802-5785

213/495-4449

As one of the nation's leading environmental, earth sciences and geotechnical consulting firms, The Earth Technology Corporation's primary business activities include: Waste Management and Environmental Services, Critical Facilities Siting, and Related Advanced Technology and Testing Services.

Visit Booth 1505 for information on superior technical capabilities for government and private industry.

EcoTek

219 Banner Hill Rd.
Erwin, TN 37650

404/843-3732

EcoTek, a subsidiary of Nuclear Fuel Services, provides comprehensive services for the remediation of sites contaminated by hazardous and mixed waste materials. EcoTek's services include hazardous/chemical (CLP) and radiological laboratory services, process design, mixed waste

characterization, health and safety upgrades, procedures and equipment, decontamination and decommissioning, and resource recovery.

Ecology and Environment, Inc.

368 Pleasantview Dr.
Lancaster, NY 14086

716/684-8060

E & E is recognized worldwide as a leader in environmental science and engineering. The firm performs remedial investigations, field studies, mitigative engineering design and construction management; hazards and risk analyses; spill emergency response and asbestos removal management; regulatory compliance audits; environmental impact assessments; air, water and groundwater pollution control; industrial hygiene; analytical laboratory services.

Empire Soils Investigations, Inc.

140 Telegraph Rd.

Middleport, NY 14105

716/735-3502

Empire Soils Investigations, Inc., along with its laboratory division—Huntingdon Analytical Services—and its wholly owned subsidiary, Asteco, Inc., provides the following services: Contract drilling and installation of groundwater monitoring wells, geotechnical testing including contaminated soils, geotechnical engineering, chemical analytical testing, asbestos inspection and testing, and materials engineering and testing.

Engineering-Science

75 North Fair Oaks Ave.
Pasadena, CA 91103

818/440-6101

Engineering-Science (ES) is a full-service, national and international environmental engineering firm providing complete services in hazardous waste management. With offices in 23 domestic locations, ES is active in supporting industrial and military clients in all phases of site/remedial investigations, feasibility studies, remedial action plan preparation, site cleanup/closure and post-closure activities.

Entropy Environmentalists, Inc.

P.O. Box 12291
Research Triangle Park
NC 27709

919/781-3550

Entropy, the largest independent air emissions testing firm in the country, provides air emissions testing and consulting services to assist firms in effectively complying with hazardous waste regulations. Services include: RCRA/TSCA incinerator testing and analyzing; VOC emission inventories and testing; dioxin/furan, PAH, PCB testing principal organic hazardous constituents (POHC) selection, trial burn test plan preparation and permitting assistance.

Envirodyne Engineers, Inc.

1908 Innerbelt Business Center Dr.
St. Louis, MO 63114-5700

314/426-0880

Envirodyne Engineers, Inc. is a consulting engineering firm and an analytical laboratory, with offices in Chicago, New York and St. Louis. Our certified laboratory offers full service capabilities including: radioactive waste analyses, dioxins/furans, explosives, Appendix VIII/IX, EP Toxicity, TCLP, Priority Pollutants, herbicides, and all conventional inorganic parameters in wastewater, potable water, soil, air, and biological matrices. Our engineering services include site assessments, UST, treatability studies, ground-

water monitoring, RI/FS, design and construction oversight.

Environmental Audit, Inc.

P.O. Box 322
Lionville, PA 19353

215/524-7002

EAI is an environmental information company providing fast, cost-effective environmental records from federal and state government agencies. EAI's Federal Environmental Data (FED) Report provides NPL, CERCLIS, RCRA, FINDS and National Spill records for any area of the country, guaranteed within 3 to 5 days. Call (800) 542-8348 for service.

Environmental Business Journal

827 East Washington St.
San Diego, CA 92103

619/295-7685

EnviroQuest, Inc. acquires intelligence on the business of environmental health and distributes it through the *Environmental Business Journal*, market research studies and strategic consulting services.

Environmental Compliance Services, Inc.

721 East Lancaster Ave.
Downingtown, PA 19335

215/269-6731

ECS is an organization dedicated to assisting environmental companies with their insurance, safety and compliance needs through the unique combination of in-house expertise in environmental regulation, risk management, and insurance underwriting.

Environmental Instruments

2170 Commerce Ave., Unit S
Concord, CA 94520

415/686-4474

E.I.'s product line represents state-of-the-art environmental equipment. We specialize in groundwater recovery and treatment systems, soil vapor sampling and recovery systems. We also carry a full line of monitors and samplers for water and air. Come see the new Photoionization Detector, the OVM 580B, and our new Cavitation-Oxidation water treatment system at our booth.

Environmental Technology, Inc.

3705 Saunders Ave.
Richmond, VA 23227

804/358-5400

HazWaste Industries and its operating subsidiaries (Environmental Technology, Bionomics, and HazLabs) provide a full range of remediation services:

- Site Investigations, Inspections, and Audits
- Feasibility and Treatability Studies
- Engineering Design and Construction Management
- Site Remediation, Including Emergency Response and Removal
- Long-Term Monitoring

HazWaste provides complete, quality solutions to environmental problems.

Environmental Medicine Resources, Inc.

4360 Chamblee-Dunwoody Rd., Suite 202
Atlanta, GA 30341

404/455-0818

Environmental Medicine Resources, Inc. (EMR) specializes in the development and centralized management of medical surveillance programs for companies whose employees are potentially exposed to OSHA regulated hazardous materials. EMR's regulatory and medical staff, in conjunction with a national network of 300 clinical facilities, ensures consistent, cost-effective, compliance-assured programs.

Envirosafe Services, Inc.
900 E. Eighth Ave., Suite 200
King of Prussia, PA 19406 419/255-5100

Envirosafe Services, Inc. (ESI) is one of the leading providers of hazardous waste management services in the United States, providing both off-site disposal and on-site remediation services. ESI's hazardous waste disposal services include analysis, pretreatment to stabilize nonconforming wastes and disposal, and are provided to industrial and governmental customers. In addition, a wholly owned subsidiary of ESI, Enviro-safe Technology Group Inc. (ETG), furnishes remediation services primarily at industrial sites with hazardous substances. These services are provided by the Field Services Group-A.C.E.S., vapor extraction treatment by Midwest Water Resources, Inc.-(MWRI) and mobile plant stabilization. For further information on ESI and ETG capabilities, contact Greg Ballmer, Customer Service Manager, at 419/255-5100.

Espey, Huston & Associates, Inc.
7600-B Leesburg Pike, Suite 440
Falls Church, VA 22043 703/556-7770

Espey, Huston is a full-spectrum engineering and environmental consulting firm providing investigation, assessment, design, construction management and O&M. Company managed Superfund site from RI/FS through to RD, RA and O&M. Offices in Northern and Tidewater Virginia, North Carolina, Tennessee, Houston, Dallas, Austin, Albuquerque and on the West Coast. Specializes in full-service support to private and municipal clients.

Essex Environmental/Berlin Packaging
10500 Tube Dr.
Hurst, TX 76053 817/267-3319

Essex Environmental Industries offers a 85 gallon DOT#E-9775 Polyethylene Overpack Salvage Drum for 55 gallon or smaller drums. The enviropack is solely distributed nationwide by Berlin Packaging, with 17 stocking warehouses throughout the United States and Canada.

Four Seasons Industrial Services, Inc.
207 Robbins St.
Greensboro, NC 27416 919/273-2718

Industrial Field Services

- Tank Cleaning and Decontamination
- Tank Removal and Disposal
- Tank System Construction and Installation
- Liquid and Dry Bulk Vacuum Pumping
- Transport Tanker Cleaning
- Petroleum Spill Cleanup Services
- Permitted Hazardous Waste Transporter

Remedial Field Services

- Leaking Underground Storage Tanks
- Landfill and Lagoon Closures
- Uncontrolled Hazardous Waste Sites
- On-Site Treatment Processes
- Off-Site Hazardous Waste Disposal
- Haz-Mat Emergency Response Services

Technical Services

- Project Engineering and Design
- PRP Project Planning and Formulation
- Treatment Technologies Development

- HydroGeo Assessment and Engineering
- Cover and Barrier Design and Monitoring
- Environmental Equipment Design and Fabrication

Fenn-Vac, Inc.
P.O. Box 62679
Charleston, SC 29419-2679 803/552-8306

Fenn-Vac, Inc. provides hazardous waste transportation services as well as remedial and emergency response cleanup services. We have added a new 30 cubic foot filter press to complement our sludge dewatering service capabilities. Tank cleaning, vacuum truck, high pressure water cleaning and tank removals complete our service package.

Fluor Daniel, Inc.
10500 Tube Dr.
Hurst, TX 76053 817/267-3319

Fluor Daniel provides a broad range of environmental services ranging from new facility support (permitting EIR/EIS), to regulatory compliance (audits, UST, and emissions, etc.) and remediation (RI/FS, Remedial Design, Remedial Action). Fluor Daniel's environmental capabilities are unique in that they are backed by the full engineering, construction, management and maintenance experience of Fluor Daniel, Inc.

Forestry Suppliers, Inc.
P.O. Box 8397
Jackson, MS 39284-8397 601/354-3565

Environmental equipment catalog company displaying soil recovery augers and probes, ground-water/surface water sampling and testing equipment, safety wear for workers exposed to hazardous wastes, surveying/engineering instruments and supplies—and more! Sign up for our free, 432 page catalog.

Foster Wheeler Enviroresponse, Inc.
8 Peach Tree Hill Rd.
Livingston, NJ 07039 201/535-2434

Foster Wheeler Enviroresponse, Inc. is a full-service environmental engineering firm and a wholly owned subsidiary of Foster Wheeler Corporation. Founded in 1984, FWEI has provided environmental regulatory, technical, design and remediation services for well over 500 environmental projects for the U.S. EPA, U.S. DOD, U.S. DOE, and various commercial clientele.

The Foxboro Company
Dept. 120, E Bldg. N-30-1E
Foxboro, MA 02035 508/549-8750

Instrumentation for providing quantitative and qualitative information on hazardous waste and spill site contaminants. The CENTURY Organic Vapor Analyzers (OVA) can be used at the waste site to easily locate areas of high vapor concentration, to identify and determine concentration levels of various organic compounds, and to provide rapid, reliable screening/analysis for volatile hydrocarbons in groundwater samples. The OVAs are Factory Mutual (FM) approved for use in Class I, Division I, Groups A, B, C, and D hazardous areas.

GKN Hayward Baker Inc.
1875 Mayfield Road
Odenton, MD 21113 301/551-8200

OKN Hayward Baker is the foremost Ground Modification contractor in the United States.

Affiliated with the worldwide GKN Foundations Division, we have developed technologies in remedial and ground improvement work that can now be transferred to solve problems in environmental engineering. Our Ground Improvement methods include: Slurry Trench Cut-Off Walls, In-Place Mixing, Sludge Stabilization and Encapsulation Grouting.

GTEL Environmental Laboratories, Inc.
Meadowbrook Industrial Park
Milford, NH 03055 800/522-4835

GTEL Environmental Laboratories, Inc. is a full-service nationwide network of environmental laboratories and support groups able to take diverse jobs from inception to completion. GTEL offers technical depth, broad environmental expertise, and financial resources for large-scale commitments to industrial, manufacturing, and government projects.

Galaber Settlements Company
260 Franklin St., #1510
Boston, MA 02110 617/439-6260

Pioneering the use of structured settlements in environmental cases, Galaber Settlements reinforces its position as a leading national firm specializing in the development of creative periodic payment programs individually tailored to the present and future needs of all parties. Contact our specialists today—There is *no charge* for our service.

General Physics Corporation
6700 Alexander Bell Dr.
Columbia, MD 21046 301/290-2514

General Physics Corporation is a full-service company applying state-of-the-art engineering technologies and laboratory facilities to meet client needs. We offer specialized expertise in design engineering, occupational health, radiological health, radwaste management, mixed waste handling, geosciences, SPCC Plan, UST, CLP laboratory, bioremediation, treatment technologies, environmental regulations, and safety training.

General Sciences Corporation (GSC)
6100 Chevy Chase Dr., Suite 200
Laurel, MD 20707 301/953-2700

RISKPRO is an integrated exposure assessment system that allows modeling of releases to air, soil, and surface and groundwater. It estimates population exposed and excess cancer cases. RISKPRO also includes chemical property estimation programs, data management programs, graphic programs, and conversion utilities, making it a wholly self-contained exposure assessment tool.

Geo-Con, Inc.
P.O. Box 17380
Pittsburgh, PA 15135 412/856-7700

Geo-Con, Inc. is a national remedial construction company specializing in on-site hazardous waste treatment. Capabilities of the company include Turn-key project execution; In-situ solidification and stabilization. Containment systems such as vertical barriers, capping and liners; RCRA landfill construction and retrofit; Deep Soil and Shallow Soil Mixing; Groundwater collection and treatment; VOC removal from soil; Bio-remediation; Plant Decontamination and decommissioning and Construction management.

Geo/Resource Consultants, Inc.

851 Harrison St.
San Francisco, CA 94107 415/777-3177

Geo/Resource Consultants, Inc. (GRC) is a full-service environmental consulting firm dealing with today's complex hazardous materials industry. GRC's diverse professional staff have expertise in numerous fields including: groundwater monitoring programs; landfill characterizations; UST/LUFT programs; RCRA training; environmental assessments and audits; RI/FS programs; and remedial action design.

**Geochemical Engineering/
Randol International**

1658 Cole Blvd., #6-80
Golden, CO 80401 303/233-8357

Randol Mining Directory lists all U.S. mines. *Randol Buyer's Guide* lists products and services used by all mines and mineral processing industries. Special section on Environmental Protection and hazardous materials control are included. Companies are invited to submit their free listings.

Geonics Limited

8-1745 Meyerside Dr.
Mississauga, ON L5T 1C6 416/670-9580

Geonics Limited is the world's leading manufacturer of electromagnetic geophysical instrumentation. Applications include: surface measurements for delineation of contaminant plumes and detection of buried metal; borehole conductivity measurements for mapping vertical plume structure and well screen location.

Geoprobe Systems

607 Barney St.
Salina, KS 67401 913/825-1842

Manufacturers of the Geoprobe 8-A hydraulically powered soil probing units, suitable for soil gas, water, and discrete soil sampling. Small diameter soil sampling kits, Geoprobe 1" O.D. well points and stainless steel minibailers, stainless steel sampling implants, vacuum/volume gas sampling systems, and complete mobile gas and water laboratory vans.

Geosafe Corporation

303 Parkplace, Suite 126
Kirkland, WA 98033 206/822-4000

Geosafe Corporation offers in situ vitrification (ISV) services for remediation of contaminated soil and sludge sites. The ISV process destroys hazardous organics through pyrolysis and simultaneously immobilizes hazardous inorganics in a delistable, vitrified residual. This cost-effective process offers significant advantages over conventional soil treatment processes.

Geoscience Consultants, Ltd.

500 Copper NW, Suite 200
Albuquerque, NM 87102 505/842-0001

Geoscience Consultants, Ltd. (GCL) is a minority-owned small business (8(a) Certified) and is a full-service environmental design and engineering consulting firm. GCL provides the following services:

- UST Management
- Air Quality Assessment and Permitting
- Health and Safety Training
- Remedial Engineering
- Waste Minimization and Compliance Reviews
- Groundwater Remediation
- Regulatory Negotiation

Geotechnical Fabrics Report

345 Cedar St., #800
St. Paul, MN 55101 612/222-2508

Geotechnical Fabrics Report (GFR) is an engineer's guide to geomembrane liners, geotextiles and related products. GFR regularly includes case histories, papers, industry news and other information on geosynthetic applications in hazardous waste containment. GFR will serve 14,000 engineers, contractors, landfill owners and operators and other industry members in 1990. GFR is published by the Industrial Fabrics Association International.

Gibbs & Hill, Inc.

11 Penn Plaza
New York, NY 10001 212/216-6000

Gibbs & Hill, Inc., a HILL Group Company, is a full-service consulting engineering company offering professional services in remedial investigations, feasibility studies, chemical and environmental engineering, geotechnical and hydrogeological consulting, underground tank investigation and remediation, litigation support, permitting, landfill engineering design and closure, wastewater treatment, right-to-know consulting and program management, health and safety, and construction management and claims. Additional available services from the HILL Group include asbestos management, project management oversight and PCB investigation/remediation as well as program management.

Greenhorne & O'Mara, Inc.

9001 Edmonston Rd.
Greenbelt, MD 20770 301/982-2800, X442

Greenhorne & O'Mara, Inc. provides hazardous waste management services to industry and government. Our experienced staff (most OSHA/AHERA-certified) know the requirements of RCRA, CERCLA, SARA, CWA, and CAA. Services include site characterization, property transfer assessments, asbestos management, groundwater assessments, environmental audits, RI/FSs, remedial design, waste minimization, and surveying.

Griffin Remediation Services, Inc.

500 Winding Brook Dr.
Glastonbury, CT 06033 203/657-4277

Griffin Remediation Services, Inc. (GRS) is a full-service remediation company with specialty expertise in the design and implementation of comprehensive solutions to groundwater-oriented environmental problems. An affiliate of Griffin Dewatering Corp., GRS utilizes over 50 years of groundwater control experience. From their 18 locations throughout North America, Griffin employs innovative technologies focused on the containment, recovery, treatment and/or disposal of hazardous and nonhazardous groundwater pollutants. Services include: remedial dewatering, slurry trenches, landfill gas vents, deepwells, wellpoints, monitoring wells, soil vents, air stripping, and pump sale/rentals.

Groundwater Technology, Inc.

220 Norwood Park South
Norwood, MA 02062 616/769-7600

Groundwater Technology, Inc. is a full-service, international environmental assessment and remediation firm with 55 offices and 1,300 employees dedicated to finding innovative solutions to today's environmental concerns. Considered

the world leader in integrated solutions to environmental problems, the firm has completed more than 5,000 jobs since 1975.

Grundfos Pumps Corporation

2555 Clovis Ave.
Clovis, CA 93612 209/292-8000

Manufacturer of the Redi-Flo Environmental Submersible Pump. The Redi-Flo is constructed of stainless steel and teflon and is designed to pump contaminated groundwater from a 4-inch well or larger. The Redi-Flo can provide flow rates up to 32 gallons per minute and to heads of 680 feet.

**Gulf South Environmental Laboratory, Inc. and
Pacific Northwest Environmental Laboratory,
Inc.**

6801 Press Dr., East Building
New Orleans, LA 70126 504/283-4223

Gulf South Environmental Laboratory, Inc. and Pacific Northwest Environmental Laboratory, Inc. are full-service analytical laboratories. Both provide analytical support for all major regulatory programs including CERCLA, RCRA, NPDES, drinking water and real estate transfer. FSEL and PNEL are participants in the EPA CLP program. PNEL is also California certified.

Gundle Lining Systems, Inc.

19103 Gundle Rd.
Houston, TX 77073 713/443-8564

Leaders in Synthetic Liners—Gundle Lining Systems, Inc., Houston, Texas, is recognized as the world leader in the manufacture and installation of High Density Polyethylene lining systems. Gundle manufactures HDPE (Gundline HD) in 22.5 foot seamless widths from 20 to 140 mils thick. Gundle installs HDPE using their patented extrusion welding machine and new automatic hot wedge welder. Also from Gundle is Gundnet, drainage net; Gundline HDT, a textured HDPE liner; and Hyperlastic, a very low density polyethylene liner.

HAZCO Services, Inc.

2006 Springboro West
Dayton, OH 45439 513/293-2700

National Supplier of Safety Equipment and Services for the Hazardous Waste Industry including personnel protective equipment and supplies, instrumentation rentals and repair services, hazmat equipment, environmental sampling equipment and supplies, decon trailers and information systems.

HazMat Environmental Group, Inc.

P.O. Box 676
Buffalo, NY 14217 716/876-3957

HazMat Environmental Group, Inc. specializes in full-service hazardous waste management and transportation services. Our fleet of over 100 vehicles perform safe and insured waste transport with fully permitted 48 state authority. Waste management consulting services include waste minimization and management planning, site audits, remedial project planning, and a full line of personnel regulatory training programs.

**HAZMAT Training, Information and
Services, Inc.**

6480 Dobbin Rd.
Columbia, MD 21045 800/777-8474

The mission of HAZMAT Training, Informa-

tion and Services, Inc. (Hazmat TISI) is to provide the highest quality training in the hazardous materials industry. Our services are hallmarked by a disciplined, systematic approach to training.

Our training programs, provided under direct contract with our clients, can be presented either at our Columbia, Maryland training facility or on-site at a client's location, tailored to the client's specific training needs. As a natural offshoot to our training programs, we also provide a number of consulting and information services. Additional information is available upon request at 1-800-777-TISI or 301/964-0940.

HDR Engineering, Inc.

8404 Indian Hills Dr.

Omaha, NE 68114

402/399-1000

HDR Engineering, Inc. specializes in hazardous and industrial waste management, including remedial investigations, feasibility studies, remedial design and construction management of hazardous waste sites; design of treatment, storage and disposal facilities; and closure/post-closure planning; assessment and design of underground storage tank facilities, environmental permitting, real estate transfer audits, environmental risk assessments, air pollution control and permitting, environmental modeling (air, water, groundwater, toxic contamination). Industrial projects encompass the study, design and implementation of industrial waste treatment; ultra pure water, gas and chemical systems; environmental permitting; process facilities for high-tech industries.

HMM Associates, Inc.

196 Baker Ave.

Concord, MA 01742

508/371-4305

HMM Associates is an environmental consulting, engineering and planning firm. HMM provides a wide range of hazardous materials/waste services including: Superfund RI/FS; remedial design and construction oversight; personnel protection and safety training; and Title III Emergency Preparedness Planning and Community Right-to-Know.

HNU Systems, Inc.

160 Charlemont St.

Newton Highlands, MA 02161

617/964-6690

HNU provides the following: *Model HW101-Hazardous Waste Analyzer*, *IS101-Intrinsically Safe Analyzer*, *PI101-Photounitization Analyzer* (portables), *Model 301DP-Dedicated Programmable GC*, *Model 311-Portable Gas Chromatograph*, *Model 301GC*, *Model 321-Compact Temperature Programmed GC*, *Model 331-Compact Dedicated Capillary GC*, *SEFA-Portable X-Ray Fluorescence Analyzer*, *75 Meter-Portable PHMV Temperature Meter*, *ISE-Ion Selective Electrodes*.

Hydro-Search, Inc.

235 N. Executive Dr., #309

Brookfield, WI 53005

414/784-4588

Services in hydrogeology, engineering, and project management for: Remedial Investigations/Feasibility Studies (RI/FS); Preparation of Work Plans; Managing On-Site Activities; Designing and Implementing Remedial Action Programs; Technical Guidance for Responsible Parties; Oversee EPA Contractors; Review Groundwater Monitoring Plans and Reports; Underground Storage Tank Management; Landfill

Siting and Design; Water Resource Management; Mine Tailings and Water Management.

Hanson Engineers Incorporated

1525 S. 6th St.

Springfield, IL 62703

217/788-2450

Hanson Engineers Incorporated is a multi-discipline engineering firm providing engineering services in environmental/waste management, geotechnical, structural, transportation, hydrologic/hydraulic, and material testing. HEI is registered to practice in all 48 contiguous states, and has completed over 100,000 projects throughout all 50 states and in 13 foreign countries.

Harmon Environmental Services, Inc.

2066-A West Park Place

Stone Mountain, GA 30087

404/469-3077

Total site remediation, emergency response, wastewater treatment and infectious hazardous waste incineration services; dewatering and stabilizing sludges; excavating contaminated soils; closing and capping lagoons, landfills and waste-piles; incineration of liquids, sludges and contaminated soils.

Hart Environmental Management Corporation

6981 North Park Dr.

Pennsauken, NJ 08109

609/663-0440

Engineering solutions to pollution control, hazardous waste and environmental management problems. Hart offers regulatory assistance, environmental audits, site investigation, risk assessments, design engineering, construction management and remedial services with comprehensive programs in underground storage tank management, asbestos hazard management, RCRA and CERCLA strategic and technical support.

Hazardous Waste Action Coalition

1015 15th St., NW, #802

Washington, DC 20005

202/347-7474

The Hazardous Waste Action Coalition (HWAC) responds to difficult questions facing technical consulting firms active in hazardous waste management. HWAC develops and promotes approaches that are technically sound, timely and cost-effective. HWAC also pursues needed legislative and regulatory actions, promotes sound business practices, and develops effective technical practices.

Hewlett-Packard Company

P.O. Box 10301

Palo Alto, CA 94303-0890

415/857-1501

Hewlett-Packard will display its instruments, systems and capabilities for EPA approved environmental analysis and methods.

Howard Smith Screen Company

P.O. Box 666

Houston, TX 77001

713/869-5771

Major manufacturer and supplier of well screen for application in environmental, water, oil and gas wells.

Hoyt Corporation

251 Forge Rd.

Westport, MA 02790

508/636-8811

Manufacturer of Solvent Vapor Recovery/Air Pollution Control Equipment, Distillation Equipment, Odor Control Equipment, and Liquid Purification Equipment.

Hunter/ESE Inc.

P.O. Box 1703

Gainville, FL 32602-1703

904/332-3318

Hunter offers complete one-stop environmental services, with in-house capabilities that normally require several firms. Areas of service include RI/FS/RD; asbestos management; UST management; environmental audits; toxic and hazardous materials control; water and wastewater treatment technology; source and ambient air monitoring; regulatory analysis; permitting and compliance; bioassay; and surface and groundwater monitoring.

Hydro Group, The

97 Chimney Rock Rd.

Bridgewater, NJ 08807

201/563-1400

Contractors, manufacturers and consultants specializing in contaminated groundwater. Will be exhibiting air stripping towers, aerators, gravity and pressure filters, clarifiers and GAC systems.

Hygienetics, Inc.

150 Causeway St.

Boston, MA 02114

617/723-4664

Hygienetics, Inc. is an architectural-engineering/industrial hygiene firm specializing in asbestos management consulting, indoor air quality assessments, and hazardous materials management consulting services. We are located in Boston, Hartford, New York, Washington, DC, Chicago, Los Angeles, San Francisco, Honolulu, and Frankfurt, West Germany.

I-Chem Research

23787-F Eichler St.

Hayward, CA 94545

415/782-3905

A complete line of glass and polyethylene sample bottles, jars, and vials supplied with Teflon-lined closures attached and available chemically pre-cleaned and laboratory certified to meet EPA specifications. Also available are custom cleaned sample containers, protective shipping materials, convenient sampling kits, and preservatives in ampules.

ICF Kaiser Engineers

9300 Lee Highway

Fairfax, VA 22031

703/934-3300

ICF Kaiser Engineers, headquartered in Oakland, California, provides engineering, construction, and construction management services to public and private sector clients involved with environmental, transportation, industrial, advanced technology, energy, and other infrastructure projects around the world.

ICM Laboratories

1152 Route 10

Randolph, NJ 07869

201/584-0330

Full-service laboratory specializing in environmental analysis. Laboratory services include analysis for compliance with ECRA, RCRA, NPDES, Hazardous Waste Classification, and CERCLA. Monitoring well sampling also available.

IEA, Inc.

P.O. Box 12846

Research Triangle Park

NC 27709

919/467-9919

IEA, Inc., a U.S. EPA CLP laboratory, provides complete environmental analytical services

to the engineering/consulting, industrial and governmental communities. IEA offers SW-846 3rd Edition, TCL/TAL, Priority Pollutants, and Petroleum Hydrocarbon analyses utilizing multiple, dedicated GC/MSs, GCs, AA and ICP, HPLC, IR GPC, SEM, TOC and TOX. Rapid turnaround and a chemist-staffed Client Services Group are just two examples of IEA's customer-oriented commitment to meeting your analytical requirements.

Inside EPA

P.O. Box 7167, Ben Franklin Station
Washington, DC 20044 703/892-8500

Inside EPA's environmental group of publications include *Inside EPA*, *Superfund Report* and *Environmental Policy Alert*, the preeminent, relied upon information sources for timely, essential news on the environment today. Together they cover the realm of environmental issues and policies—the major legislative, regulatory and legal actions—facing the nation and you.

In-Situ Inc.

210 South Third St., P.O. Box I
Laramie, WY 82070 307/742-8213

In-Situ Inc. designs and manufactures environmental data loggers, water-level and water-quality probes, and UST Leak Detection Systems. In-Situ develops hydrologic and geologic software for both mainframe and personal computers. In-Situ also has a professional staff for hydrology consulting and water resource management services for industrial, municipal, energy, and mining related projects and facilities.

Institute of Gas Technology

3424 South State St.
Chicago, IL 60616 312/567-3794

IGT is a not-for-profit educational, energy and environmental research and development organization established in Chicago, Illinois in 1941. IGT's environmental capabilities include waste incineration and detoxification, and catalytic and biological decontamination of hazardous and industrial wastes, soils and sludges, and groundwater. IGT programs range from fundamental investigations through bench scale and pilot plant process development to field testing.

Integrated Chemistries, Inc.

1970 Oakcrest Ave., Suite 215
St. Paul, MN 55113 612/636-2380

An environmental specialty chemical company that develops chemical processes that create more effective ways to reduce or destroy hazardous waste. Our CAPSUR system exemplifies this concept. CAPSUR is a PCB cleanup product that is environmentally sound, easy to use and has a high extraction efficiency while reducing disposal costs.

International Technology Corporation

23456 Hawthorne Blvd.
Torrance, CA 90505 213/378-9933

International Technology Corporation (IT) is an environmental management company with multiple technologies and human resources to solve a wide variety of problems involving hazardous chemical and nuclear materials. The company provides a comprehensive range of services to industry and governmental agencies in four business areas: Analytical, Engineering, Remediation Services and Environmental Products.

ness areas: Analytical, Engineering, Remediation Services and Environmental Products.

Jacobs Engineering Group, Inc.

529 14th St., NW., Suite 1234
Washington, DC 20045 202/783-1560

Jacobs Engineering Group, Inc. is an international engineering and construction firm with extensive environmental experience in waste minimization; corrective and remedial action; and planning, engineering, design and construction management of hazardous, toxic, low-level and mixed waste programs.

K-V Associates

281 Main St.
Falmouth, MA 02540 508/540-0561

Manufacturers of sub-surface tools and probes for use with soil-gas sampling and water sampling.

Kelchner Environmental Excavators, Inc.

6834 Loop Rd.
Centerville, OH 45459 513/434-1334

Kelchner Environmental Excavators, Inc. is a service company providing support to environmental consulting firms, industry, and government. These projects include: Impoundment/lagoon closures; soil/sludge solidification/stabilization; slurry cutoff walls; landfill construction, including HDPE; liner installation; leachate collection systems; and underground storage tank removal. For more information, call 800/877-5352.

Keystone Environmental Resources, Inc.

3000 Tech Center Dr.
Monroeville, PA 15146 412/825-9600

Keystone Environmental Resources, Inc., a subsidiary of The Chester Engineers, provides environmental services to industry and government in the United States and Canada. Our areas of expertise include analytical laboratory testing; treatability studies; and conceptual, design and project engineering for air quality, remediation of contaminated soils and waters, and hazardous wastes.

J.J. Keller & Associates, Inc.

8361 Hwy. 45, P.O. Box 368
Neenah, WI 54957-0368 414/722-2848

J.J. Keller & Associates, Inc. currently researches, writes, edits, and prints over 60 technical publications serving the CPI and transportation industry. Keller also offers software programs, videos, and regulatory compliance services and products. Featured at Superfund '89 will be Keller's Hazardous Waste Management Guide; Hazardous Materials Guide; Right to Know Compliance Manual; Chemical Crisis Management Guide; Chemical Regulatory Cross-reference; Small Quantity Generator Kit; Haz Mat II Software; Rega-A-Dex Software; MSDS-PC Software; Hazardous Waste Services Directory; and hazardous training booklets and videos.

James T. Warring Sons, Inc.

4545 S St.
Capitol Heights, MD 20743 301/322-5400

All types and sizes of containers—new and reconditioned—fiber, steel, plastic. Our hazardous waste containers are DOT approved and range in size from 5 to 110 gallons. We accept orders

from one to truck loads and we ship anywhere. You order a container—we don't have it—it's special—we will get it for you. No order is too small for James T. Warring Sons, Inc. Let us help you contain your hazardous waste. Also provided is empty drum removal with custom shredding and crushing done on your site.

LaBounty Manufacturing, Inc.

P.O. Box B, State Rd. 2
Two Harbors, MN 55616 218/834-2123

LaBounty RB 80 Barrel Handler Description—LaBounty Manufacturing will exhibit the LaBounty RB 80 Barrel Handler which is specifically designed to handle barrels and cylindrical containers used for toxic waste or chemical storage. LaBounty also manufactures TW Grapples for handling solid waste and Mobile Shears for cutting waste piping, tanks, and other contaminated materials.

Laboratory Resources, Inc.

363 Old Hook Road
Westwood, NJ 07675 201/666-6644

Laboratory Resources, Inc. provides high quality analytical testing services for commercial, industrial, and environmental clients with a laboratory network serving the northeast. Capabilities include a wide variety of testing services including organic, inorganic, asbestos, and industrial hygiene analysis along with being a CLP laboratory. Quality is the cornerstone upon which services are built.

Laborers—AGC Education & Training Fund

Route 97 & Murdock Rd., P.O. Box 37
Pomfret Center, CT 06259 203/974-0800

The Laborers-AGC Education and Training Fund is a labor and management trustee organization that develops and implements training programs for over 70 training centers located throughout the U.S. and Canada (32). Courses offered include Line Foreman Safety Training, Pipe Laying, Blasting, Laser Beam, Asbestos Abatement and Hazardous Waste Worker Training.

Lancaster Laboratories, Inc.

2425 New Holland Pike
Lancaster, PA 17601 717/656-2301

Lancaster Laboratories, Inc. is an independently owned and operated testing laboratory located in Lancaster, Pennsylvania. With a staff of more than 350 scientists, technicians, and support personnel housed in a 78,000 sq. ft. facility, Lancaster Labs provides a wide range of environmental, industrial hygiene and health sciences testing services.

Lancy International, Inc.

181 Thorn Hill Rd.
Warrendale, PA 15086-7527 412/772-0044

Innovative technologies for the recovery/treatment of groundwater and the treatment of sanitary and hazardous landfill leachates are on display by Lancy International, Inc., an Alcoa Separations Technology Company. Comprehensive treatment/recovery equipment, services and technologies are highlighted and information regarding the various treatment approaches are available.

Law Environmental, Inc.
112 Townpark Dr.
Kennesaw, GA 30144-5599 404/421-3400

Law Environmental, Inc.—A professional engineering and earth science consulting firm. Services include: remediation management and site cleanup, environmental review for property transfers and plant operations, environmental siting and permitting, water resources and water quality management, occupational health and safety, tank management, hazardous and solid waste management.

Layne-Western Company, Inc.
1900 Shawnee Mission Pkwy.
Mission Woods, KS 66205 913/362-0510

Layne-Western Company, Inc. brings technical knowledge and practical experience to the specialized fields of investigative drilling, remedial action and environmental monitoring. From offices located coast-to-coast, we provide clients with a pool of talented professionals and a high commitment to professionalism, safety and quality.

Lewis Publishers, Inc.
121 South Main St., P.O. Drawer 519
Chelsea, MI 48118 313/475-8619

Publisher of scientific and environmental books that cover toxic and hazardous waste, groundwater, wastewater, and other vital topics in the environmental field.

Lopat Enterprises, Inc.
1750 Bloomsbury Ave.
Wanamassa, NJ 07712 201/922-6600

Lopat's K-20/LSC is used in the control and remediation of all hazardous leachable toxic metals mandated by the U.S. EPA, state and local authorities in incinerator ash, soil, soil-like solids or semi-solid wastes. K-20/TCC is used in the control of PCBs and other chlorinated and organic compounds in soil-like particulate matter and on various cementitious surfaces.

Louisiana Surety & Bonding, Inc.
P.O. Box 40371
Baton Rouge, LA 70835 504/272-7052

Louisiana Surety & Bonding, Inc. is a nationwide construction bonding agency specializing in Bid, Performance, and Payment Bonding for the hazardous waste remediation industry.

MAC Corporation/Saturn Shredders
201 E. Shady Grove Rd.
Grand Prairie, TX 75050 214/790-7800

Manufacturers, designers and fabricators of reduction systems to address the needs of PCB, haz waste, low rad waste, and steel-drummed chem waste processors. If incineration or other treatment requires preparing the infed through shredding, opening, separating, disengaging or reducing the size of same, our expertise will positively contribute to your decision-making process.

METCO Environmental, Inc.
P.O. Box 598
Addison, TX 75001 214/931-7127

Source emissions testing services including trial burn testing, trial burn plan preparation, compliance testing, ambient air monitoring, and continuous emission certification.

MK-Environmental Services
P.O. Box 79
Boise, ID 83707 208/386-6172

Morrison Knudsen from start to finish...MK-Environmental Services offers full-service capability to manage environmental and hazardous waste programs. Continuing Morrison Knudsen's 77-year history as a major international engineer and constructor, MK-Environmental fully integrates scientific, engineering, procurement, and remediation activities to support private- and public-sector clients.

MPC Environmental
8631 W. Jefferson
Detroit, MI 48209 313/849-2333

MPC Environmental is a full-service environmental company. The show emphasis will be with our high capacity, low viscosity pumping system for movement of hazardous or petroleum type products. We offer site cleanups, immediate response to spills of all types, groundwater remediation and marine services.

MSA
P.O. Box 426
Pittsburgh, PA 15230 412/967-3000

MSA will display a full line of personal protective equipment including products for respiratory protection and environmental monitoring.

MWR, Inc.
615 W. Shepherd St., P.O. Box 10
Charlotte, MI 48813 517/543-8155

Remedial services emphasizing patented soil vapor extraction process.

Matarah Industries, Inc.
1339 N. Milwaukee St.
Milwaukee, WI 53202 414/272-1965

Matarah Industries supplies a superior quality industrial sorbent for both in-plant and on-water spill prevention, containment and/or clean-up. Matarah Industries offers MATASORB, an oil and chemical sorbent, which does not absorb water and shows superior strength, sorbent capacity, and cleanliness. Matarah also offers SORB-X, an advanced all-liquid sorbent material. Both products incinerate cleanly for disposal adding BTU value to the burning process.

Metcalf & Eddy
P.O. Box 4043
Woburn, MA 01888-4043 617/246-5200

Metcalf & Eddy provides a full range of hazardous waste services, from remedial investigations and feasibility studies, to remedial design and construction, to long-term operations. Metcalf & Eddy also provides emergency response services using licensed equipment, as well as environmental audits, permitting assistance, and underground storage tank management.

metaTRACE, Inc.
13715 Rider Trail North
Earth City, MO 63045 314/298-8566

metaTRACE is an analytical laboratory offering full-service capabilities for organic, inorganic and radio chemistry analyses of air, groundwater, surface water, wastewater, potable water, soil, hazardous wastes and biological samples. Routine analyses include organic/inorganics, dioxins/furans, mixed waste, radiochemistry, TCLP, Appendix VIII and IX, explosives, indus-

trial hygiene, air quality, and EPA priority pollutant, RCRA and SARA analyses.

Minnesota Geophysical Associates
8616 Xylon Ave. North, Suite O
Brooklyn Park, MN 55445 612/493-3595

Minnesota Geophysical Associates offers consulting and contracting services in high-resolution surface and downhole geophysics. Surface geophysical methods include seismic reflection and refraction, electromagnetics (EM), and resistivity. Downhole methods include natural gamma, spontaneous potential (SP), single-point resistance, caliper, and borehole video.

Nanco Environmental Services, Inc.
RD#6 Robinson Lane
Wappingers Falls, NY 12590 914/227-4100

Nanco Laboratories, a U.S. EPA, New Jersey D.E.P. and Commonwealth of Virginia contract laboratory, provides complete environmental analytical services nationwide. Nanco is a Haz-waste approved laboratory. Nanco's services include: analysis for CLP, RCRA, ECRA, land transfer, data interpretation, data validation, electronic data delivery and quick turn-around time analysis.

Neri/Petrex
309 Farmington Ave., Suite A-100
Farmington, CT 06032 203/677-9666

The Petrex Technique is an innovative geochemical method for identifying and mapping volatile organic compounds from soils and groundwater contamination. The technique utilizes Petrex monitors, which are placed in the ground in a strategic pattern. After a representative subsurface sampling period, the monitors are removed and analyzed by mass spectrometry.

NTH Consultants Ltd.
38955 Hills Tech Dr.
Farmington Hills, MI 48331-3432 313/553-6300

Geoenvironmental Services: hydrogeologic studies, groundwater modeling, environmental site assessments, geophysical surveys, underground storage tank management, facility closure engineering, compliance investigations, permitting assistance, geoenvironmental monitoring, expert witness testimony, health and safety plans for environmental projects, construction monitoring, as-built drawings and documentation, laboratory test services, leachate compatibility, sludge stabilization and liner performance.

NUS Corp.
Waste Management Services Group
Pittsburgh, PA 15275 412/788-1080
Gaithersburg, MD 20878 301/258-6055

For 27 years NUS Corporation has provided the environmental and engineering expertise to solve industry and government waste management problems with cost-effective solutions. Our staff of over 2,000 multidisciplinary professionals offers a full range of services including environmental assessment, environmental engineering, remedial design and implementation, hydrogeologic and geologic services, risk assessment, regulatory assistance, environmental health and safety and analytical services.

Napoli Trucking Corporation
P.O. Box 510
Matawan, NJ 07747 201/566-3000
Transportation and storage of hazardous and non-hazardous waste.

National Draeger, Inc.
101 Technology
Pittsburgh, PA 15275 412/787-8383

National Draeger offers a wide range of products within the respiratory, instrumentation, and detector tube lines. The Model 190 Data logger is the most advanced portable gas monitor available for industrial hygiene and safety professionals. It detects toxic gas and alarms independent of the microprocessor function. National Draeger's air-purifying respirators include cartridges for organic vapors, and gases and ammonia, as well as high efficiency particulate filters for dust, fumes, mists, radionuclides and asbestos.

National Environmental Testing, Inc.
Woodland Falls Corporate Park
220 Lake Dr. East, Suite 301
Cherry Hill, NJ 08002 609/779-3373

A growing nationwide network of environmental testing laboratories dedicated to providing high quality analytical data and superior customer service. We offer a full range of environmental analytical services backed by comprehensive field services which include field sampling, stack testing and industrial hygiene services.

National Lime Association
3601 N. Fairfax Dr.
Arlington, VA 22201 703/243-5463

Association of commercial lime producers who supply quicklime and hydrated lime for treatment of acidic and related wastes, many of which are "hazardous." Lime is also used with fly ash for the stabilization of hazardous waste. The Association has movies and literature available on lime including use in hazardous waste.

National Solid Waste Management Association
1730 Rhode Island Ave., NW, #1000
Washington, DC 20036 202/659-4613

CWTI (Chemical Waste Transporters Institute) and RCI (Remedial Contractors Institute) are components of National Solid Wastes Management Association to promote safe transport and cleanup of hazardous waste sites. NSWMA is the only association representing these interests for Superfund and other state cleanups.

National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161 703/487-4815

The National Technical Information Service (NTIS) provides access to the results of both U.S. and foreign government-sponsored R&D and engineering activities. NTIS announces these completed and ongoing results in its two databases, the NTIS Bibliographic Database and FEDRIP. The NTIS Bibliographic Database contains over 1.4 million citations of completed research, including technical reports, theses, bibliographies, software, datafiles, and inventions available for licensing. It is available from BRS, DATA-STAR, DIALOG, ORBIT, and STN in the United States and several European vendors including ESA-IRS and CISTI. The Federal Re-

search in Progress (FEDRIP) Database contains citations of current and ongoing research from nine Federal government agencies, including the U.S. Public Health Service, NASA, and the Department of Energy.

Northeastern Analytical Corp.
4 East Stow Rd.
Marlton, NJ 08053 609/985-8000

Environmental services include complete environmental field sampling, in-house gas chromatography/mass spectrometry (GC/MS) laboratory analysis, hazardous site training (40 hours), asbestos inspection and management and abatement monitoring services, asbestos analysis by transmission electron and optical microscopy, underground storage tank testing, excavation, removal and installation, stack emission and ambient air testing.

OHM Corp.
16406 U.S. Route 224 East
Findlay, OH 45840 419/423-3526

OHM Corporation applies fully integrated environmental assessment, design, engineering, implementation and treatment/disposal services to hazardous waste and hazardous material contaminations nationwide and in Canada. Facilities include 19 remediation service centers, 6 engineering and technical centers, 6 laboratories, and a fully permitted, fixed-base transfer, storage and treatment facility.

OSCA Environmental Services, Inc.
1515 Poydras, Suite 2250
New Orleans, LA 70112 504/528-9184

OSCA Environmental Services, a subsidiary of Great Lakes Chemical Co., provides a complete line of Geo environmental engineering and field remediation services. These services include project management; site investigation and assessments, UST remediation, installation of monitoring and recovery wells; excavation/decontamination; dewatering; pit, pond, lagoon or tank retrofit or closure.

OSCO, Inc.
P.O. Box 1203
Columbia, TN 38402 615/381-4999

OSCO is an environmental management company which operates a hazardous waste treatment facility in Columbia, Tennessee. Materials accepted are acids, bases, flammables, oily waste, and many others in drums or bulk. Remedial services, including design, are provided for clients. A fleet of transportation equipment allows OSCO to handle the customers needs.

Occupational Hazards
1100 Superior Ave.
Cleveland, OH 44114 216/696-7000

Occupational Hazards Magazine is edited for management officials who are responsible for workplace safety, health and environment. Editorial material includes coverage of major legislative, regulatory, scientific and other developments affecting the field, as well as, practical "how-to" articles.

Ogden Environmental Services
P.O. Box 85178
San Diego, CA 92138-5178 619/455-3045

Ogden Environmental Services has the solution for Superfund cleanups. We specialize in provid-

ing a turnkey service for site remediation. This service includes utilization of Ogden's transportable circulating bed combustor (CBC). The CBC is capable to safely and economically destroying a wide variety of hazardous wastes to levels over 99.99% without discharging harmful emissions.

On-Site Instruments
689 North James Rd.
Columbus, OH 43219 800/551-2783

On-Site Instruments/EnviroRENTAL sells, rents, and services a complete line of industrial hygiene, laboratory, and environmental monitoring instruments and equipment. Rent-to-own and leasing options also available. Our service department provides technical and applications assistance, while our distribution center handles all accessory orders. On-Site also offers training classes at our Columbus, Ohio facility.

PACE Laboratories, Inc.
1710 Douglas Dr. North
Minneapolis, MN 55422 612/544-5543

PACE Laboratories, Inc. provides field services, laboratory services, industrial hygiene services, asbestos services and air sampling services.

PDC (Peoria Disposal Company)
4700 N. Sterling Ave.
Peoria, IL 61611 309/688-0760

PDC and its subsidiaries own and operate Part B permitted hazardous waste disposal and treatment facilities; and provide transportation services, laboratory analysis, remedial response, and consulting engineering.

**Pollution Equipment News/
Rimbach Publishing Inc.**
8650 Babcock Blvd.
Pittsburgh, PA 15237 412/364-5366

Pollution Equipment News, published bi-monthly, provides product information to the person responsible for air, water, wastewater and hazardous waste. An annual *Catalog & Buyer's Guide* provides source information. *Industrial Hygiene News*, published bi-monthly, provides information on products and services for measuring and controlling health hazards in the work environment. An annual *Catalog & Buyer's Guide* provides buying source information.

PRC Environmental Management, Inc.
303 East Wacker Dr., Suite 500
Chicago, IL 60601 312/856-8700

PRC EMI provides environmental services to both government and industry. Headquartered in Chicago, Illinois, PRC EMI maintains major offices in McLean, Virginia and San Francisco, California as well as 10 other offices throughout the country. Specialties include remedial investigations/feasibility studies, endangerment assessments, remedial design and implementation, compliance audits, permitting support, waste reduction audits, risk management support, environmental and systems engineering, policy and regulatory analysis, economic analysis, and program management support.

Pacific Analytical, Inc.
1989-B Palomar Oaks Way
Carlsbad, CA 92009 619/931-1766
Environmental analytical laboratory services

with emphasis on CLP and SW-846 Methods: Organics by GC, HPLC and/or GC/MS, metals by ICP-mass spectrometry. Specialties include non-routine compounds, low level concentrations, unusually complex matrices, sludge, biological tissue. CLP, CA DOHS certified.

Pennsylvania Drilling Company
500 Thompson Ave.
McKees Rocks, PA 15136 412/771-2110

Pennsylvania Drilling Company has been installing monitoring wells and drilling for hazardous wastes for many years. The company began in 1900 to service the coal industry. To serve the hazardous waste industry, we have OSHA trained over 40 employees and invested in the latest drilling equipment. In 1989 we moved into newly renovated shops and offices to more efficiently manage and coordinate projects. Our manufacturing facilities provide our customers with unlimited options for trying out new and unique ideas.

The Perkin-Elmer Corp.
761 Main Ave.
Norwalk, CT 06859-0012 203/762-1000

Perkin-Elmer offers products which perform a wide range of analyses of hazardous materials and materials of environmental concern. Specifically, gas chromatography, gas chromatography-ion trap detection; Zeeman furnace atomic absorption, inductively coupled plasma-mass spectrometry, and other techniques help you solve both routine and complex problems. Applications specialists will be on hand to discuss specific analytical situation.

Peroxidation Services, Inc.
4400 E. Broadway, Suite 602
Tucson, AZ 85711 517/456-4126

UV/peroxidation water treatment equipment and services. Destroys organics in contaminated water with zero air emissions and no solid waste residual.

Photovac International Inc.
741 Park Ave.
Huntington, NY 11743 516/351-5809

Photovac will display portable instruments for environmental toxic monitoring in groundwater, soil, and ambient air: TIPTM, a hand-held Total Organics analyzer; the 10S Series Portable Gas Chromatograph; and MicroTIPTM, a hand-held analyzer which incorporates advanced microprocessor technology for real time digital or graphic assessment of toxic gases and vapors.

Poly-America
2000 W. Marshall Dr.
Grand Prairie, TX 75051 214/647-4374, x355

Poly-America offers polyethylene geomembrane for hazardous waste containment, landfill caps, and waterways.

Polyfelt, Inc.
1000 Abernathy Rd.
Atlanta, GA 30328 404/668-2115

Producer of spunbond, continuous filament, polypropylene nonwovens for soils engineering applications. Specific uses include gas venting, liner cushioning, and drainage infiltration. Weight range from 2.7 to 22.0 oz/sq. yd.

Princeton Testing Laboratory
P.O. Box 3108
Princeton, NJ 08543 609/452-9050

Environmental analysis, industrial hygiene, RCRA/ECRA, industrial wastewater NPDES, groundwater, OSHA workplace surveys, asbestos monitoring and evaluation, complete NIOSH lab methodology, asbestos and HAZMAT training courses, Right-to-Know compliance, microbiology, bioassay, underground storage tank testing, AIHA accredited. Certified for: NJ DEP, NYDOH, PA DER, CT, RI, DE.

QED Environmental Systems Inc.
P.O. Box 3726
Ann Arbor, MI 48106 313/995-2547

The QED Environmental Systems family of products features Well Wizard®, the original dedicated bladder pump for groundwater monitoring; Sample Pro® portable samplers and supplies; Pulse Pump™ pneumatic pumping systems for groundwater clean-up, and recovery, and HydroPunch™ for groundwater sampling without wells.

QUALTEC, Inc.
11300 U.S Hwy. One, Suite 500
Palm Beach Gardens, FL 33408 407/775-8396

QUALTEC, Inc. provides full-service on-site environmental remediation including: consulting, site assessments, remedial investigations/feasibility studies, treatability studies, bench/full-scale pilot studies, landfill construction/closures, and the fixation/solidification of most types of contaminated soils, sludges and ash. QUALTEC's subsidiary, ENVECO, Inc., provides leasing of specialized fixation equipment.

R.E. Wright Associates, Inc. (ERS)
3240 Schoolhouse Rd.
Middletown, PA 17057 717/944-5501

Air stripping towers for removal of volatile organic compounds (VOCs) from groundwater or process water; Auto-Skimmer for automatic recovery of floating hydrocarbons from water wells; Wright modular recovery system pneumatic pumping system for recovery of floating hydrocarbons or heavier-than-water contaminants; Depression pumps and controls for use in subsurface oil spill recovery and aquifer restoration projects; Liquid interface sampler for quick sampling of liquids of differing densities in the field.

R.E. Wright Associates, Inc. (ERC)
3240 Schoolhouse Rd.
Middletown, PA 17057 717/944-5501

R.E. Wright Associates, Inc. (REWAI) offers comprehensive environmental consulting and engineering services. REWAI has extensive experience in the area of hazardous waste and hydrocarbon pollution remediation. The firm's professional involvement has spanned the full spectrum of necessary investigative functions. REWAI routinely performs feasibility studies utilizing contaminant transport modeling analyses. In addition, REWAI regularly handles projects through final design and construction. REWAI also provides technical services in the areas of solid waste management, wastewater treatment and disposal, groundwater resources management, and environmental engineering and planning.

RMC Environmental Services
RD #1, Fricks Lock Rd.
Pottstown, PA 19464 215/326-9662

Analytical Laboratory Services; Geotechnical Services, including groundwater monitoring, well siting and installation, hazardous site investigations; environmental consulting, including natural resource inventories, population studies, biological sampling, tissue analysis, bioassays, wetlands studies.

RMT, Inc.
P.O. Box 8923
Madison, WI 53708-8923 608/832-4444

RMT is a consulting engineering firm specializing in solid and hazardous waste management, groundwater monitoring and analysis, industrial hygiene engineering, environmental control, and lab services. Business includes planning, design, and permitting of hazardous waste treatment, storage, and disposal facilities, and the investigation, design, implementation and monitoring of remedial measures.

Radian Corp.
P.O. Box 201088
Austin, TX 78720-1088 512/454-4797

Radian Corporation provides a full range of process, solid and hazardous waste engineering services...including site assessment to remediation design and construction, waste minimization to the design of waste treatment or disposal systems, and preparing permit applications to responding to consent orders. In addition, the company has three full-service laboratories providing complete characterization and classification of soils, groundwater, run-off, leachates, air emissions, soil vapors, and virtually any other substance or material for which measurements are required. Radian also has the unique ability to perform remedial pilot studies on site. This is accomplished through our transportable treatment systems. The unit physical-chemical operations incorporated into these systems can be configured to treat most contaminated waste streams. These systems have sufficient capacity to provide full-scale groundwater remediation.

Recra Environmental, Inc.
10 Hazelwood Dr., Suite 106
Amherst, NY 14150 716/691-2600

Recra Environmental, Inc., with laboratory facilities in Amherst, New York (Buffalo) and Columbia, Maryland (Washington/Baltimore), offers full-service environmental testing services encompassing all matrices. Both of our facilities are U.S. EPA CLP contractors and are certified in numerous states. Services include data management and electronic data transfer.

Remcor, Inc.
701 Alpha Dr.
Pittsburgh, PA 15238 412/963-1106

Remcor provides the full spectrum of hazardous waste consulting and remediation services. By uniquely integrating expertise in engineering, construction, and environmental field services, Remcor performs projects ranging from investigations through actual remediation. As a turnkey contractor, Remcor has completed numerous projects including building decontamination, surface impoundment closure, landfill clean-ups, storage tank management, asbestos removal and groundwater remediation.

Remediation Technology, Inc. (REMTECH)

273 Franklin Rd.

Randolph, NJ 07869

201/361-8840

Remediation Technology, Inc. (REMTECH) provides services related to on-site remediation of contaminated sites, engineering services aimed at providing innovative solutions to environmental problems, and technology transfer of unique and novel cleanup technologies.

Resource Analysts, Inc.

Box 778

Hampton, NH 03842

603/926-7777

Resource Analysts, Inc., a subsidiary of Millipore Corporation, provides environmental chemistry, aquatic toxicology and field sampling services to industrial and governmental clients. Resource Analysts, Inc. participates in EPA's Contract Laboratory Program and is Army and Navy approved for DOD site restoration services. Facilities include 24,000 sq. ft. dedicated to chemistry laboratory and 10,000 sq. ft. dedicated to fresh water and marine aquatic toxicology laboratory. RAI maintains a professional staff of 85 scientists, technicians and administrators. The company prides itself on its unique customer satisfaction program.

Response Rentals

1460 Ridge Rd. East

Rochester, NY 14621

800/242-3910

Response Rentals provides rental instrumentation for remedial investigation studies, compliance surveys and substance emergencies. The instrumentation is easy to operate, reliable and represents the best names in the industry. Broad product line meets virtually every application need and includes OVAs, CGIs, PIDs, Isothermal GCs and more.

Roy F. Weston, Inc.

Weston Way

West Chester, PA 19380

215/430-3025

Weston is a full-service environmental engineering firm specializing in analytical laboratory services, consulting and engineering, remediation, facility construction and operations, technical information management and the management of major programs. Weston employs more than 2,600 people from various disciplines, wholly owns 8 subsidiaries and now has 42 offices nationwide.

Ruska Laboratories, Inc.

3601 Dunvale Rd.

Houston, TX 77063

713/975-0547

The Ruska PYRAN ThermoChrom™ universal spectrometer interface will be featured via photographs and data displays. This Thermal Chromatograph™ permits the direct analysis of soils, sludges and other solid and semi-solid materials for organic contamination without the need for solvent extraction or other sample preparation techniques. Both mobile and fixed lab configurations will be depicted.

S-CUBED,**A Division of Maxwell Laboratories, Inc.**

P.O. Box 1620

La Jolla, CA 92038

619/453-0060

Chemical Analysis Services: CLP organic analyses, RCRA analyses, Methods 1618, 1624, 1625 analysis for OWRS samples, Appendix IX com-

pounds, inorganic Analytes; Quality Assurance Support-BDAT, SITE, OPP Projects: QA project plan reviews, final report reviews, field audits, QA training; Analytical Methods Development and Research; Environmental Engineering: site investigation/field sampling and monitoring, treatability studies, solidification/stabilization.

SCS Engineers

11260 Roger Bacon Dr.

Reston, VA 22090

703/471-6150

Solid and hazardous waste consulting services since 1970. Specialists in control and treatment of subsurface gases; a subsidiary of the firm offers construction services in this area. Remedial investigations, feasibility studies, design, construction management. Analytical laboratory, underground tank testing, construction. Real estate contamination assessments. Hazardous waste facility design and permitting.

Sensidyne, Inc.

16333 Bay Vista Dr.

Clearwater, FL 34620

813/530-3602

Portable and fixed gas detection and air sampling equipment. Equipment includes monitoring instruments such as Sensidyne's FID, Odor Monitor, Hazardous Material Kits, Detector Tubes, Personal Toxic Monitors, Personal Sampling Pumps, Continuous Toxic and Combustible Monitors.

Sentex Sensing Technology Inc.

553 Broad Ave.

Ridgefield, NJ 07657

201/945-3694

Manufacturer of: portable gas chromatographs; used to monitor TLV levels of contaminants in air, water or soil. Multi-point monitoring systems: for continuous PPM/PPB analysis of hazardous gases. Portable purge and trap gas chromatograph: for automatic/accurate analysis of VOCs in water.

SLT North America, Inc.

16945 Northchase, Suite 1750

Houston, TX 77060

713/874-2150

The pioneer in HDPE lining systems, SLT manufactures and installs 34-ft wide seamless monolithic sheets, with engineered innovations such as: Hyperflex™, PolyLock™, and Friction-Flex™. Manufactured material thickness from 40 to 240 mils, SLT is your solution for ponds, tanks, tunnels, landfills, and mining applications.

SMC Environmental Services Group

P.O. Box 859

Valley Forge, PA 19482

215/265-2700

SMC Environmental Services Group provides consulting services in the fields of geology, hydrogeology, biology, civil and environmental engineering, planning, surveying, environmental science, and computer technology. Founded more than 35 years ago, SMC is comprised of a staff of nearly 60 engineers and scientists and serves a broad range of clients from Fortune 500 industries to municipal authorities.

SSI Shredding Systems

28655 SW Boones Ferry Rd., P.O. Box 707

Wilsonville, OR 97070

503/682-3633

SSI Shredding Systems provides on-site volume reduction and material processing of solid haz-

ardous waste prior to material treatment. Specific services include pre-processing, feedstock preparation and volume reduction of solid hazardous waste utilizing mobile low-speed, rotary shear shredders. This low rpm equipment is easy to trailer mount and once on-site is operational within hours. OSHA certified operators are provided.

Systech Environmental Corp.

245 N. Valley Rd.

Xenia, OH 45385

513/372-8077

Supplemental fuel use of organic liquid wastes in a rotary cement kiln.

Science Applications International Corp.

8400 Westpark Dr.

McLean, VA 22102

703/734-4302

SAIC has been providing environmental management services to government and commercial clients for nearly 20 years from offices across the country. Our services include RI/FS, design engineering, construction management and compliance programs for air, water and hazardous waste regulations. Special capabilities include laboratory services, health and safety training and clean-up technology development and demonstration.

Scientific Specialties Service, Inc.

P.O. Box 352

Randallstown, MD 21133

301/964-9666

Scientific Specialties Service, Inc. is showing its line of environmental sampling supplies including precleaned and regular vials, bottles, and jars in both glass (which is also available Safety-Coated if desired) and plastic. They are also showing their Teflon® Capliners and Teflon®/Silicone septa and their line of Teflon® sealing tapes in an extensive range of sizes.

Serrot Corp.

5401 Argosy Dr.

Huntington Beach, CA 92647

714/895-3010

Serrot Corporation is a full-service company specializing in the fabrication and installation of geomembrane lining systems and floating covers. Serrot is fully experienced in the full range of materials available for a multitude of applications including: hazardous waste, sanitary landfills, potable water, wastewater, tanks, mining, leach pads, process water, methane barriers, floating covers and specialty applications. Service is available on a national basis.

Sevenson Environmental Services, Inc.

2749 Lockport Rd.

Niagara Falls, NY 14302

716/284-0431

Sevenson Environmental Services, Inc. provides remedial construction services to government and industry in site remediation; excavation, characterization, transportation, and disposal of bulk and drummed wastes; secure landfill and lagoon construction/closure; slurry wall construction; sludge solidification and fixation; recovery and treatment systems installations for groundwater soils; leachate collection and treatment systems installations for groundwater soils; leachate collection and treatment systems construction; on-site incineration, biological remediation; facilities decontamination and demolition; dewatering; and storage tank removal/remediation.

Site Reclamation Systems

P.O. Box 11
Howey-in-the-Hills, FL 34737 904/324-3651

Site Reclamation Systems, Inc. (SRS) designs, constructs, and operates mobile soil volatilizers which clean soils contaminated with petroleum hydrocarbons (e.g., gasoline, #2 fuel oil, jet fuel, kerosene, etc.). The distinct advantages over conventional disposal options are:

- Eliminates long-term liability associated with conventional transportation and disposal
- The process is cost-effective and competitive with conventional disposal methods
- Complies with new federal and state regulations which require waste destruction and minimization whenever possible

Skolnik Industries, Inc.

4900 S. Kilbourn Ave.
Chicago, IL 60632 312/735-0700

New steel containers (Overpack/Salvage, carbon, composite and stainless) from 8 to 110 gallons for shipping and storing hazardous and non-hazardous waste materials, as well as container liners, HazMat containment kits, components, dollies, utility carts, tools and accessories. Custom design and fabrication is also available.

Solinst Canada Ltd.

The Williams Mill, 515 Main St.
Glen Williams, ON L7G 3P5 416/873-2255

Solinst manufactures high quality groundwater monitoring instrumentation. New on display at Superfund '89 will be an oil/water "Interface Probe." The probe has the rugged durability and easy operation of Solinst Water Level Meters, and accurately measures depth of product layers and depth to water. The Waterloo Multilevel System will also be on display.

Southwest Laboratory of Oklahoma

1700 West Albany, Suite C
Broken Arrow, OK 74012 918/251-2858

Quality and service oriented analytical laboratory offering comprehensive analysis for CERCLA, SARA, RCRA, priority pollutants, Dioxins/Furans, Appendix IX, explosives and TCLP. SWL is a full participant in the U.S. EPA CLP with multiple contracts in organics, high hazards and inorganics. Also certified by Corps of Engineers for DERA projects.

Southwest Research Institute

6220 Culebra Rd.
San Antonio, TX 78228-0510 512/522-2687

Southwest Research Institute provides commercial leak location surveys of geomembrane liners for landfills, impoundments, and lined tanks to accurately locate leaks in the material and seams. Analytical laboratory systems and techniques will be presented for both the sampling and analysis of environmental pollutants. Bio-degradation techniques will also be discussed.

Specialized Environmental Equip., Inc.

Rt. 4, Box 216
Easley, SC 29540 803/859-8277

Specialized Environmental provides Mobile Laboratories: chemical analysis units, water pollution analysis units, and decontamination units; Special Service Units; Bioassay Dilutor Systems; and Water Baths, Dual Purpose Pumps and Oxygen Demand Apparatus.

Stout Environmental Inc.

2880 Bergey Rd.
Hatfield, PA 19440 215/822-2676

Stout Environmental, Inc. is a full-service environmental management company providing treatment and disposal of hazardous, industrial, and municipal wastes, along with a broad range of specialized support services. Our 15 service divisions enable us to offer a turnkey approach to environmental problems providing timely and cost-effective solutions.

Summit Interests

1801 Sunset Pl., Suite D
Longmont, CO 80501 303/772-3073

SIP-1000 Portable Gas Analyzer—The SIP-1000 is a small, portable, self-contained instrument that is both a continuous monitor and gas chromatograph and is capable of detecting gases in the PPB range. "A New Twist on Detectors" allows the operator to quickly change detector types (PID, FID, TCD). Another feature is the incorporation of a solid state carrier gas system that utilizes metal hydrides.

Surety Specialists, Inc.

1501 2nd Ave. E., P.O. Box 5098
Tampa, FL 33675-5098 813/247-0118

Surety Specialists, Inc.—Our name says it all. Surety provides Surety Bonds for all types of contractors. We are experts with "tough" cases, including asbestos, environmental and demolition contractors. We specialize in creative underwriting and represent Treasury-listed and Best-rated bonding companies.

Surety Technicians, Inc.

6200 Courtney Campbell Cswy., Suite 685
Tampa, FL 33607 813/872-1810

National bond agency specializing in the placement of all types of hard to write contract bonds, including environmental remediation, asbestos abatement, and demolition contracts; representing over two dozen carriers including Treasury-listed and Best-rated companies.

Sybron Chemicals Inc./Biochemical Division

Birmingham Rd., P.O. Box 66
Birmingham, NJ 08011 609/893-1100

Leaders in the application of augmented bio-reclamation (ABR) for the treatment of contaminated soil and groundwater. Capabilities include biosystems engineering services and supply of selectively adapted organisms for specific contaminants. Technology useful for cleanup of chemicals from leaking storage tanks, pipeline spills, train derailments, etc. Advantages are ultimate disposal technology and low cost.

TAMS Consultants, Inc.

655 Third Ave.
New York, NY 10017 212/867-1777

TAMS, a leading international engineering and scientific firm, offers comprehensive services in solid and hazardous waste management. Significant experience includes RI/FS; health/safety; risk assessment; community relations; remedial design; construction oversight; site closure; waste geotechnics; chemical/process design; watershed management; hydrogeology/mathematical modeling. TAMS provides services to clients in government, military and private sectors through offices in major cities.

TARGET Soil Gas Surveys

8940-A Rte. 108 Oakland Center
Columbia, MD 21045 301/992-6622

TARGET specializes *solely* in providing soil gas services nationwide for fast and accurate screening of VOCs in the subsurface. TARGET's *advanced* soil gas surveys have been used for detecting and assessing suspected VOC problems, delineating the extent of a spill, and/or monitoring the progress and success of a remediation effort.

Tigg Corp.

P.O. Box 11661
Pittsburgh, PA 15228 412/563-4300

Manufacturers of modular adsorbers designed for the remediation of vapor and water pollution. The combination of over 30 years of experience with adsorbents and systems provides unique capabilities of technical expertise and product availability to address specific remedial problems with the most appropriate technology.

TPS Technologies Inc.

2070 S. Orange Blossom Trail
Apopka, FL 32703 407/886-2000

TPS Technologies Inc. provides on-site thermal treatment for petroleum-contaminated soils. TPS Technologies' thermal treatment units have statewide permits and can be operated anywhere in the State of Florida, as well as in many other states. TPS Technologies offers the optimum package: reduced liability exposure, competitive pricing, minimum site disruption and immediate response.

TechLaw Inc.

14500 Avion Pkwy., Suite 300
Chantilly, VA 22021-1101 703/818-1000

TechLaw, an environmental consulting firm experienced in the application of legal and technical principles to tasks in support of RCRA and CERCLA litigation activities, provides enforcement services including: PRP search, imaging services, tracking systems, evidence audits, document control systems, legal research, full text database, transactional database, data validation and compliance audits.

Tekmar Company

P.O. Box 371856
Cincinnati, OH 45222-1856 513/761-0633

LSC 2000 Series Purge and Trap Concentrators for analysis of volatile organic compounds in environmental samples of water, soils, and sludges. Also dynamic headspace analysis on food samples and polymers. MS010GT Automatic Thermal Desorber for analysis of volatile organic compounds in air samples (both ambient and industrial hygiene).

Tenax Corp.

8291 Patuxent Range Rd.
Jessup, MD 20794 301/725-5910

Tenax Corporation manufactures a full line of Geosynthetics for waste management applications. The Tenax line of products include Drainage nets and Geocomposites for leachate collection, Geogrids for side slope reinforcement and haul road stabilization, fencing for safety delimitation and litter control. Technical assistance and design are available from Tenax Engineering Department.

Tetra Tech, Inc.
630 N. Rosemead Blvd.
Pasadena, CA 91107

818/449-6400

Tetra Tech specializes in environmental science and engineering, hazardous waste management, and assessment of risks to human health and the environment. Tetra Tech has more than 20 years experience managing and conducting major environmental and engineering services contracts for industry and government, including extensive nationwide experience in hazardous waste and underground storage tank management.

Thermo Analytical, Inc.
5635 Jefferson Blvd. NE
Albuquerque, NM 87109

505/345-9931

TMA's network of laboratories and service facilities provides a full range of analyses of organic and inorganic chemicals and radioactive materials in soil, water, air, industrial wastes, and biological materials. In addition to these analytical services, TMA offers health physics, industrial hygiene, and dosimetry consulting services.

Thermo Environmental Instruments
8 W. Forge Pkwy.

Franklin, MA 02038

508/520-0430

Thermo Environmental Instruments, Inc. is the world's leading manufacturer of U.S. EPA approved Ambient Air Pollution Analyzers, Extractive and In-Situ Stack Emission Monitoring Systems and Toxic Chemical Analyzers. Analyzers included in our product line are NO_x, CO₂, SO₂, CO, O₃, OVM, HC, and GCs.

Toney Drilling Supplies, Inc.
14060 NW 19th Ave.
Miami, FL 33054

305/685-2453

Complete line of drilling equipment: New/used drill rigs, drill rods, subs and bits. Diamond bits, core barrels, mud and additives; augers, casing and plugs; stainless steel screens, PVC screens, points and pcaps; monitoring and sampling devices; safety clothing, masks, gloves and boots. Consultation and instruction are also available.

Tracer Research Corporation
3855 N. Business Center Dr.
Tucson, AZ 85705

602/888-9400

Tracer Research Corporation specializes in Leak Detection for underground storage tanks, bulk storage, above ground tanks and pipelines; Tracer Technology for groundwater monitoring and landfill liner tightness testing; and on-site detection of subsurface volatile organic contaminants (soil gas analysis). Tracer offers full-service organic analysis laboratory services.

Tracor Xray, Inc.
345 E. Middlefield Rd.
Mountain View, CA 94043

415/967-0350

Field model XRF system for on-site screening for priority metals in contaminated soil without site specific standards. System uses single source, X-ray tube excitation, electrically cooled solid state detector and an IBM PC.

TreaTek® , Inc.
2801 Long Rd.
Grand Island, NY 14072

716/773-8660

TreaTek® is an environmental service subsidiary of Occidental Chemical Corporation, and

has as its commercial objective the application of advanced microbial and chemical treatment technologies to the remediation of waste streams and contaminated soil. TreaTek® can provide remedial consultation, laboratory treatability study (biological, chemical and physical), analytical support, system design and specification and turnkey project management.

Triangle Laboratories, Inc.
801-10 Capitola Dr., P.O. Box 13485
Research Triangle Park
NC 27709

919/544-5729

Triangle Laboratories, Inc. is an EPA-approved contract laboratory for Organics. The company was founded in 1984 and is privately owned. Its 20,000 sq. ft. facilities are located in Alston Technical Park in Research Triangle Park, North Carolina. Services include high resolution GC/MS analysis for Dioxin and Furans.

U.S. Analytical Instruments
1511 Industrial Rd.
San Carlos, CA 94070

415/595-8200

Available for rent and immediate delivery—HNU Model 101s, FOXBOROL OVA 128GCs, and MIRAN 1Bs from U.S. Analytical Instruments. In addition, USAI offers for rent or lease GC, HPLC, Fluorescence, UV/VIS, AA and ICP, IR and FTIR instrumentation from major manufacturers such as Hewlett-Packard, Perkin Elmer, Varian, Foxboro, Hitachi and Waters. We offer flexible rental and purchase option plans designed to meet your financial and instrumentation needs.

U.S. Army Corps of Engineers
P.O. Box 103, Downtown Station
Omaha, NE 68101-0103

402/691-4533

The U.S. Army Corps of Engineers and the U.S. EPA have joined forces to clean up Federal lead hazardous waste sites under the Superfund program. The booth will be manned by Corps personnel to assist architect-engineer firms and construction contractors to take advantage of work available to them through the Corps of Engineers.

U.S. Army Toxic & Hazardous Materials Agency
Bldg. E4460, ATTN: CETHA-PA
Aberdeen Proving Ground
MD 21010-5401

301/671-2556

The U.S. Army Toxic & Hazardous Materials Agency, located at Aberdeen Proving Ground, Maryland, is a field operating agency of the U.S. Army Corps of Engineers that offers a wide spectrum of environmental support services to Army installations nationwide.

U.S. Bureau of Mines
2401 E St., NW, MS 6201
Washington, DC 20241

202/634-1224

The Bureau of Mines is a Federal Government agency under the U.S. Department of the Interior. The Bureau's mission involves conducting research and gathering minerals-related data that will help strengthen our domestic minerals industry. Among its many research programs is a program dedicated to alleviating or solving environmental problems plaguing the minerals industry. Promising technologies have evolved from this program and are readily available to companies desiring to use them through technology transfer.

U.S. Bureau of Reclamation
Mail Code D-3210, P.O. Box 25007
Denver, CO 80225-0007

303/236-8646

The U.S. Bureau of Reclamation provides Total Project Management in hazardous waste site cleanup—PA/SI, RI/FS, RD, RA, and O&M. Work may be completed for other government agencies in planning, design, construction, construction oversight, reviews, or research. Work has been completed under RCRA, Superfund, and Federal Facilities section of CERCLA.

U.S. Envirosearch, Inc.
445 Union Blvd., Suite 225
Lakewood, CO 80228

303/980-6600

A nationwide recruiting firm based in Denver, Colorado, specializing in the recruitment of hazardous waste, environmental and incineration personnel. U.S. Envirosearch represents client companies in the areas of hazardous waste disposal, site remediation, environmental engineering, air quality, analytical labs, solvent recycling, PCB disposal, industrial cleaning and generators.

U.S. Geological Survey
790 National Center
Reston, VA 22092

703/648-4377

Panels depicting research and products of the U.S. Geological Survey dealing with earth sciences will be displayed.

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Port Washington, NY 11050

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VFL Technology Corporation
42 Lloyd Ave.
Malvern, PA 19355 215/296-2233

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Baltimore, MD 21225-0878 301/636-1490

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YWC, Inc.
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