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FOURTH FORUM ON INNOVATIVE HAZARDOUS WASTE TREATMENT TECHNOLOGIES: DOMESTIC AND INTERNATIONAL

San Francisco, CA
November 17-19, 1992

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ABSTRACT

On November 17-19, 1992, the U.S. Environmental Protection Agency's Technology Innovation Office and Risk Reduction Engineering Laboratory, Department of Energy, Corps of Engineers, and California Environmental Protection Agency, hosted an international conference in San Francisco, CA, to exchange solutions to hazardous waste treatment problems. This conference, the Fourth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, was attended by approximately 1,000 representatives from the U.S. and 25 foreign countries. During the conference, scientists and engineers representing government agencies, industry, and academia attended 42 technical presentations and case studies describing domestic and international technologies for the treatment of waste, sludges, and contaminated soils at uncontrolled hazardous waste disposal sites. Technologies included physical/chemical, biological, thermal, and stabilization techniques. Presentations were made by EPA, their Superfund Innovative Technology Evaluation (SITE) program participants, other Federal and State agencies and their contractors, international scientists and vendors. Over 70 posters were on display.

This compendium includes the papers that were made available by authors and their institutions. The papers are published as received and the quality may vary.

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TABLE OF CONTENTS

ABR-CIS bioremediation: full-scale experiences with an in-situ treatment system for sediment volume-reduction and contaminant mineralisation in harbours and waterways
B. Malherbe, HAECON N.V., Harbour and Engineering Consultants 1

In Situ Bioventing of a Diesel Fuel Spill
T.L. Bulman, Campbell Environmental 22

Remediation of Ground Water Contaminated with Organic Wood Preservatives Using Physical and Biological Treatment Technologies
J.G. Mueller, SBP Technologies, Inc. 35

The Design Criteria and Economics of Operating a Full-Scale Above-Ground Bioremediation Facility for the Treatment of Hydrocarbon Contaminated Soils
Robert Mall, KJC Operating Company 40

Biopur® An Innovative Bioreactor for the Simultaneous Treatment of Groundwater and Soil Vapour Contaminated with Xenobiotic Compounds
J.M.H. Vijgen, TAUW Infra Consult, B.V. 48

Bio-Rem Inc.'s Augmented In Situ Subsurface Bioremediation Process (TM) Using Bio-Rem, Inc.'s Proprietary Biocultures (H-10) for the Remediation of JP-4 Contaminated Soils at Williams AFB, AZ
David Mann, Bio-Rem, Inc. 62

Bioremediation of Soils at a Waste Oil Facility
Gary Guerra, U.S. EPA, Robert S. Kerr Environmental Laboratory 64

Low Temperature Thermal Treatment LT^3 Site Demonstration
Michael G. Cosmos, Roy F. Weston, Inc. 71

Plasma Arc Vitrification
Richard C. Eschenbach, Retech, Inc. 78

Thermal Desorption of PCB-Contaminated Waste at the Waukegan Harbor Superfund Site (A Case Study)
Robert Shanks, SoilTech ATP Systems, Inc. 90

The Babcock & Wilcox Cyclone Vitrification Technology for Contaminated Soil
J.M. Czuczwa, Babcock & Wilcox R&DD 119

The ECO LOGIC Process
D.J. Hallett, ELI Eco Logic International, Inc. 129

BioGenesis℠ Soil Washing Process Technology Summary
Charles Wilde, BioGenesis Enterprises, Inc. 136

Steam Enhanced Recovery Process (SERP)
William R. Van Sickle, Hughes Environmental Services, Inc. 142

Soil Venting to Remove DBCP from Subsurface Soil: A Case History
M.B. Bennedsen, Woodward-Clyde Consultants 146

5 Years Operational Experience with the Harbauer Soil Washing Plants
Winfried Gröschel, Harbauer GmbH & Co. KG 161

Field Demonstration of Soil Washing at the King of Prussia Superfund Site
Michael J. Mann, Alternative Remedial Technologies, Inc. 175

The Lurgi-DECONTERRA® Process Soil Washing
Ted J. Pollaert, Lurgi Corporation 192

Efficient and Cost-Effective Programs for Soils and Groundwater Restoration
J.J. Malot, Terra-Vac 200

Radiolytic Remediation of a TCE Ground Spill Using an Electron Accelerator
S.M. Matthews, Lawrence Livermore National Laboratory 206

Rethinking the hydraulic cage concept for hazardous waste disposal facilities and mitigation of contaminated sites
Charles Voss, Golder Associates, Inc. 212

Innovative Contracting Strategies for Equipment Procurement - Bofors Nobel Superfund Site - Muskegon, MI
Ted H. Streckfuss, U.S. Army Corps of Engineers 226

Remediation of Groundwater Contaminated with Volatile Organic Compounds in the Saturated Zone at a California Superfund Site in Mountain View, California
R.F. Battey, The Earth Technology Corporation 254

Soil Washing of Lead-Contaminated Soil at a Former Gun Club Site
Christine Parent, CAL/EPA Department of Toxic Substances Control 261

Improvements in the Conventional High Temperature Rotary Kiln Incineration Technology
Markku Aaltonen, EKOKEM Limited 270

Evaluation of Grouting Technology: DOE Perspective
W. Roberds, Golder Associates, Inc. 276

Du Pont/Oberlin Microfiltration Technology (SITE)
Ernest Mayer, E.I. du Pont de Nemours, Inc. 296

Composting of Explosives-Contaminated Soil at the U.S. Army Depot Activity
Captain Kevin R. Keehan, U.S. Army Toxic and Hazardous Materials Agency 313

United States/German Bilateral Agreement on Hazardous Waste Site Clean-Up Projects
H. Stietzel, Federal Ministry for Research and Technology, Germany 324

Groundwater Remediation: Extraction and Removal of TCE & Cr^{6+} at an NPL Site
Subijoy Dutta, U.S. EPA, Office of Solid Waste 340

The Use of Horizontal Wells in Remediating and Containing a Jet Fuel Plume - Preliminary Findings
Mark Thacker, CDM Federal Programs Corporation 346

Evaluation of Thermal Extraction Technologies for Treatment of Soils Contaminated with Coal Tars and Wood Preservatives at the Pacific Place Site, Vancouver, B.C.
Sandra Whiting, SCS Engineers 358

CF Systems' Solvent Extraction Technology for Site Remediation: A Post "Site Demonstration Update"
Chris Shallice, CF Systems Corporation 373

Commercialization of Innovative Technologies - Challenges and Solutions (A Technology Vendor's Perspective)
Frederic A. Eidsness, Jr., Canonie Environmental Services Corp. 385

Bioremediation of Chromium (VI) Contaminated Solid Residues Using Sulfate Reducing Bacteria
Louis J. DeFilippi, Allied-Signal Research and Technology 417

ABR-CIS bioremediation : full-scale experiences with an in-situ treatment system for sediment volume-reduction and contaminant mineralisation in harbours and waterways

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ABSTRACT

The improvement of the in-situ natural microbiological degradation of organic matter or organic compounds present a very attractive solution for the management of (contaminated) sediments in harbours and waterways. To get efficient biodegradation as much aerobic bacterial strains as possible have to be reactivated. This natural biodegradation process is particularly interesting for the achievement of an in-situ volume reduction of the deposit and/or in-situ decontamination of organic contaminants. ABR-CIS (Augmented Bio Reclamation - Conditioning In-Situ) is such an in-situ treatment technique which has been applied on full-scale. The projects executed with the ABR-CIS system will be discussed and the monitoring results will be presented. Moreover, the application of the ABR-CIS may represent major savings with respect to the classical dredging and disposal costs.

The accumulation of mud deposits in aquatic systems goes often parallel with the accumulation of organic micro-pollutants and nutrients and with eutrophication. This causes problems for the management (disposal) of these sediments to be dredged for navigation, calibration or even sanitation reasons.

The "over-supply" of organic wastes in river-systems from sewers, domestic or agricultural effluents has caused a saturation of the natural biodegradation processes in the aquatic environment (figure 1).

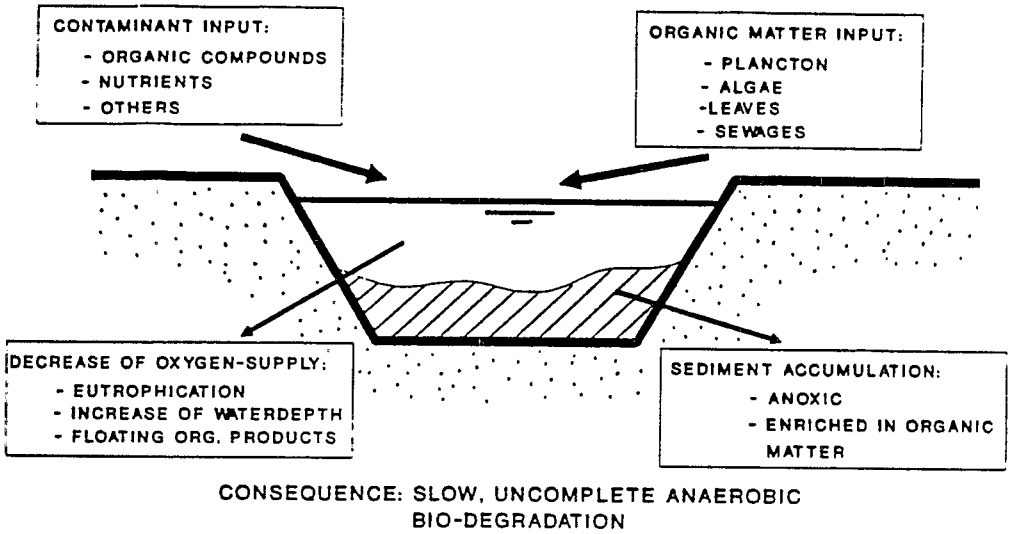

Figure 1 : Mechanism of creation of saturated anoxic sediment deposits

During the search for a simple technique to re-activate aerobic mineralisation processes. the ABR-CIS system was developed (ABR : Augmented Bio Reclamation - CIS : Conditioning In-Situ).

This presentation goes through some elementary concepts in microbiological processes to illustrate the potential of the ABR-CIS system which is an in-situ microbiological treatment system of sediments.

The potentiality of ABR-CIS lies in a mineralisation of organic matter (= microbiological dredging) and a mineralisation of organic micro-pollutants (= treatment in-situ).

BACTERIA AS PART OF THE NATURAL ECOSYSTEM OF SEDIMENT DEPOSITS

Fine-grained sediments are deposited in a wide variety of aquatic environments. These deposits, often called "muds", are a specific habitat for different organisms. The specificity of mud habitats is related to the high accumulations in the deposits of decaying biomass, adsorbed organic compounds, nutrients or man-induced contaminants. The sediment is making part of the global aquatic ecosystem composed of atmosphere, water column and sediment deposit. The typical aquatic ecosystem is described by the trophic chains illustrated on figure 2.

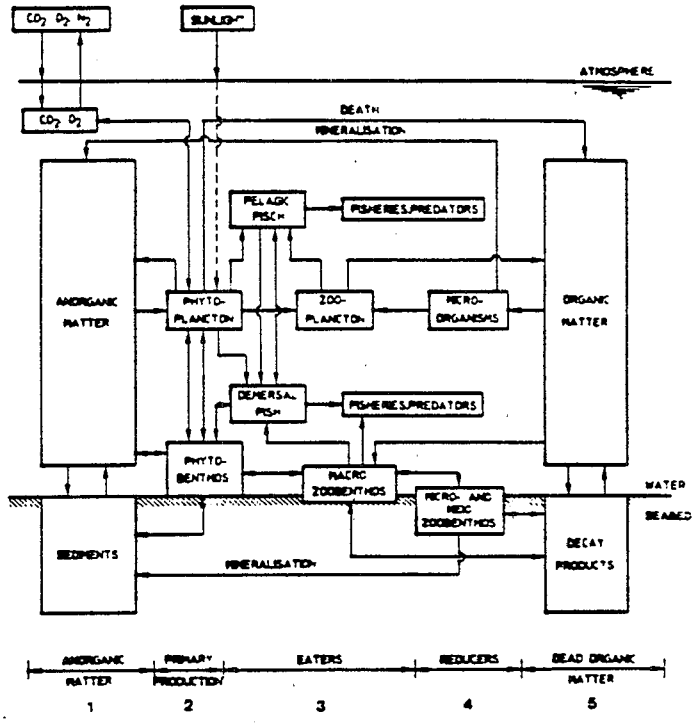

Figure 2 : Description of ecosystem elements in aquatic environment

Micro-organisms, such as bacteria, are occuring in the atmosphere, the water column and the sediment deposit (micro-benthos). On figure 2 it is clear that bacteria play a fundamental role in the mineralisation of organic products in water and sediment. Within the ecosystem bacterial activity is obviously related to the development and activity of other organisms such as e.g. diatoms (Hamilton, 1987).

Types of bacteria occuring in mud deposits

The environment where mud is deposited is also favourable for the deposition of e.g. dead phytoplancton (primary producers) or other fine-grained products. The presence

in mud of the clay-humic complex stimulates particular physico-chemical and biochemical reactions important to understand the environment of bacteria.

Bacteria are micro-organisms (diameter ca. 0,0001 - 0,02 mm). They are systematically classified in 3 types (Vogel, 1970) :

1. Eubacteria (unicellular most common bacteria species) :
   - coccae
   - bacilli
   - vibrionic.b.
   - spirillic.b.
2. String bacteria (composed of micro-colonies interconnected with fibres).
3. Actinomycetes (sessile cells with radiating filaments).

Bacteria can also be classified according to the feeding function, i.e. :

- autotrophic : assimilation of carbonic acid by photosynthesis or, more commonly, by chemosynthesis of compounds present in the sediment or the water ;
- heterotrophic where the assimilation is done out of living or dead organic matter; as such they are essential in the C- and N-cyclus between lower and higher organisms.

The above mentioned classification suggests consequently that bacteria are essentially food- and environment specific. In fact, the bacterial flora of sediments show a wide range of adaptative variability relative to :

- the sediment texture related to the penetration of water, gases or even other organisms ;
- the type and quantity of organic matter (governing the biodegradability or the specific food) ;
- the bio-available oxygen content;
- the temperature;
- other organisms and their seasonal cycli (including respiration cycli) ;
- particular contaminants adsorbed to the mineral or organic mud particles and/or with a toxicity vs. bacteria.

Bacteria are also classified according to their respiratory mode (aerobic and anaerobic bacteria). In fact, the classification of bacteria according to the respiratory mode is the best adapted to describe the bacterial ecosystem in aquatic and fine-grained sedimentary environments. The reason for this is related to the relative low vertical diffusion of atmospheric oxygen through the water column and the sediment deposit ; all ecosystem equilibria are governed by this oxygen input which may be strongly affected by a lot of external reasons, such as water circulation, agitation, water depths, turbidity, dwelling organisms, ...

Metabolism processes of bacteria

The above mentioned adaptative bacterial variability and heterogeneity related to the cited factors is a function of the availibility through the water of essential chemical components for bacterial growth , such as oxygen , nitrates , phosphates, sulphates, etc. ... The biodegradation products of bacterial activity (H_2S, ammonium, N_2, CO_2, H_2O) are diffused back to the water column and the atmosphere.

The carbonic acid assimilation, which forms the basis of bacterial metabolism (by photosynthesis or chemosynthesis) is done by resorption through the cell-membrane (diffusion, osmose). To activate the assimilation, bacteria are secreting selective and species - specific exoenzymes (biocatalysators) able to decompose and mineralize a wide range of organic compounds.

Not only humic acids but also more complex organic chains such as phenols, PAH's , mineral oils, ... can theoretically be decayed by bacterial metabolism processes.(fig. 3).

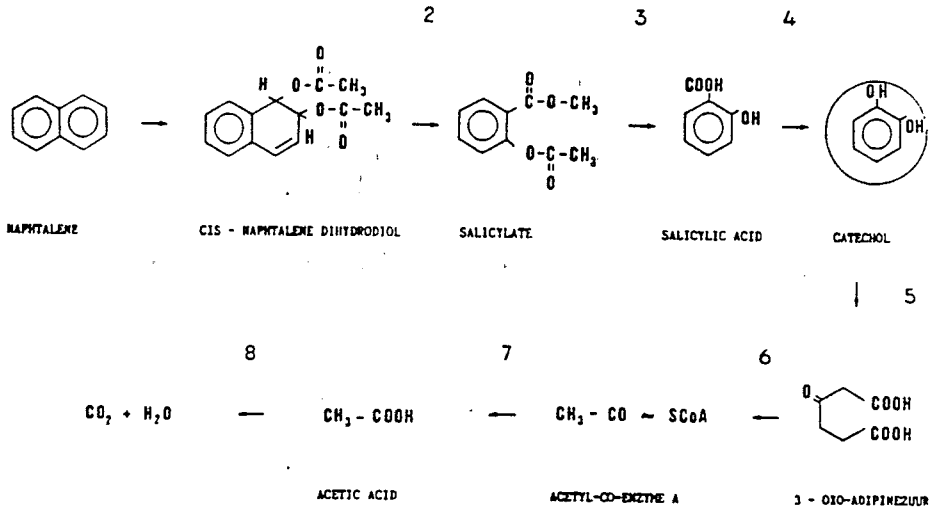

Figure 3 : Biodegradation process of naphtalene, a common PAH contaminant in sediments

But not all organic matter is even bio-degradable and most of the mud deposits have a lack of energy and nutrients to assure continuous bacterial activity and/or growth. The important ecosystem cycli (e.g. diatom cycli) are of primary importance in bacterial activity. The illustration of typical marine ecosystem cycli is illustrated on figure 4. The spring and late-summer bloom of diatoms abundancy is clearly visible on this diagram.

These time cycli are important because the supply of nutrients and organic matter to the sediment bed, the temperature and the available oxygen (from respiration or from diffusion) will know large fluctuations. The micro-organisms will have to adapt themselves to these fluctuations.

When living conditions are becoming worse, bacteria have interesting defense/preservation modes, such as (Pommepuy et al., 1989) :

- spore formation (formation of a thick-walled resistant spore) .
- dwarfcell formation (formation of a small cell with limited metabolism) .
- somnicell stage (the bacteria are putting themselves in a kind of lethargic state).

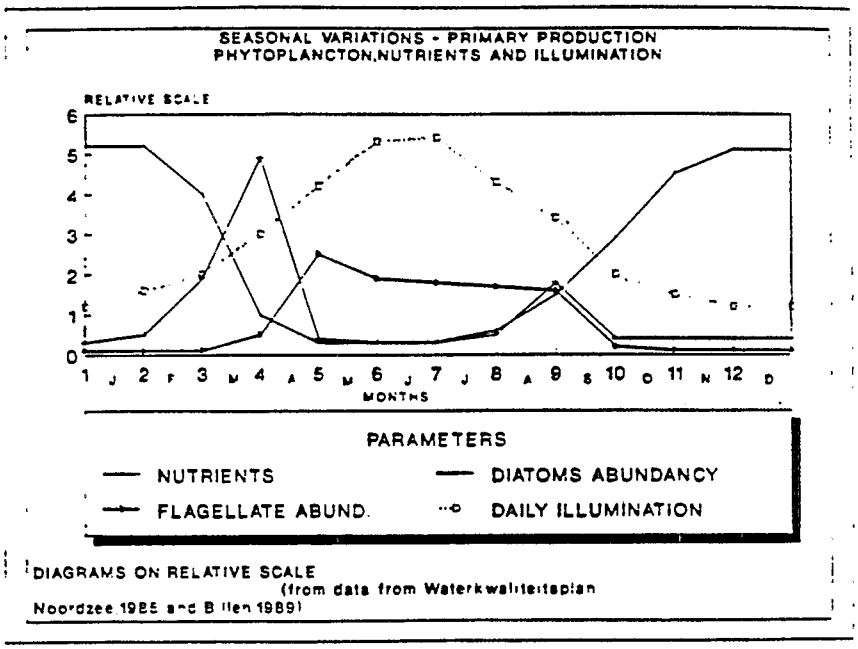

Figure 4 : Ecosystem cycli related to primary production in marine environment

When growing conditions are becoming better the bacteria are reactivated from these spores, dwarfcells or somnicells. The survival of the bacteria depends on their ability to store energy reserves (e.g. in the form of glycogens).

Bacteria are able to improve the environmental conditions which they need to develop their specific activities. They may adhere to sediment particles, to organisms or form long chains of bacteria. This adhesion is done with polysaccharic fibres such as glycocalix, which is secreted by the bacteria themselves. The glycocalix (Moureau and Richelle - Maurer, 1990) has specific characteristics :

- it maintains bacteria on the substrate regardless current action ;
- it traps nutrients ;
- it retains the digestive exoenzymes ;

- it forms a physico-chemical protection against toxins, virusses, antibiotica and predators ;
- it maintains appropriate physico-chemical conditions to allow bacterial growth and activity.

Anyway, the survival time of bacterial population in sediments can be very long and reach over several months to years (Rosack and Colwell, 1987).

As for all living organisms and as mentioned before, the bioavailable oxygen is of primary importance for bacterial metabolism life and growth. Therefore, by many researchers, bacteria are rather classified according to their respiratory mode :

- aerobic bacteria : bacteria which use free (dissolved) oxygen; degradation of organic compounds is fast and complete (high burning efficiency) ;
- anaerobic bacteria : bacteria which use chemically bound oxygen (no free oxygen available): biodegradation is slow and incomplete.

Aerobic and anaerobic bacteria in sediments

When mud is deposited in an aquatic environment the oxygen supply to the sediment deposit is limited because of several reasons :

- mud is often deposited in water with slow water circulation and consequently low dissolved oxygen contents (< 5 mg O_2/l) ;
- the distance between the mud and the atmosphere increases (due to the presence of the water column and the mud for increased water depths) ;
- the mud has low permeability due to clay minerals and fine grains and horizontal layering ; this decreases vertical oxygen diffusion ;
- the presence in mud of high proportions of Fe-hydroxydes increases the COD (chemical oxygen demand) ; in general the COD of mud deposits is high.

The main electron terminal acceptors used during the decomposition of organic matter are in decreasing order of efficiency (Claypool and Kaplan, 1974) :

1. free oxygen;
2. nitrates;
3. sulphates;
4. (bi)carbonates.

This biochemical succession is accompanied by chemical reduction processes in the sediment and, consequently, by a decrease of the redox potential, Eh (redoxpotential as low as -350 mV).

This vertical layering in mud deposits has been schematised by Claypool and Kaplan (1974) and is also illustrated on figure 5.

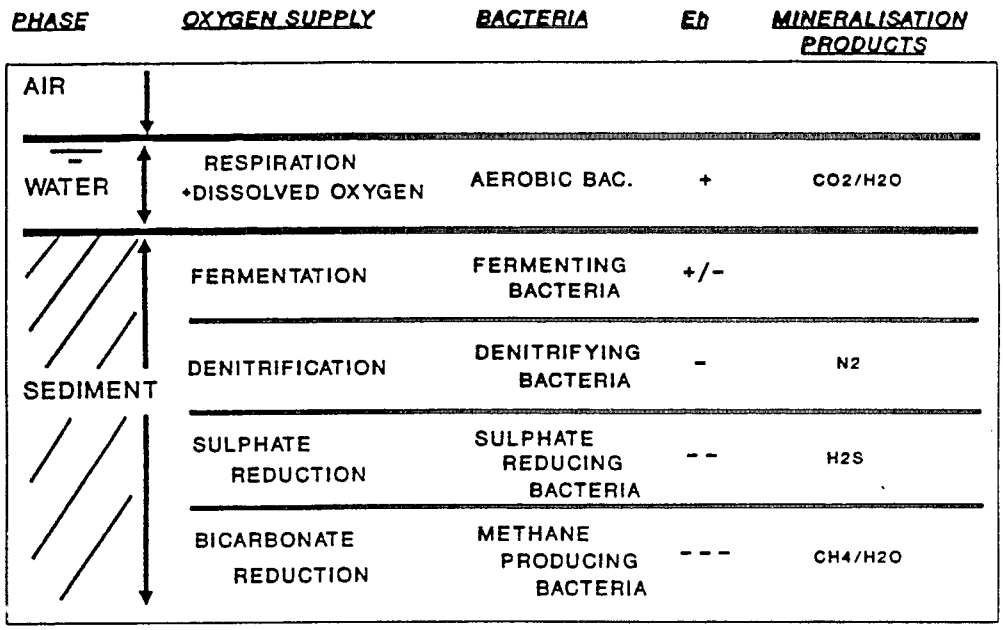

Figure 5 : Schematic presentation of bacterial layering in mud deposits

The natural vertical layering explains why most of bacterial activity in mud is essentially anaerobic resulting thus in a slow and uncomplete degradation of organic matter. The vertical bacterial layering will be analysed more in detail below (Pommepuy et al., 1989).

The aerobic surface layer

This very thin layer is colonized by an abundant microbial flora (10^9-10^{10} bacteria/ml). Numbers decrease with depth because of the reduction of available substrates (Atlas & Bartha, 1981). The bacterial population may represent from 0,2 to 2 % of the total organic matter (Meyer-Reil, 1984). The surface bacteria are mainly *Pseudomonas* and *Vibrio-gram* negative bacilli along with other bacterial-types such as *Nitrosomonas* and Nitrobacter, autotrophic bacteria which are responsible for nitrification (oxidation of ammonium salts to nitrites and then to nitrates (Martin, 1979).

Other organisms like Diatoms (*Navicula*, *Nitschia*, etc. ...) and blue algae (*Spirulina*, etc. ...) are also proliferating in this aerobic surface layer especially if light is penetrating as deep (Francis - Boeuf, 1949). Gen. *Thiorodo* bacterium may oxydize sulphur compounds and is part of the sulphur cyclus (similar to the N-cyclus).

In the presence of molecular oxygen, the surface flora use aerobic respiration to breakdown organic matter; this type of respiration is most energetically efficient. In this surface layer, aerobic bacterial production and decomposition of organic matter are greatest and total organic carbon mineralisation (H_2O/CO_2 state) may occur. There is intense floral competition for the utilization of released intermediate decomposition products, and bacteria with the highest intrinsic growth rates are favoured.

Fecal flora can settle at the same time as organic matter from anthropogenic discharges. The main species found are fecal Streptococci and Enterobacters *Escherichia coli, Klebsiella, Salmonella.* These latter bacteria are pathogenic and can be dangerous for humans when contaminated shellfish are ingested. Hernandez (1985) has recorded the presence of very high concentrations of fecal Streptococci in fine harbour sediments.

Anaerobic levels

In the lower layers, there is an observed reduction in the number of bacteria and a floral change , which may be partially explained by the appearance of gram-positive bacteria genus *Clostridium* ... (Bianchi et al., 1977; Bensoussan et al. 1981). Bacterial flora use either facultative or strict anaerobic respiration, or fermentative processes. At all levels Ferrobacteria are occuring reducing the ferricompounds to ferro-compounds and delivering the typical black color to reduced mud.

Fermentative bacteria

The genus *Clostridium* (spore-forming) may account for a major part of the strict anaerobic fermentative bacterial population (Atlas & Bartha, 1981). These bacteria play a major role in mineralisation of organic matter (cellulose, ...) since they are capable of utilizing organic material which other bacteria have difficulties breaking down, and also they synthesize exoenzymes which can hydrolyze many macromolecules into small molecules that can be self-assimilated, or assimilated by other micro-organisms (Marty et al., 1989). Spore *Clostridia* which are pathogenic for man (*Clostridium perfringens* and possibly *Clostridium tetani, Clostridium botulinum*), are also found amongst these flora.

Denitrifying bacteria

Denitrifying bacterial numbers vary from 10^4 to 10^9 per gram of dry sediment (Jones, 1979). The *Pseudomonas* and *Aeromonas* strains are those most frequently isolated, as well as some vibrobacteria. In fact it seems that we know very little about the bacterial species involved (Heitzer & Ottow, 1976). For denitrification processes, the

sediment must be anoxic, and there must also be nitrates in the underlying waters and sufficient nitrate diffusion within the sediment. Two processes are involved in denitrification : the first process includes catabolic reduction to transform nitrate ($N0_3$) into nitrite and into nitrous oxide (N_20) and molecular nitrogen (N_2). More recently a second process has been discovered, which involves formation of an ammoniumion (NH_4^+) from nitrite by catabolic fermentation. Current studies have not yet established whether or not this is a major phenomena. These two processes seem to operate simultaneously but their importance varies according to the concentration of organic matter. The percentage of nitrate transformed into ammonium was found to vary from 20 to 72 % in previously studied sediments (Koike & Hattori, 1978).

Nitrobacteria and Ferrobacteria have wide varieties of species able to reduce anorganic compounds.

Denitrification, which develops oxydation-reduction potentials that are higher than those accomplished by sulphate reduction, takes place within the sediment above the sulphate-reduction zone.

Sulphate reducing bacteria

In seawater, oxygen associated with sulphur, in the form of sulphate, is 200-fold more abundant than molecular oxygen. Moreover, sulphate can be found deep within the sediment (a few meters). In anoxic marine deposits, sulphate reduction is an important phase in the mineralisation of organic matter (Marty et al., 1989). The abundance of these sulphate reducing bacteria (classified in 7 genera *Desulfobacter, Desulfobacterium, Desulfobulbus, Desulfococcus, Desulfomonas, Desulfonema* and *Desulfosarcina*) is linked with sulphate availability and amounts of organic matter (closeness to pollutant discharges). Their densities are estimated to be 10^3-10^6 bacteria/ml. These bacteria are involved in the final phases of organic matter mineralization within anoxic sediments and could be responsible for 50 % of the oxidation of organic carbon (Jorgensen, 1983), compared to 2-3 % for denitrification (Fenche & Blackburn, 1979; Jorgensen, 1983).

The high activity of sulphate reducing bacteria in muds is also the cause of the typical H_2S smell problems associated to waters with such sediment deposits.

Methane producing bacteria

At very low redoxpotential values the bicarbonate molecule is reduced by specific bacteria to methane. Bicarbonate is available from coprecipitation from aquatic plancton and necton deposits or from early diagenesis processes.

Methane is produced e.g. in marsh areas and in the early petroleum-genesis processes in mudstone.

Some interesting properties of bacteria

The above mentioned considerations show that bacteria, in good environmental conditions of oxygen, nutrients, temperature, etc... can execute interesting actions to serve man : mineralisation of organic mud or the clay-humic flocks (= microbiologic dredging) and mineralisation of organic micro-pollutants (= decontamination treatment in-situ).

It is important to notice some other particularities of bacteria :

- at different development stages some bacteria may have plasma-filaments which act as flagellae to execute displacements ; however, most of bacteria are sessile organisms ;
- in good environmental conditions bacteria multiply by cell (mitosis) ; each 20-40 minutes bacteria may divide (1 organism can deliver ca. 2^{48} successors in 24 hours) ;
- the small dimensions of bacteria facilitate the dispersion ;
- in contact with toxic substances bacteria secrete organic acids or produce metabolic products, causing a bio-leaching.

Bio-leaching of metals is a well-known phenomenon used in mining (Cu, Co, Au ore extraction), in mineral valorisation or in corrosion protection. All metals in the aquatic environment are susceptible to microfouling by bacteria, protozoa and algae. Regarding corrosion, bacteria are thought to be responsible for ca. 50 % of the failures of buried pipelines and cables.

CONTEXT OF MODERN AQUATIC ENVIRONMENTS VS. THE ABR-CIS TREATMENT METHOD

It is now obvious that the early 60's idiom "The solution to pollution is dilution" is a bad and non-appropriate management rule regarding the protection of aquatic environments. The large supply of nutrients to surface water systems combined with the input of organic-rich and contaminated effluents has caused the well-known problems of eutrophication contamination of water (direct) and contamination of sediments (indirect).

The problem is complex because phenomena like eutrophication and desequilibria in oxygen-balance is also linked to the decrease of light penetration due to turbidity increase. Turbidity increase may itself be caused by unappropriate agricultural sand-

use (increased run-off of fine sediments), over-saturation by organic compound effluents (floating at the surface of the water) and/or other man-related activities (dumping, dredging, ...) .

Eutrophication is a situation where the aquatic system has an over-abundanccy of nutrients such as phosphates and nitrates, and where the natural biodegradation process by micro-organisms has become over-saturated. The direct effect of eutrophication is oxygen depletion and important deficits in oxygen supply. This oxygen deficit is most important in the deeper parts of the water column and in the sediment deposits. Indirect effects are e.g. specific and intense algae blooms, reduction of diversity and abundancy of aquatic organism species, bad smell and other unattractive phenomena affecting the aquatic system.

Phosphates can be treated in-situ by Ca-rich compounds or $FeCl_3$ (precipitation). Such treatment precipitates the phosphates to poor-soluble salts. Nitrates are difficult to combine into insoluble compounds. The problem with nitrates and phosphates is also the diffuse input into surface waters (from many small effluents or from run-off).

The only efficient treatment method of organic and anorganic contamination of aquatic systems is the tackling at the source, i.e. the strong reduction or prohibition of effluents.

Muddy sediments tend to accumulate and concentrate all kinds of organic and anorganic contaminants from the water column through different mechanisms :
- adsorption of contaminants to humic-clay complex or Fe-compounds
- ion-exchange to clay particles (heavy metals) ;
- co-precipitation ;
- accumulation through plancton deposition.

Consequently, highly industrialised countries face serious problems of environmental protection of the aquatic system due to the contamination of water and sediments. Regarding the sediments the problem becomes accute because :

1. canals, waterways and rivers have to be maintained at a given (artificial ?) design profile to ascertain safe navigation, to prevent floodings or even for sanitation reasons (smell, pollution, ...) ; the dredged quantities to be disposed (on land or in aquatic system) are quite important with respect to the available disposal capacity : there is a lack of disposal facilities resulting in drastic rise of disposal prices (upland disposal fee in 1990 up to 80 U.S. $/m^3) ;
2. industrial treatment of the sediments is generally considered as unfeasible due to (high) treatment costs, due to low treatment production rates and to too specific treatment methods with low efficiencies.

These facts have lead to the development of in-situ microbiological treatment methods where the natural indigeneous bacterial flora is used and stimulated to obtain the following :

a) mineralisation of organic matter resulting in microbiological dredging ;
b) mineralisation of organic contaminants by treatment in-situ ;
c) re-establishment of normal oxygen balances in the whole aquatic system.

This experimental research has led to the development of ABR-CIS.

Optimum conditions to re-activate normal bacterial degradation processes

The transformation of organic products into basic minerals such as CO_2 and H_2O is efficiently done by aerobic bacterial degradation. From the previous chapters it appears how the normal biodegradation processes may be inhibited, i.e. essentially by oxygen deficits.

To re-activate the desired aerobic biodegradation one should work to get optimum conditions in the sediment deposit i.e. :

- oxygen supply in very dispersed and very bio-available way, to allow fast metabolism and population growth,
- temperature : bacteria are active above ca. 8°C ; the higher the temperature (up to 30-40° C) the greater the bacterial activity ;
- season : the season is important in relation to temperature and ecosystem cycli ;
- toxicity : no toxic elements to bacteria should be present in the environment ;
- organic matter : type and quantity of organic matter is important for optimal aerobic biodegradation ;
- specificity and mutant population : for particular contaminants it is important to assure complete biodegradation without formation of toxic intermediate products.

Augmented Bio Reclamation (ABR) - Conditioning In-Situ (CIS)

The ABR-CIS-system (Augmented Bio Reclamation - Conditioning In-Situ) is a joint effort of the companies Ebiox A.G. (Sursee, Switzerland), EMR b.v.b.a. (Ghent, Belgium) and HAECON N.V. (Ghent, Belgium).
ABR micro-organisms are extracted and isolated from the sediment. Thereafter they are cultured on carbon substrates, similar to the target contaminants to be treated. The ABR micro-organisms are then grafted on wood chips for transport. ABR is a development and a trade mark of the company Sybron.

ABR micro-organisms are aerobic and the strains are selected in order to achieve an as complete mineralisation of the contaminants as possible.

Conditioning In-Situ, CIS is a technique in which carefully selected and blended natural mineral products are injected into the sediment deposits. The CIS products are rich in free and bio-available oxygen (porous structure) and supply the ecosystem with the required oligo-elements and nutrients. CIS is stimulating and re-activating all

indigeneous natural aerobic bacterial activity causing an increased biodegradation of the undesired sedimentation products in the aquatic system. CIS products are guaranteed to be harmless to components of the aquatic trophic chain, including man.

ABR-CIS is designed to be a microbiological in-situ treatment technique of organic muddy sediments contaminated with particular organic biodegradable micro-pollutants :

- BTX and derivates ;
- mineral oil and compounds
- PAH's ;
- phenols, formaldehydes ;
- pulp, cellulose, starch, proteins, fats ;
- ...

Process of ABR-CIS treatment

Each project is first analysed on the microbiological treatment of the mud sediments and the organic contaminants. Therefore samples of the sediments are cultured in the laboratory and microbiological proliferation is monitored with respirometer-testing (oxygen uptake) and total resp. selective plate counts. When the treatability of the mud is confirmed the ABR-CIS treatment is designed (dosage, type of bacteria, injection scheme, ...).

The treatment process is executed as follows :

1. culture of ABR micro-organisms ;
2. blending of CIS-conditioner ;
3. mixing, drumming and transport of ABR-CIS powders ;
4. dilution and aeration of ABR-CIS powder with water of the waterway ;
5. injection of ABR-CIS suspension in the sediment by using adapted dredging equipment or high pressure jetting ;
6. monitoring of the sediment-level and sediment-quality.

Up till June 1992, 7 ABR-CIS full-scale projects have yet been executed on industrial scale. Volumes ranging between 100 m^3 and 5.000 m^3 have been treated in-site and monitored during 12 to 20 months after injection.

Reasons for applying in-situ treatment are related to :

a) volume-reduction of the sediment (and avoiding upland disposal) ;
b) decontamination of mineral oils and/or PAH's.

RESULTS OF MICROBIOLOGICAL TREATMENT OF SEDIMENTS

To evaluate the efficiency of ABR-CIS treatments this last chapter will focus on some projects already executed and the treatment results obtained.

Re-establishment of oxygen balance

The best way to measure the physico-chemical and biochemical status of a sediment deposit regarding oxygen balances in the determination of the redox potential, Eh. It has been stated previously that anaerobic conditions are associated to reducing conditions, i.e. with negative Eh.

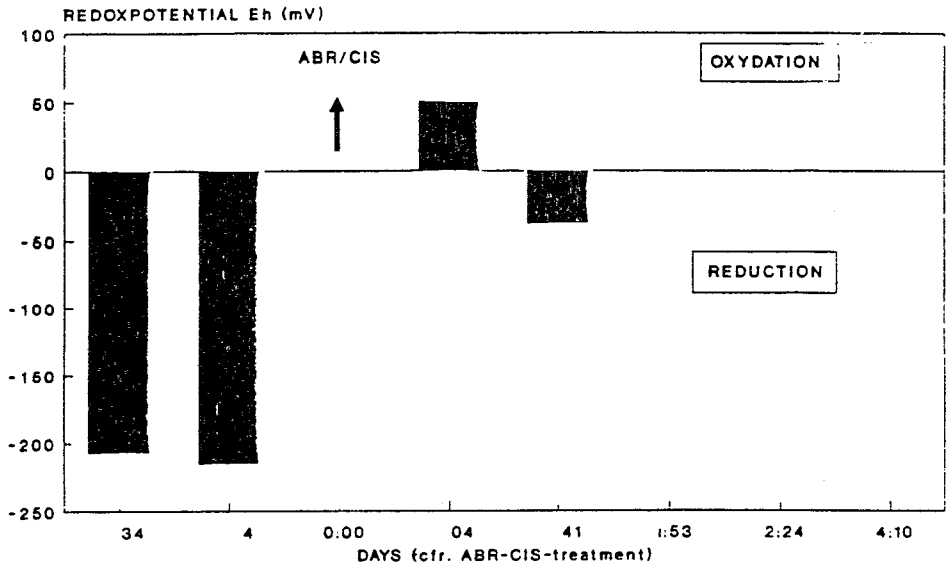

Figure 6 : Evolution of redox potential in mud deposits after ABR-CIS treatment (project Zonh.)

Shortly after ABR-CIS treatment the black reduced mud deposit is changing to mud with neutral or even positive Eh-values. This is illustrated on figure 6 where Eh values measured on the field show a quick evolution from ca. -200 m V to positive / neutral values.

Improvement of microbiological activity

The oxygen input by CIS allows the ABR and indigeneous bacteria to proliferate. This is measured by taking samples at regular time intervals and by measuring the total plate count.

This is illustrated on figure 7 where the strong increase in total plate count after treatment can be seen.

Volume reduction of sediment deposit by mineralisation

The biodegradation of organic matter in the mud deposit causes a volume reduction of the sediment deposit (mineralisation of organic matter and/or disruption of the mud flock-structure). This can be seen on comparative sounding-diagrams. This is illustrated by cross-sectional soundings of waterways in which the sediment deposit was treated with ABR-CIS. Figure 8 shows the volume reduction of the sediment deposit in a small freshwater river where ABR-CIS was applied (project Krimpenerwaard, The Netherlands, project ordered and executed in collaboration with Consulmij B.V.).

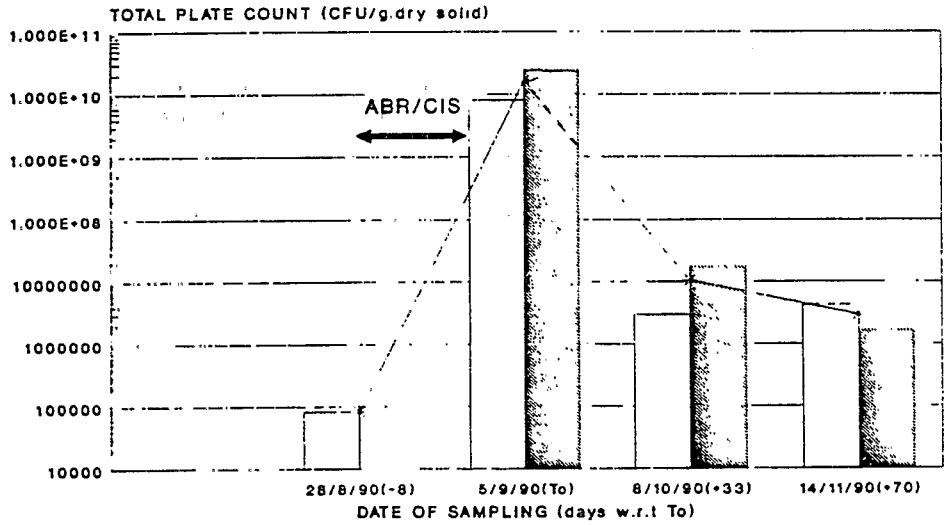

Figure 7 : Increase of total plate count (TPC) after ABR-CIS treatment

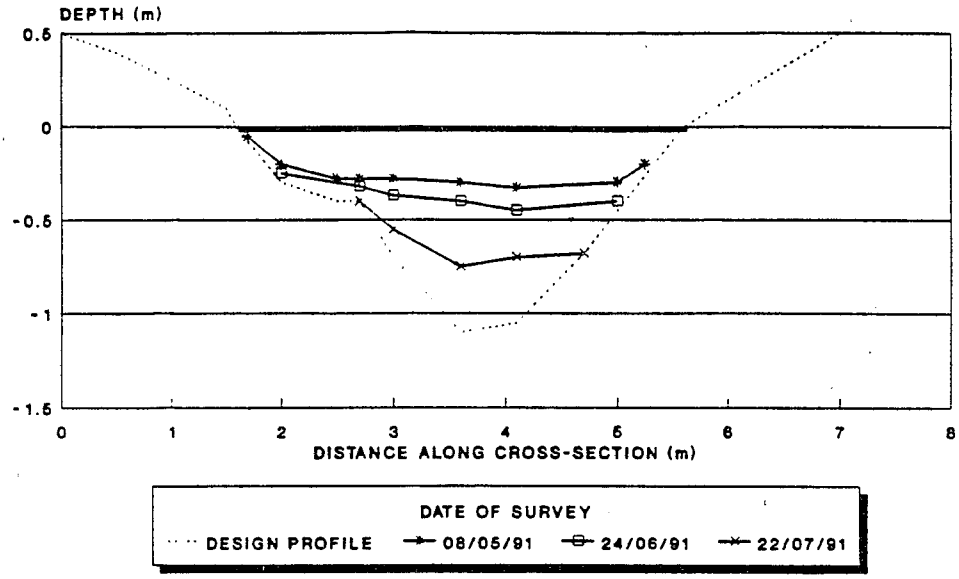

Figure 8 : Volume reduction of sediment deposit after ABR-CIS treatment (project Krimpenerwaard, the Netherlands)

A global volume reduction of ca. 50-60% of the original volume has been realized by this microbiological dredging. Figure 9 shows a simular cross-secitonal view with sounding results at different time intervals showing the progressive volume reduction of the sediment deposit in a brackish/fresh water canal (Bakhuistervaart, the Netherlands, project ordered by J. Klip B.V.).

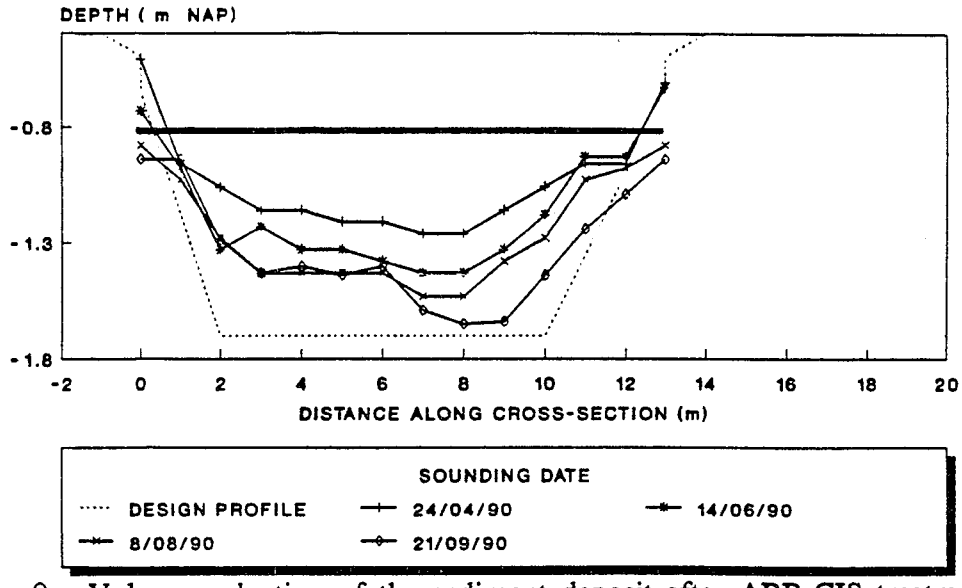

Figure 9 : Volume reduction of the sediment deposit after ABR-CIS treatment over the whole deposit thickness (Bakhuistervaart, the Netherlands)

On figure 10 the reference cross-sectional profile of the Bakhuistervaart is shown to analyse the natural volume-evolution of the sediment deposit when this is not treated.

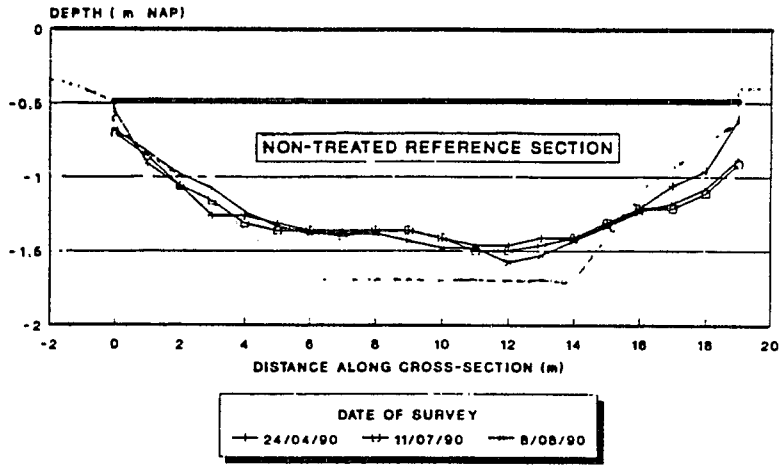

Figure 10 : Result of sounding survey of the canal in a non-treated section (reference section).

A global volume reduction of ca. 50% has been realised in ca. 18 months.

Biodegradation of organic compounds

For the Bakhuistervaart project 3.100 m³ of sediments were heavily contaminated with mineral oil (2000-3000 ppm). After ABR-CIS treatment (18 months after injection) the mineral oil content had significantly decreased down to acceptable legal levels (fig. 11).

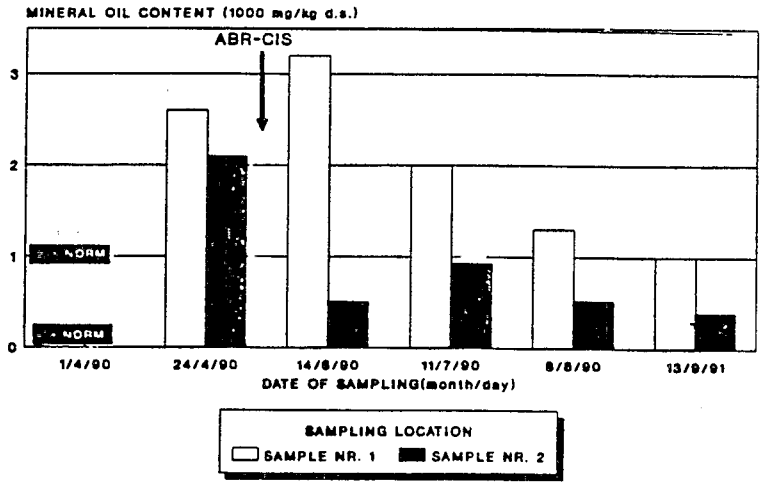

Figure 11 : Illustration of biodegradation of mineral oils as a result of ABR-CIS treatment of the Bakhuistervaart

A similar in-situ biodegradation of mineral oil has been obtained in the Park River (project Edegem ; figure 12) and the Westeindse Waterweg (project Zoeterwoude, ordered by and executed with Consulmij B.V. ; figure 13).

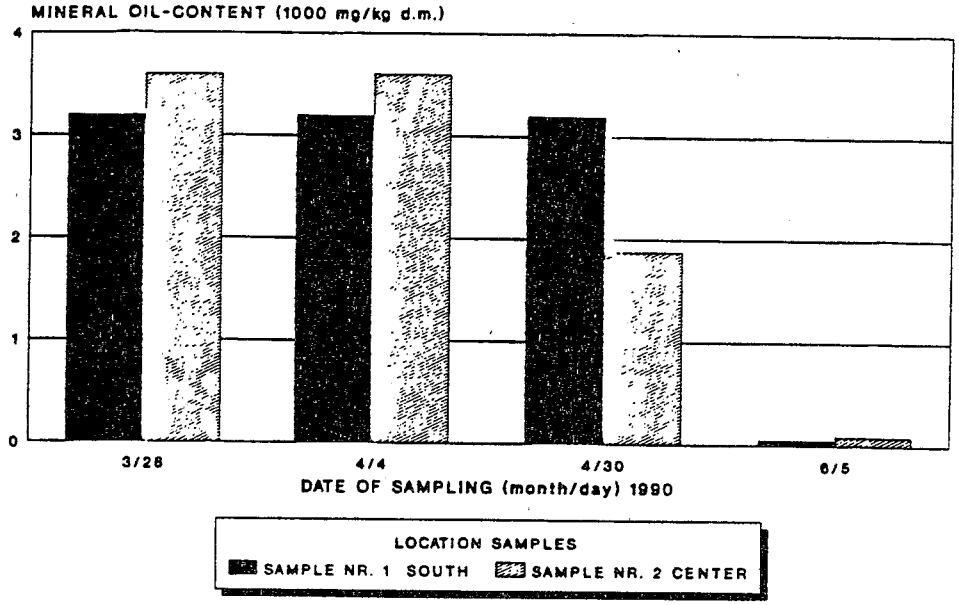

Figure 12 : Biodegradation of mineral oil in Edegem Park River (Belgium)

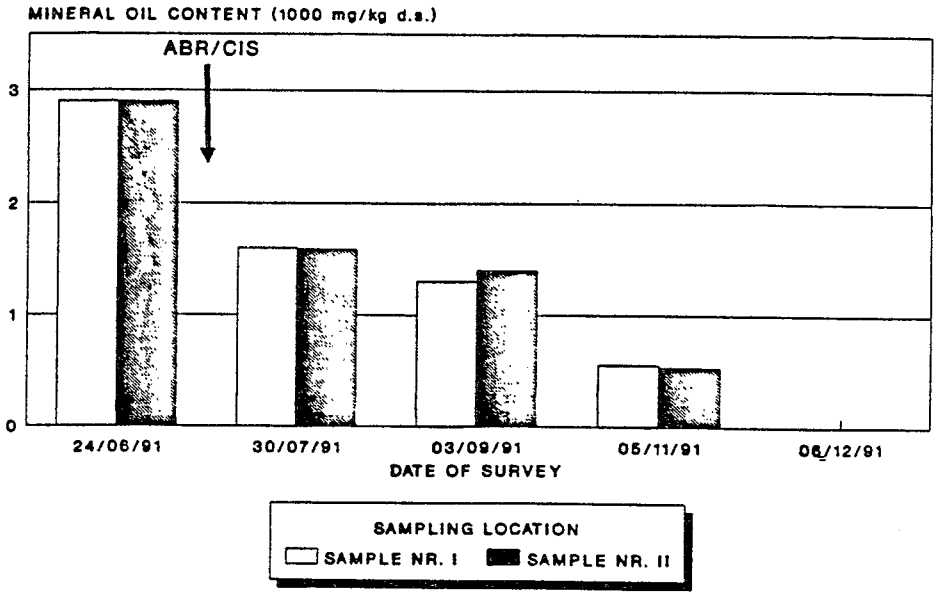

Figure 13 : Biodegradation of mineral oil in Westeindse Waterweg (Zoeterwoude, the Netherlands).

In the Zoeterwoude project a significant contamination with PAH's occured as well (major PAH's : Fluoranthene, Pyrene).

On figure 14 the global evolution of the contaminant-content is shown illustrating the progressive biodegradation of the considered contaminants although less spectacular than with e.g. mineral oil content. Some fluctuations occur in the detected PAH levels ; these are supposed to be caused by analytical uncertainties, sample representativity / reproducability and release due to microbiological action.

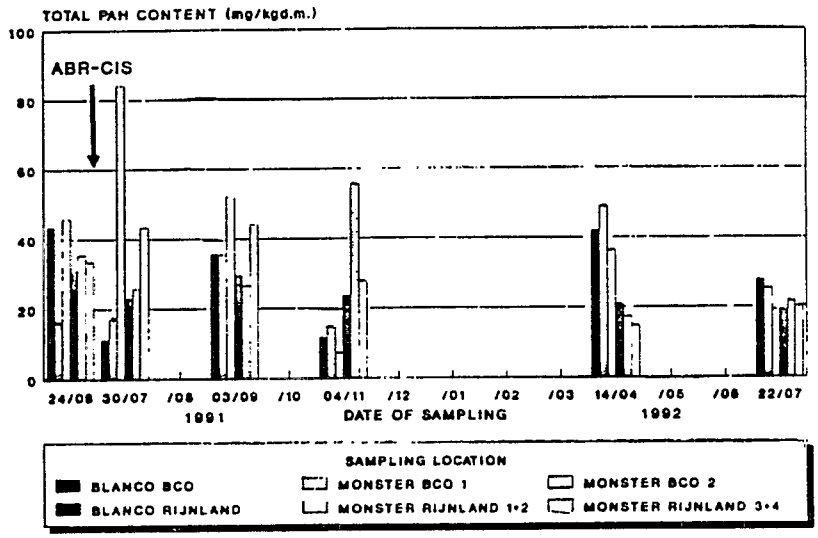

Figure 14 : Biodegradation of PAH's in the mud of the Westeindse Waterway (Zoeterwoude, the Netherlands).

Further additional scientific research is necessary however to analyse the exact biodegradation process and the variations in adsorption of contaminants to the clay-humic complex.

ABR-CIS process costs

The project preparation product and injection costs for a typical ABR-CIS project range between 20 and 30 U.S.$ par m³ of sediment in-situ to be treated. When a 50% volume reduction is achieved by microbiological ABR-CIS dredging, the cost of the dredging of 1 m³ will consequently range between 40 and 60 U.S.$.

These costs must be compared with the classical dredging and disposal costs (for contaminated sediments) :

-	dredging	:	ca. 15 U.S.$/m³
-	dewatering	:	ca. 60 U.S.$/m³
-	disposal	:	ca. 80 U.S.$/m³
			---
	total	:	ca. 155 U.S.$/m³

This has been confirmed by different cost/benefit calculations executed by the managers of the waterways treated with ABR-CIS.

In the Bakhuistervaart project the municipality has officially declared that the application of ABR-CIS system represented a saving of ca. 70% with respect to the classical approach of dredging and disposal.

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In Situ Bioventing of a Diesel Fuel Spill

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A diesel fuel spill occurred at a state rail yard late in 1989. The leak occurred from a corroded buried pipe leading from an above ground tank. Fuel accumulated at the surface of a shallow (2.5 m) unconfined aquifer comprising sand and silty sands of the Guildford formation. An area near the storage tank of 2000 m^2 and over a depth of 1.5 to 2.5 m was contaminated with fuel. A total of 135,000 L of fuel was recovered using oil skimmers in groundwater drawdown wells. An estimated 50,000 L (approximately 1.5% w/w in soil) remained *in situ*, smeared in the areas of drawdown wells to a depth of 3.5 m.

The potential for active and passive *in situ* bioremediation was explored through laboratory assessment of oil mobility and biodegradation rates and field assessment of contaminant distribution and groundwater flow. Oxygen supply was identified as the factor most limiting biodegradation of the hydrocarbons, while the rate of degradation was further increased by supply of the nutrients nitrogen and phosphorus. Although the groundwater flow velocity achievable under drawdown conditions was rapid (2×10^{-3} cm/sec) it would require many years to supply sufficient oxygen *in situ* to effect bioremediation. In contrast, supply of oxygen (as air) to unsaturated aquifer material was predicted to achieve bioremediation in approximately 18 months.

A plan for remediation was designed in which the contaminated area was dewatered, oxygen was supplied via air extraction from cased bores slotted throughout the contaminated zone and nutrients were supplied via a micro-irrigation system. A pilot scale remediation on one quarter of the site is currently underway to confirm rates of degradation achievable in the field. Progress to date has indicated hydrocarbon reductions of 2000 to 4000 mg/kg (10 to 30%) in the unsaturated soil to a depth of 3 m over a six month period of venting only. Dewatering in the 3 to 3.5 m zone, however, was incomplete and subject to fluctuating water levels. A further reduction averaging 30% took place over the subsequent six months of venting and nutrient addition and extended to the 3.5 m depth. Further investigations to be carried out during the pilot period include 1) an evaluation of the efficiency of oxygen supply via vacuum or air injection, 2) the fate of nutrients in unsaturated and saturated zones, 3) extent of remediation in the unsaturated and saturated portion of the contaminated area.

Keywords: *in situ* bioremediation, bioventing, hydrocarbon contamination

INTRODUCTION

A major diesel spill from a fuel line at the State Railway (Westrail) Marshalling Yard occurred in 1989. The spill resulted in migration of fuel through a storm water drain to the Perth Airport Southern Main Drain, necessitating immediate cleanup action along a 3 km length of the drain. Further investigations on the Westrail site itself revealed an area near the storage tank of approximately 2000 m^2 and over a depth of 1.5 to 2.5 m was contaminated with fuel (Figure 1). Fuel recovery operations were immediately put into effect and options were explored for complete remediation of the site.

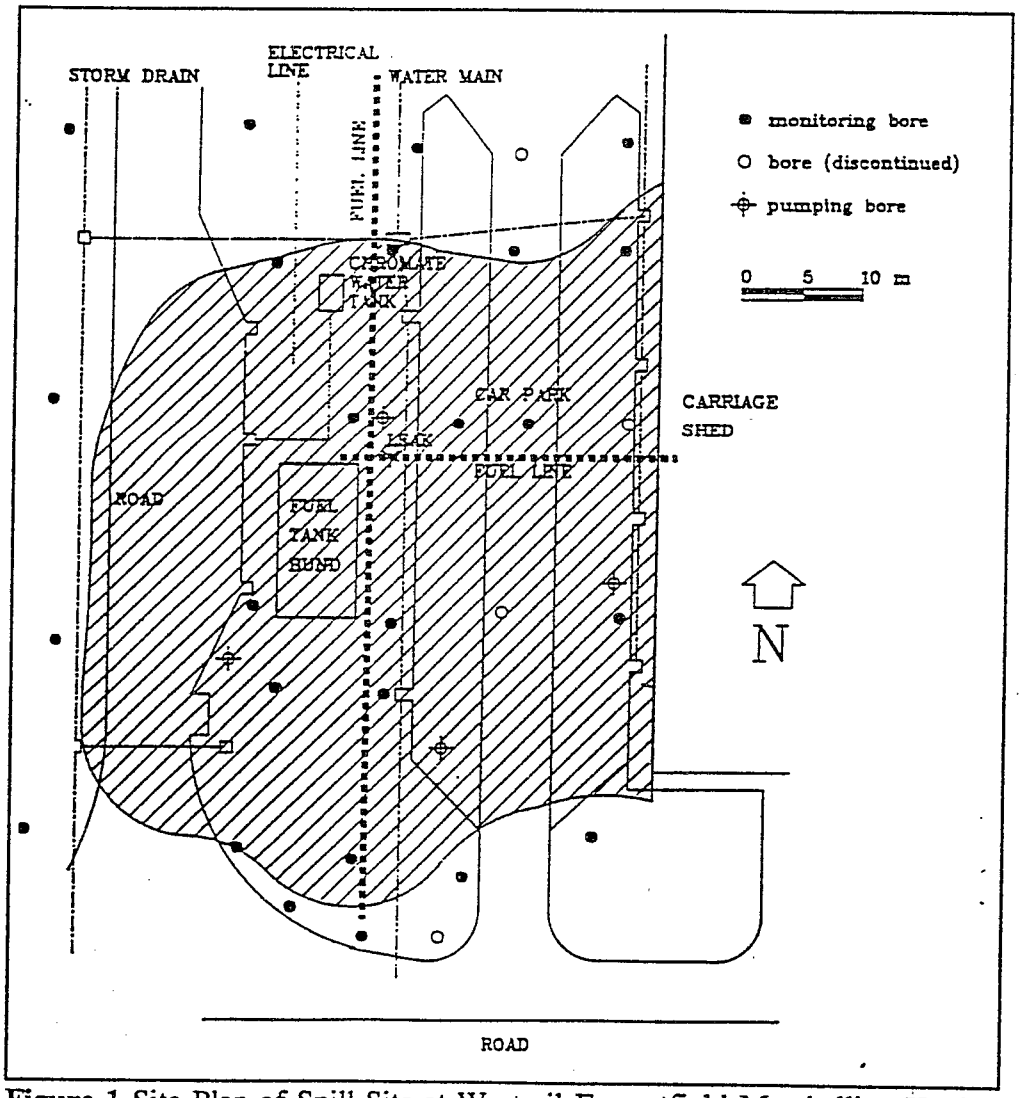

Figure 1 Site Plan of Spill Site at Westrail Forrestfield Marshalling Yard

Due to the number of buried services and above ground tanks in the spill area, the proximity of a carriage shed in full use and the low slope stability of site soil, excavation was considered undesirable for remediation of the site. The potential for active and passive *in situ* bioremediation was explored through 1) site investigations of diesel concentrations, soil and aquifer characteristics, 2) laboratory assessment of oil mobility and biodegradation rates and 3) pilot scale evaluation of *in situ* bioventing. Having collected information in laboratory and field trials, it was desired to determine if commercially available bioremediation models would be useful in designing full scale remediation.

SITE DESCRIPTION

SPILL DELINEATION

An initial survey to determine the extent of contamination was performed by the Geological Survey staff of the Western Australian Department of Mines. A total of 29 holes were augered to a depth of 4 to 5 meters. Soil was recovered for analysis from above the water table at 1.8 to 2.5 m. Soil samples could not be recovered from the saturated zone as the sand could not be held in the core barrel. The soil samples consisted of 2.25 m coarse to medium sand fill over Guildford Formation sediments of silty sand. Clayey sand lenses were intersected in 5 boreholes at a depth of 4 to 4.5 m. Each borehole was lined with slotted PVC pipe for future use in water sampling.

A total of 280 soil samples were analysed by Westrail staff and indicated a well defined contaminated area extending in a radius of 20 to 25 m from the source of the spill (approximately 2000 m^2) from a depth of 1.5 to 2.25 m (average thickness 0.75 m). Oil concentrations ranged from 0.01 to 10% w/w.

Free product recovery was implemented on the site through trenching and installation of soak wells, and finally through installation of four drawdown wells supplied with skimmer pumps.

Following recovery of approximately 135,000 L of free product, removal efficiency was reduced to approximately 1 L/day. At this point a second set of soil cores were collected to determine the content of fuel remaining in the soil and to collect samples for laboratory treatability testing.

AQUIFER CHARACTERISATION

The initial site survey performed by the State Geological Survey in March 1990 described an unconfined aquifer of coarse to medium sand with clayey lenses at 4 to 4.5 m depth. The depth of the aquifer, based on regional information, was estimated at 20 m. The natural hydraulic gradient across the site was 0.003 m/m. Subsequent intact cores collected in August 1990 following recovery of free product identified bulk densities ranging from 1.5 to 1.8 g/cm^3, porosities of 0.28 to 0.44 and oil contamination of 1.5% w/w in the 2 to 2.5 m depth and 2.5% w/w in the 2.5 to 4 m depth.

Pumping tests were performed during installation of the drawdown wells. These wells were fully slotted over a 12 m depth. The depth averaged hydraulic conductivity which was measured using these wells was 3×10^{-4} to 2×10^{-3} cm/sec.

To evaluate the practicality of an injection/withdrawal method of bioremediation, a field tracer test was conducted during continued water drawdown pumping. The test was performed by injecting 1500 litres of a solution of 100 mg/kg Li as LiCl. The concentration of Li was subsequently monitored in all monitoring wells on the site over a 21 day period. Concentrations of Li in groundwater were used to estimate the rate and direction of groundwater movement under drawdown conditions. Under these conditions the average gradient from the point of injection to the drawdown well was 0.1 m/m. Discrete flow directions, however, were observed with differing flow velocities. Flow circumvented the contaminated zone with velocities of 1.5 to 4×10^{-3} cm/sec, in preference to the direction of the drawdown well in the contaminated zone which had a velocity of 2×10^{-4} cm/sec.

TREATABILITY TESTING

SHAKE FLASK TESTS

Preliminary screening experiments were conducted in shake flasks using treatments of either water or nutrient solution under aerobic and anoxic conditions. These trials demonstrated that aerobic conditions with added nutrients resulted in the greatest rate of microbial growth and concurrent hydrocarbon degradation. Very limited degradation occurred under anoxic conditions, even with nutrient supplementation. Results from trials with nutrient and oxygen supplementation and the control treatment (no oxygen or nutrients supplied) are illustrated in Figure 2. These trials confirmed that native soil organisms were capable of degrading the diesel, however oxygen and nutrients were limiting to degradation.

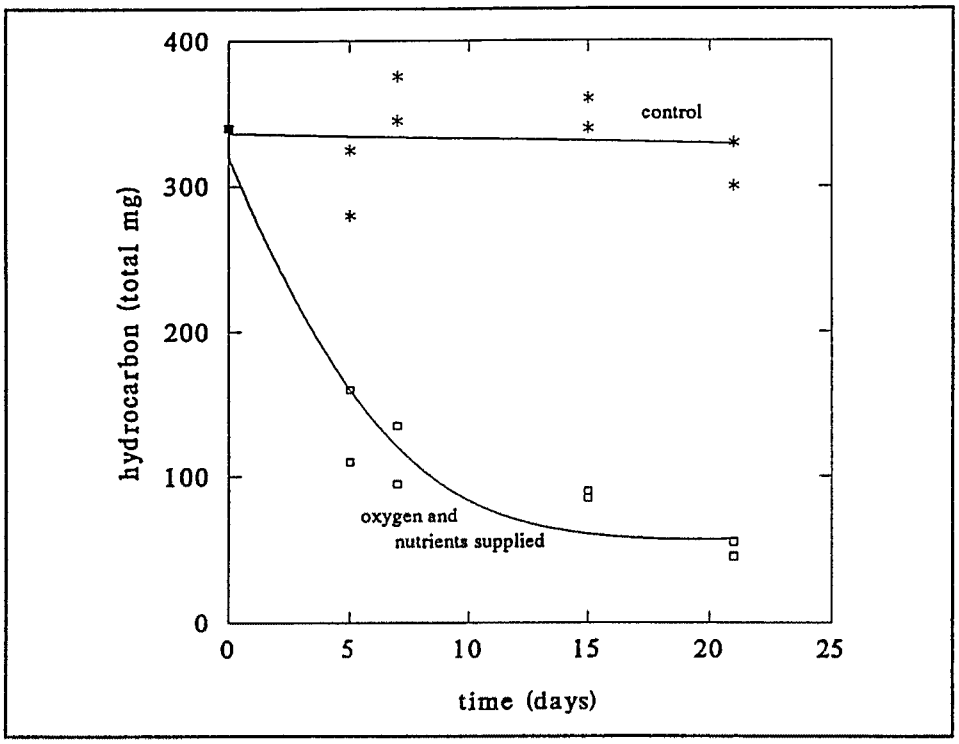

Figure 2 Results of Shake Flask Tests for Biodegradability of Diesel Product With and Without Supply of Oxygen and Nutrients

COLUMN TESTS

Oxygen supply, in particular, was a problem in subsequent trials using saturated soil columns supplied with a flow of well aerated water. Columns were set up to simulate a control (water flow only) and supply of oxygen and nutrients in water at a rate designed to simulate field conditions. Column flow rates and effluent nutrient concentrations were monitored on a daily basis. Flow was initially restricted but increased as oxygen and nutrient utilization increased. Over the length of the 60 cm column roughly 50% of the added N, 80% of the added P and almost all supplied oxygen was consumed. An encouraging increase in microorganism numbers was also noted. No degradation of hydrocarbon was detected, however, within the 8 week study. The initial diesel contamination of the soil was very high (15000 mg/kg) and the amount degraded according to stoichiometric calculations (60 mg/kg) was well within experimental uncertainty.

Trials were also conducted under unsaturated conditions in which a drip irrigation system supplied nutrients and kept the soil moist. Microorganism counts increased 1000 fold within a few weeks and 20% of the residual hydrocarbon was degraded after 4 weeks.

Calculations based on the stoichiometric amount of oxygen required to totally mineralise the residual hydrocarbon content in site soil supported the results of the column tests. Based on an assumed carbon content of 85% in the hydrocarbon, approximately 3.5 mg of O_2 would be required to mineralise 1 mg of hydrocarbon. On the basis of measured hydrocarbon concentrations of 1.5%, supply of oxygen at a solubility limit of 8 mg/L in water, would be insufficient to mineralize substantial hydrocarbon in site soil within a manageable time period. In contrast, supply of oxygen in the air phase, at a concentration of 20% by volume, would support degradation of the hydrocarbon in site soil within 1 to 2 years.

These studies confirmed the presence of indigenous petroleum degrading organisms. In view of its history as a fuel storage area this was not unexpected. Oxygen and nutrients are limiting degradation, however, under field conditions. Residual diesel concentration on the site was very high after recovery of free product. Consequently bioremediation requires a significant supply of oxygen to meet the demand for total oil removed. It is evident that groundwater flow through the site would make saturated phase supply of oxygen impractical. Remediation under unsaturated conditions with supply of oxygen through vented air was therefore viewed as the most practical approach.

PILOT TEST PERFORMANCE

OBJECTIVE

A six month pilot scale remediation was designed involving dewatering one quarter of the site and encouraging *in situ* bioremediation through bioventing. The primary objective of the pilot trial was to confirm the effectiveness of nutrient supply and bioventing to meet proposed remediation criteria for diesel of 1500 mg/kg. The extent of remediation was to be determined by periodic monitoring of soil for hydrocarbon contamination and monitoring of groundwater for hydrocarbon and nutrients. A second objective was to provide sufficient data on rates of oxygen uptake and hydrocarbon degradation for calibration of the VIP and BIOPLUME II models. These models would then be used to predict hydrocarbon loss for a full scale bioremediation design involving the saturated and unsaturated zones. The design would subsequently be tested in full scale remediation.

DEWATERING

The natural groundwater table resided at 2 to 2.5 m below grade, with seasonal variation within that range. This was depressed by the weight of diesel in the contaminated area and through generation of cones of depression to facilitate diesel recovery. As a consequence, residual contamination was smeared within the 1.5 to 3.5 m zone. Dewatering for bioventing of this zone was carried out to a designed depth of 3.5 m via electric submersible pumps installed in three shallow wells spaced around the

northeast corner of the site (Figure 3). These wells are also supplied with skimmer pumps for recovery of any additional oil which becomes mobilised and collects in the wells as a result of dewatering. The deep (12 m) recovery wells and skimmers have also continued in operation.

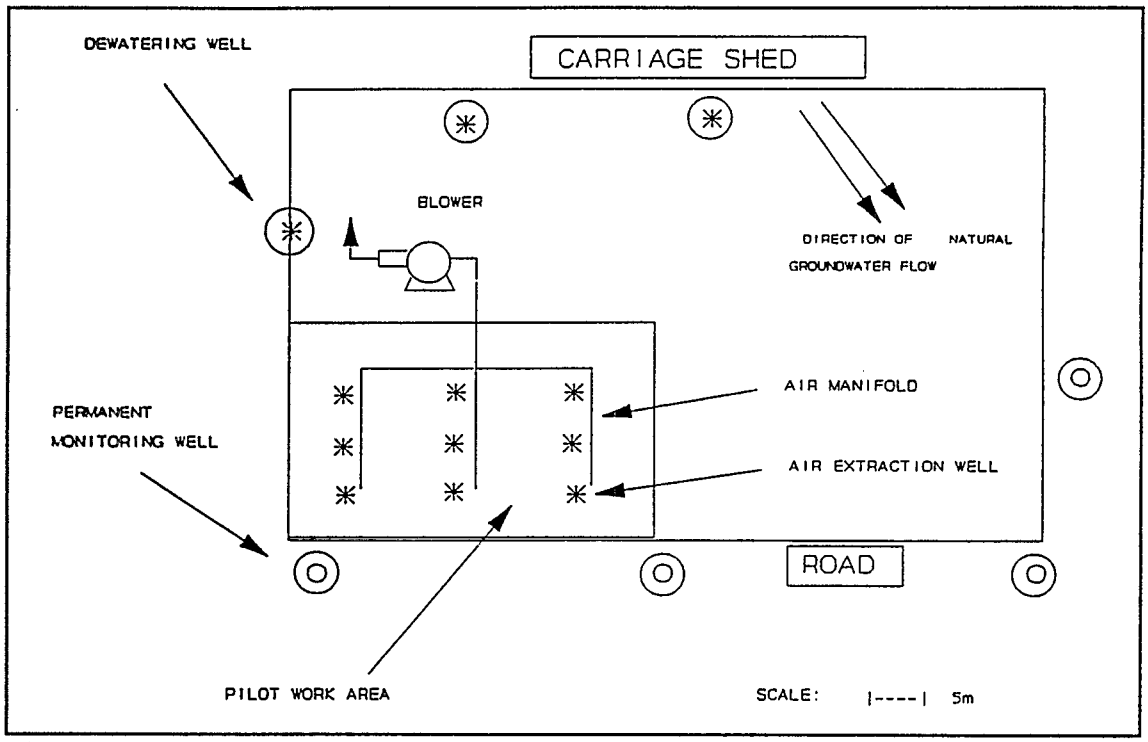

Figure 3 Schematic Diagram of Bioventing Pilot Trial - Plan View

Intermittent failure of one or more of the groundwater extraction pumps has resulted in a fluctuating water table between 3 and 3.5 m depth for the first four months of the pilot study. This problem was compounded by water entering the venting system and tripping out the air extraction exhauster.

AIR SUPPLY

Soil aeration has been performed via air extraction from 9 bores installed to 4 m with 50 mm PVC casing slotted between 2.5 and 4.5 m bgl (Figures 3 and 4). A coarse sand filter pack was installed around the slotted interval with a bentonite seal to the soil surface. The wells are joined to a valved and instrumented PVC header system connected, through a moisture "knock-out pot", to the suction side of a small blower. Exhaust is direct to atmosphere.

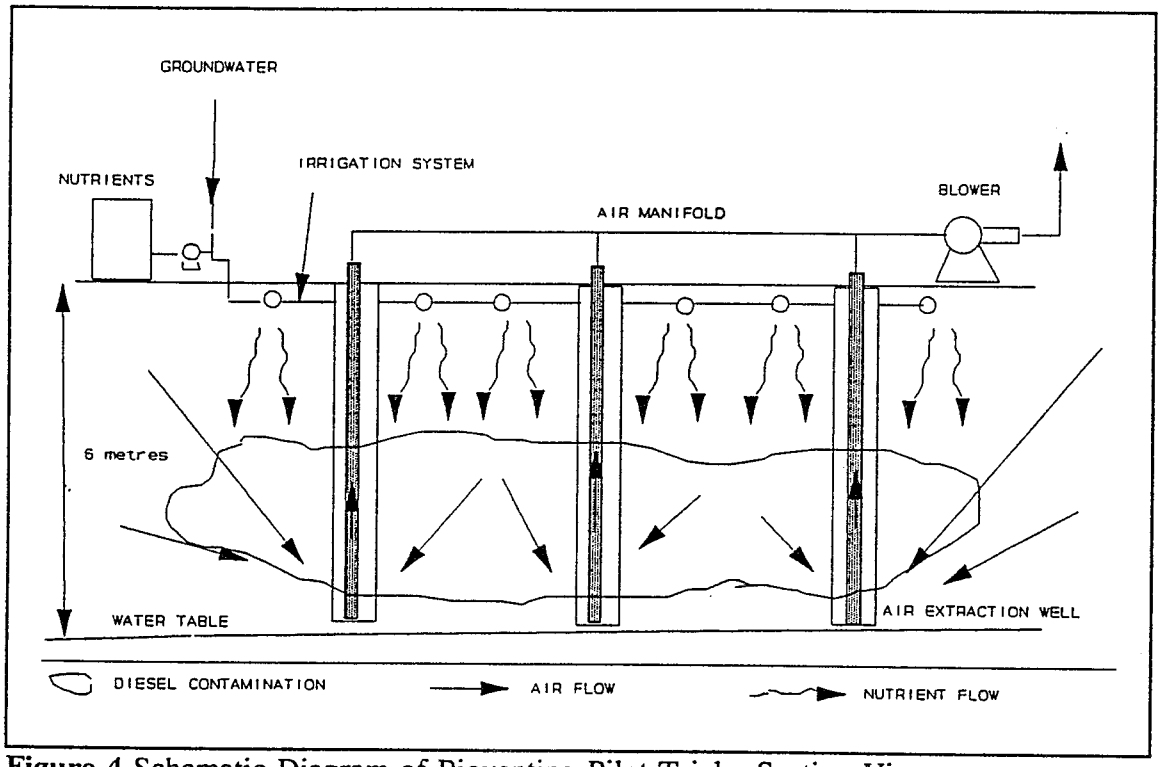

Figure 4 Schematic Diagram of Bioventing Pilot Trial - Section View

Influx of air is facilitated by the existing fully slotted monitoring and drawdown wells, as well as exposed soil surfaces. Trenches which were used for free product recovery have been back filled and provide zones of high permeability for air flow. A vacuum of less than 2 kPa has been measured at all air extraction wells during continuous operation. All wells are in an area of the site which is not sealed (i.e. no asphalt or concrete cover).

Dewatering problems have resulted in intermittent function of the aeration system over the first four month period. A strong hydrocarbon odour was initially evident in the exhausted air, which has decreased with time.

The area of influence of the air extraction bores has been assessed by applying a 3 to 5 kPa vacuum to each well separately and measuring vacuum pressures in the other wells. Vacuum pressures of approximately 20 Pa were measured at radii of 3 to 4 m from the source well. Well spacing and configuration at final scale will be optimized based on these results.

NUTRIENT MOBILITY

The supply of nutrients to the study area was delayed and began six months after initiation of site dewatering. Nitrogen and phosphorus are supplied through a drip irrigation system installed 15 cm below the soil surface. Stock nutrient solution is prepared using potable water and is added to recovered groundwater via a dosing pump for irrigation. Addition of nutrient solution is adjusted to balance the uptake rate of nutrients and maintain a soil moisture content of approximately 60% of the water holding capacity.

To date the mobility of nutrients has been monitored in groundwater only. Three new monitoring wells fitted with dedicated bladder pumps were installed down-gradient of the site (Figure 3). Groundwater concentrations of nitrogen or phosphorus measured down-gradient of the site have demonstrated no response to nutrient addition levels. It is planned to install soil pore water monitoring devices to collected additional data on nutrient availability in order to better estimate uptake rates occurring in the field and allow better optimization of nutrient addition.

OXYGEN UPTAKE

The rates of oxygen uptake in the unsaturated zone were monitored towards the end of the six month pilot trial (July 1992). A total of 15 holes were hand augered to the capillary zone (3 to 3.5 m) along transects through the pilot study area, with varying distance from the air extraction wells, and into the uncontaminated and unremediated portions of the site. Soil samples were collected from all locations. In 10 locations, samples were taken at several depths. PVC probes fitted with soil oxygen sensors (Jensen Instruments) were installed in all locations. To date, oxygen consumption has been assessed at 4 locations, including in the uncontaminated and contaminated unremediated areas of the site. Initial oxygen readings were recorded (during venting). The blower was then turned off and oxygen concentrations were recorded over a period of 2.5 hours and 3 days. The rate of oxygen consumption was assessed as the decrease in oxygen content over time. Initial concentrations and rates of oxygen uptake are provided in Table 1 with the measured hydrocarbon content. High hydrocarbon concentrations correspond to high initial oxygen uptake rates to a maximum of approximately 2.5 %/hour. Uptake rates did not correspond to initial oxygen concentration.

Location	DO C_o (%)	DO $Rate_o$ (%/hr)	Diesel (mg/kg)	Microbial Number (CFU/gram)
unremediated				
#11 (2.8 m)	1	-0.4	3800	9×10^2
uncontaminated				
#2 (2.8 m)	11	-0.429	0.2	4×10^2
pilot area				
#4 (2.8 m)	22	-2.43	3600	8×10^3
(2.5 m)	21	-2.4	na	8×10^3
#5 (2.8 m)	22	-2.49	7700	8×10^3
(2 m)	21	-0.686	0.2	$5 - 70 \times 10^3$
(2.5 m)	21	-1.37	860	8×10^3

Table 1. Diesel concentrations, microbial numbers and initial oxygen concentrations and uptake rates measured during bioventing pilot trial

DIESEL CONCENTRATIONS

Diesel concentrations in soil are currently available for five monitoring periods. The first three periods were prior to the pilot study, as follows; 1) prior to free product recovery (March 1990), 2) following recovery of most free product (September 1990), 3) immediately prior to the pilot test (June 1991). The last two monitoring periods included 4) following six months venting but prior to nutrient supply (January, 1992) and 5) following six months of both nutrient supply and bioventing (July, 1992). Cores taken following free product recovery were located according to distance from drawdown and oil recovery wells. Those taken following the initiation of venting were located according to distance from the air extraction wells.

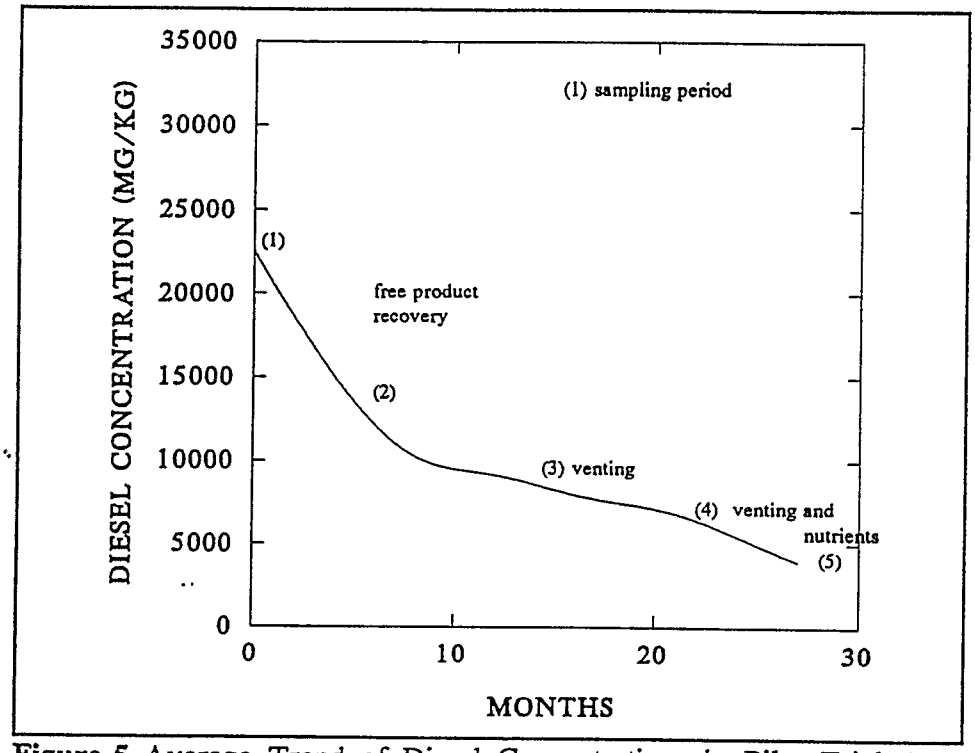

Figure 5 Average Trend of Diesel Concentrations in Pilot Trial Area During Product Recovery and Bioventing Operations

The trend of overall concentration (averaged over depth and location) with time is illustrated in Figure 5. The line illustrated has been fitted to all data using a distance weighted least squares smoothing routine (SYSTAT). The majority of the decrease in concentration (55%) occurred over the period of free product recovery of 15 months. A further 13% decrease occurred over the following 6 months, during the period of dewatering and venting. During the subsequent 6 month pilot trial period (venting and nutrient supply) hydrocarbon concentrations decreased by 18% of the original concentration, or 50% of the concentration remaining after free product recovery.

This decrease in concentration is not consistent over the site, however. The concentrations measured at specific depths are illustrated in Figure 6 for the four sampling periods during remediation of the site. A distance weighted least squares routine was used to illustrate average trends in hydrocarbon concentration with depth. The initial spill was located in the 2 to 2.5 m depth. The first six months of product recovery involved cones of depression which reduced the average concentration but extended it over a greater depth (2 to 3.5 m) in some locations. More extensive dewatering lowered the water table to 3.5 m and extended the contamination over a greater depth (2 to 4.5 m) prior to the pilot test (t=15). Following 6 months of venting, the average concentrations decreased in the unsaturated zone above a 3 m depth.

Concentrations remained high, however, in the 3 to 3.5 m depth interval which constituted a fluctuating water table depth (t=21). Following 6 months of venting and nutrient supply (t=27), average concentrations had decreased over all depths.

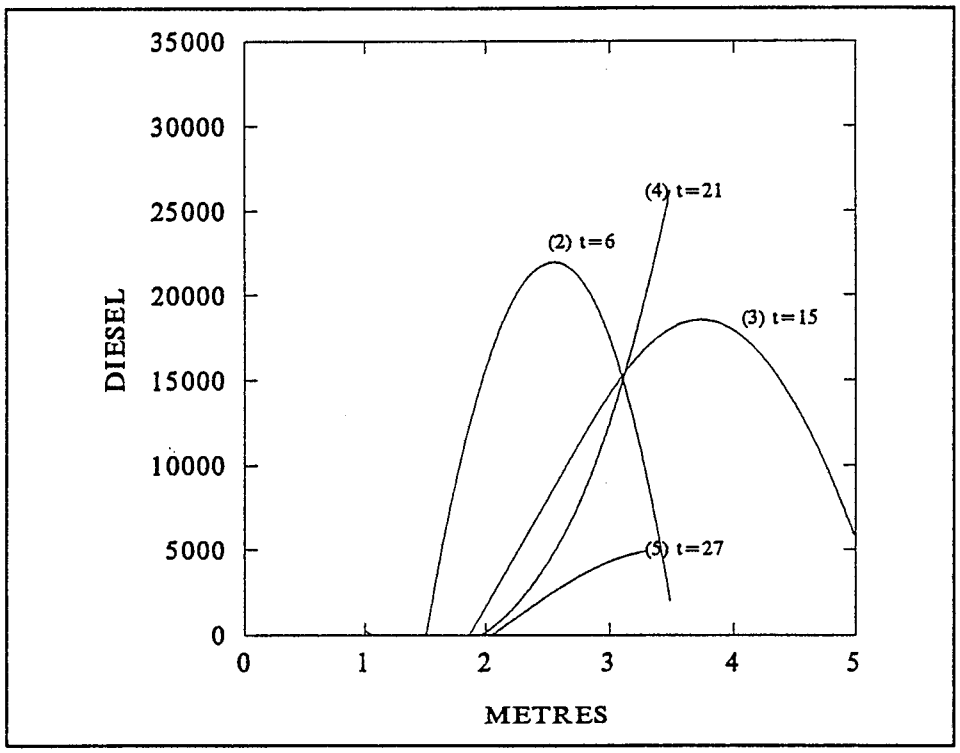

Figure 6 Average Trends of Diesel Concentrations in Pilot Trial Area at Discrete Depths at 6, 15, 21 and 27 month Sampling Periods

During the course of the pilot trial a sequence of visible changes was also observed in free hydrocarbon collecting in the monitoring wells. Initially increased darkening (oxidization) was observed in the free product followed by formation of a gel (emulsification) and a grey slime. Finally only clear water was evident in the wells. A small amount of free product continues to collect in certain monitoring wells within the pilot study area, while FP2, outside the study area, shows evidence of oxidization and emulsification.

Although average concentrations in both Figures 5 and 6 show decreases with time, the range of concentrations showed little change over the last 12 months of study. Work is continuing on analysis of the data according to distance from air extraction wells and oxygen supply.

CONCLUSIONS

Both venting alone and bioventing with the addition of a nutrient supply have proven a valuable adjunct to free product recovery for attainment of cleanup criteria. The average rate of hydrocarbon removal was greater with the supply of nutrients and venting than with venting alone. Much work remains to be done in relating the decrease in hydrocarbon concentration to localised oxygen and nutrient supply within the pilot area. Data collected to date suggest that the cleanup criteria of 1500 mg/kg will be met within the next 12 month period. The data will also provide a good basis for design of the full scale remediation.

REMEDIATION OF GROUND WATER CONTAMINATED WITH ORGANIC WOOD PRESERVATIVES USING PHYSICAL AND BIOLOGICAL TREATMENT TECHNOLOGIES

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Abstract

Pilot-scale field studies at the American Creosote Works Superfund Site, Pensacola, Florida, evaluated two technologies for their ability to treat ground water contaminated with creosote and pentachlorophenol (PCP): 1) Hyperfiltration (volume reduction), and 2) Bioremediation using specially-selected microorganisms (terminal destruction). The hyperfiltration unit was operated in a cross-flow mode yielding "concentrate" (containing excluded chemicals) and "permeate" (clean, aqueous material passing through the membrane.) Operating over a 6-day period on site, a total of 6,300 gallons of creosote- and PCP-contaminated ground water (average total semi-volatile concentration was 88.5 mg/L) was processed thereby reducing the volume of contaminated material >80% while removing >95% of the PAHs. Simultaneously, the concentration of chlorinated dioxins and furans were reduced from 22.5 ppb in the feed to 0.047 ppb (cumulative) in the permeate. Based on chemical analyses and biological toxicity and teratogenicity assays, the permeate stream was acceptable for direct discharge.

A two-stage, continuous-flow, sequential inoculation bioreactor strategy for the bioremediation of ground water contaminated with creosote and pentachlorophenol (PCP) was also evaluated. Performance of continually stirred tank reactors using specially-selected microorganisms was assessed according to chemical analyses of system influent, effluent and bioreactor residues, a chemical mass balance evaluation, and comparative biological toxicity and teratogenicity measurements. When specially-selected bacteria capable of utilizing high-molecular-weight polycyclic aromatic hydrocarbons (HMW PAHs) as primary growth substrates were used in pilot-scale bioreactors (454 L), the concentration of creosote constituents was reduced from ca. 1,000 ppm in the ground water feed (flow rate = 114 L/day) to <9 ppm in the system effluent (removal efficiency of >99%). Notably, the cumulative concentration of 8 HMW PAHs (containing 4 or more fused rings) was reduced from 368 ppm in the ground water feed to 5.2 ppm in the system effluent. Moreover, the toxicity and teratogenicity of the bioreactor effluent was significantly reduced. Biodegradation of PCP was limited (ca. 24%) due in large part to poor inoculation and a high degree of abiotic loss (bioaccumulation and adsorption).

Introduction

Since 1988, SBP Technologies, Inc. (SBP) has been developing the concept of a "multi-phasic bioremediation strategy" in cooperation with the U.S. EPA Environmental Research Laboratory at Gulf Breeze, Florida (1-3). This strategy integrates physical and biological treatment processes for effective and cost-efficient remediation of a variety of substrates (soil, sediment, aqueous) contaminated by myriad hazardous wastes; organic and inorganic wastes and mixtures thereof. Depending on the nature of the contaminated substrate (*i.e.*, soil or aqueous material), the treatment strategy may consist of several discrete phases. For example, treatment of soil or sediment contaminated with organic and inorganic wood preservatives could entail three phases: Phase 1, soil washing; Phase 2, dewatering of soil slurry, volume reduction of wash waters, and/or fractionation of pollutant chemicals by hyperfiltration; and Phase 3, terminal destruction of concentrated pollutants or recovery/recycling of valuable resources (*eg.* heavy metals).

In the event that the concentrated pollutants are biodegradable, terminal destruction is accomplished most effectively via some form of bioremediation. Since the material has already been concentrated, bioreactor systems are usually more appropriate than other approaches (*eg.*, land farming). For pollutants not amenable to biological treatment (*eg.*, heavy metals), then other technologies, such as incineration, chemical oxidation or solidification, become more cost effective due to the reduced volume of material requiring treatment.

Other advantages of the multi-phasic strategy using integrated technologies include: 1) Holistic approach to site remediation: simultaneous treatment of surface water, ground water, soil and sediment, 2) Ability to treat complex mixtures of organic, inorganic and radioactive wastes, 3) Pollutants are immediately removed from contaminated matrices and separated into discrete fractions which greatly facilitates biological degradation, 4) Toxic compounds (*i.e.*, metals, radionuclides) are removed or recycled prior to biological treatment, 5) Contained systems are amenable to the future integration of intergeneric microorganisms capable of degrading recalcitrant compounds, 6) Sole source utilization of high-molecular-weight PAHs by patented microorganisms facilitates the efficient removal of recalcitrant, carcinogenic and teratogenic creosote constituents which commonly persist during conventional biological treatment, 7) Ability to recover/recycle valuable products from hazardous waste sites/industrial effluent: heavy metal (lead, chromium), petroleum products, 8) Entirely mobile treatment systems for on-site remediation, and 9) Flexible, versatile systems with broad applicability that can be specially designed and readily modified for particular needs.

In this paper, we describe pilot-scale field demonstrations of two technologies for the treatment of ground water contaminated with organic wood preservatives (creosote, pentachlorophenol) and associated chemicals (chlorinated dioxins/furans): 1) hyperfiltration (volume reduction), and 2) bioremediation using specially-selected microorganisms (terminal destruction). These studies were performed at the American Creosote Works Superfund site (ACW), Pensacola, Florida, in cooperation with the U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program. The other component of the multi-phasic treatment strategy, namely soil washing, was not demonstrated since this is basically a "proven" technology, with experience and expertise being provided by Dredging International, Belgium, and their subsidiaries.

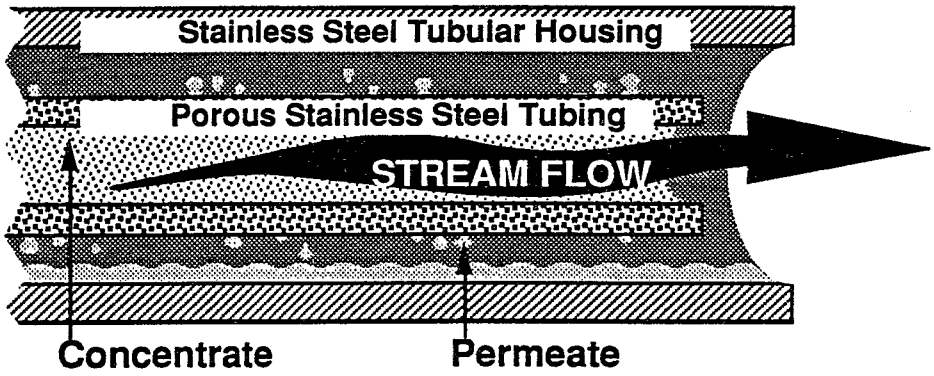
Hyperfiltration System

Technology description: The hyperfiltration system consists of porous, sintered, stainless steel tubes coated with multi-layered inorganic and polymeric "formed-in-place" membranes. Membranes are coated at microscopic thickness on the inside diameter of the stainless steel tubing by the recirculation of an aqueous slurry of membrane formation chemicals exclusive to SBP. Membranes are specially designed and formulated on a site-specific basis according to the characteristics of the chemical pollutants and the contaminated substrate. As shown in **Figure 1**, the hyperfiltration unit operates in a cross-flow mode yielding "concentrate" (containing excluded chemicals) and "permeate" (clean, aqueous material passing through the membrane.) The device can perform filtration ranging from microfiltration to hyperfiltration. In-house and independent analyses have demonstrated the ability of SBP membrane systems to extract (retain) heavy metals, caustics and various organic pollutants including petroleum products, PCP, chlorinated dioxins/furans and creosote (4). Most recent efforts are geared toward the design and construction of hyperfiltration systems for the recovery of heavy metals (*eg.*, arsenic, mercury), PCBs, and chlorinated solvents such as TCE.

Pilot-scale field demonstration: Ground water was removed from the shallow aquifer at the ACW site and transferred to an equilibration tank where oil-phases were passively separated (upper and lower oil phases and aqueous phase). The resultant aqueous phase was used as the feed water containing an average total semi-volatile concentration of 88.5 ppm with phenanthrene (17.1 ppm) and naphthalene (12.9 ppm) as the major contaminants plus 22.5 ppb cumulative chlorinated dioxins/furans. Operating over a 6-day period on site, a total of 23,850 L of creosote- and PCP-contaminated ground water was processed (ca. 4000 L/day) with the objectives of 80% volume reduction and >90% removal efficiency of monitored contaminants. Process operating data collected included flow rates, temperatures, pressures and electrical and potable water usage. The feed water, permeate, concentrate and wash water were analyzed for volatile organic compounds, semi-volatiles, chlorinated dioxins/furans, total dissolved and

suspended solids, oil and grease, total organic carbon and chemical oxygen demand.

Figure 1: Cross section illustrates stream flow within tubing.



Biodegradation System

Technology description: In conjunction with the U.S. EPA Environmental Research Laboratory at Gulf Breeze, Florida (GBERL), SBP isolated and characterized the first axenic bacterial cultures capable of utilizing high-molecular-weight PAHs as sole sources of carbon and energy for growth (U.S. Patent No. 5,132,224). The action of these and other organisms toward 43 priority creosote constituents has been reported previously (5-8). These findings represent a major advancement in bioremediation technology since the targeted pollutants (*i.e.*, fluoranthene, pyrene, benzo[a]pyrene) typically persist during conventional biotreatment operations (*eg.*,land farming). Unfortunately, this same group of compounds represents the most serious threat to human and environmental health. Thus, with the use of these proprietary microorganisms, the efficiency and applicability of bioremediation technologies has been greatly expanded to include creosote, coal tar and related wastes.

Pilot-scale field demonstration: A two-stage, sequential inoculation, bioremediation process was field-tested with ground water, highly contaminated by creosote and PCP, recovered from the ACW Superfund Site. The first stage of the pilot-scale system used a 454 L completely stirred tank reactor (EIMCO, Denver, CO) designated FBR1 (field bioreactor 1). The second stage of the process made use of three, 227 L stirred tank batch reactors (bioreactors FBR2a, 2b and 2c). The bioreactor was operated at a flow rate of 114 L/day with raw ground water containing ca. 1000 ppm semi-volatile creosote constituents and ca. 15 ppm PCP. Additional information on bioreactor design and operation, including inoculation, sampling and analyses, can be found elsewhere (7). Efficiency and performance of the bioremediation system using bioreactors and specially-selected microorganisms was assessed according to chemical analyses of system influent, effluent and bioreactor residues, a chemical mass balance evaluation, and comparative biological toxicity and teratogenicity measurements. Liquid/liquid extraction of PCP and creosote constituents from bioreactor feeds, aqueous effluents, settled biomass and reactor residues was performed as previously described (3,8); creosote and PCP were extracted from activated carbon samples as described previously (3,8). Toxicity and teratogenicity analyses using embryonic fish, *Menidia beryllina,* Microtox™ assays, *Mysidopsis bahia* and *Ceriodaphnia dubia* tests were performed as previously described (4,7,8).

Results and Discussion

Hyperfiltration system: Over the entire course of the 6-day period, the goal of reducing the volume of contaminated material >80% was consistently achieved. For every 1000 gallons of feed water processed, 200 gallons of concentrate were generated and 800 gallons of permeate was produced. Chemical analyses showed that >95% of the PAHs were removed, and the concentration of chlorinated dioxins and furans were reduced from 22.5 ppb in the feed to 0.047

ppb (cumulative) in the permeate. The system was less effective in removing the lower-molecular-weight contaminants, specifically phenol (30% removal efficiency). However, physical analyses and biological toxicity and teratogenicity assays showed that the permeate stream was acceptable for direct discharge to the public water treatment plant.

Biodegradation system: Mass balance chemical analyses showed that ca. 64, 77, and 70% of the Group 1 (2 ring PAHs), Group 2 (3-ring PAHs) and Group 3 PAHs (4 or more fused rings) were biodegraded, respectively (Table 1). Relatively poor performance toward PCP (24% biodegraded) was attributed to the use of inocula of insufficient quality (incomplete induction and low cell viability) which was not discovered until after the time of application. During continuous-flow operations, an average 113 L of ground water feed containing approximately 31, 539, 368, 106, <1 and 25 mg/L Group 1 PAHs, Group 2 PAHs, Group 3 PAHs, heterocycles, phenolics, and PCP, respectively, was added to FBR1 on a daily basis. Based on these removal efficiencies, the system effluent contained, on average, 0.1, 1.6, 5.2, 1.8 and 5.6 mg/L Group 1, 2 and 3 PAHs, heterocycles, and PCP, respectively. A secondary treatment process using the same hyperfiltration unit to separate of residual contaminants has been developed in the event that reactor effluent of this quality requires subsequent treatment prior to discharge.

Table 1. Mass balance evaluation[a] of pilot-scale studies on the biodegradation of 30 monitored creosote constituents and PCP by specially-selected microbial strains.

Chemical Group	Total System Input	System Discharge (Output)	% Removal[b]	Residue In: Settled Biomass	Residue In: Bioreactor and lines	Amount Volatilized[c]	Amount Biodegraded (%)[d]	
	mg							
Group 1 PAHs	28256.2	47.2	99.8	186.0	10020.6	44.3	17958.1	(63.6)
Group 2 PAHs	484936.8	1298.8	99.7	1320.0	107811.1	32.9	374474.0	(77.2)
Group 3 PAHs	331599.9	5548.0	98.3	5160.0	88115.3	1.5	232775.1	(70.2)
Hetero-cyclics	95506.3	1603.0	98.3	1090.0	28437.7	47.4	64328.2	(67.4)
PCP	12061.9	2674.0	77.8	2376.1	4101.8	<1.0	9151.8	(24.1)

[a]cumulative values following 14 days of field operation (8 days continuous-flow operation);
[b]% removal = (total system input - system discharge)/total system input x 100;
[c]calculated value based on intermittent measurements; [d]% biodegradation =

$$100 \times \frac{\text{total system input - (system discharge + biomass residue + line residue + volatilization)}}{\text{total system input}}$$

Whereas analytical chemistry data indicate loss of parent compounds, it is often wrongly assumed that this loss correlates with a removal of the hazards associated with the original wastes. This is especially true in the case of bioremediation where slight modification of contaminants can result in their apparent "degradation". Therefore, in these studies, a series of toxicity and teratogenicity assays were performed on all starting materials, bioreactor effluent and membrane permeate. For both the hyperfiltration and bioreactor technologies, loss of parent compound correlated with a significant reduction in the toxicity/teratogenicity of treated material. potential hazard associated with the treated wastes along with a decrease in the concentration of parent compound. Based on Microtox™ assays, the reduction in toxicity of ground water by specially-selected microorganisms was approximately 230- and 130-fold for FBR1 and FBR2, respectively; tests with mysids indicated a 34- to 75-fold reduction in toxicity for FBR1 and FBR2, respectively, when compared to ground water. In tests with daphnids, a 75- to 100-fold reduction in toxicity was noted. Exposure of *Menidia* embryos to a 1% concentration of ground water resulted in rapid embryotoxicity (100%). In contrast, the FBR1 effluent was teratogenic (an indication of reduced

toxicity), and 86% of the embryos exposed to effluent from FBR2 developed normally and hatched without discernible terata; these larva were essentially identical to controls.

Conclusions

The effectiveness of two key components of SBP's multi-phasic remediation strategy was rigorously evaluated under field operating conditions and ultimately proven at the pilot-scale: volume reduction via hyperfiltration, and biodegradation of persistent organic contaminants in bioreactors using specially-selected microorganisms. The integrated use of physical and biological treatment technologies expands the applicability of bioremediation technologies, and provides a cost-effective, viable remedial approach for creosote- and similarly-contaminated sites.

Acknowledgments

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THE DESIGN CRITERIA AND ECONOMICS OF OPERATING A FULL-SCALE ABOVE-GROUND BIOREMEDIATION FACILITY FOR THE TREATMENT OF HYDROCARBON CONTAMINATED SOILS

by

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SUMMARY

The bioremediation of soil contaminated with certain hydrocarbons, has been demonstrated as an effective and economical alternative waste treatment technology. This paper focuses on a project which was specifically designed and implemented to treat soils contaminated with a synthetic heat transfer fluid.

INTRODUCTION

Due to increasing hazardous waste disposal costs, rapid regulatory changes, and a corporate policy of sound environmental practices, the operators of the world's largest solar electric generating systems (SEGS) embarked on a program to eliminate the need for off-site disposal of hydrocarbon contaminated soils.

The SEGS technology employ line-focus parabolic trough mirror collectors to focus and concentrate sunlight onto heat collection elements (HCE). The HCE's are filled with a unique heat transfer fluid (HTF) which is circulated through the solar fields and heated to between 600 and 750 degrees Fahrenheit. The HTF is pumped through a series of heat exchangers, generating steam which in turn passes through a turbine generating electricity. HTF is an eutectic mixture of 26.5% Biphenyl and 73.5% Diphenyl Oxide.

Accidental releases of HTF from the SEGS systems sometimes result in contamination of soil. Historically, this meant excavation, transport, and disposal in a class I hazardous waste landfill. In an effort to reduce the cost of disposal, conserve limited landfill space, and implement a soils recycling program, bioremediation was studied as an on-site alternative treatment technology.

TREATMENT PROCESS DESCRIPTION

The treatment technology employs solid phase bioremediation which is environmentally controlled to optimize degradation processes. By utilizing naturally occurring microorganisms, HTF soil contaminants are metabolized into harmless by-products. Treatment is conducted within a fixed containment facility.

MEDIA AND POLLUTANTS TREATED

The waste stream consists of well-defined coarse and medium grained sands and a small percent of clayey silts and gravel contaminated with HTF (biphenyl and diphenyl oxide).

PROJECT DEVELOPMENT STATUS

Two pilot scale projects, conducted over an 18-month period, were successful in reducing HTF concentrations to below the target "clean-up" level of 1000 ppm. The positive results achieved prompted the implementation of a full-scale project. A full-scale treatment demonstration project has been underway for the last 24 months.

INITIAL AND FINAL POLLUTANT CONCENTRATION

Initial contaminant concentrations vary with the quantity of HTF released and surface area of contamination. Concentrations typically average about 7,500 parts per million (ppm); with an observed range from less than 2,000 ppm to as high as 20,000 ppm. Treatment requires approximately 90 days to accomplish contaminant removal to below 1000 ppm. Treatment to levels less than 100 ppm are possible, however this lower treatment level is contingent upon initial concentrations, favorable environmental conditions and is generally time dependent.

PROCESS LIMITATIONS

Treatability studies have shown that the most critical limiting factors are:

1.	Soil pH	(6 to 8)
2.	Moisture	(40 to 60 % of saturation)
3.	Temperature	(65 to 85 degrees F)
4.	Nutrients	(Variable)
5.	Oxygen supply	(Variable)

The ability of the operator to manage these conditions will determine whether an ideal environment can be created to stimulate bacterial population growth and enhance the degradation process.

To enhance aerobic bacterial growth and reduce the potential odor problems associated with anaerobic conditions, the soils are tilled on a 72-hours schedule. A good oxygen supply, in concert with a sufficient moisture content, stimulates bacterial growth and promotes mobility.

PROCESS WASTE STREAMS

If properly managed, the process produces no residual hazardous waste or other conditions of concern. Treatment is viewed as a form of "geo-reclamation"; the recycled material is to be used as "clean" backfill on site.

AGENCY INVOLVEMENT

As with any project of this nature, it is necessary to consult with a variety of regulatory agencies. It is important to gain a full understanding of the regulatory conditions before spending too much time and money on development. In order to avoid duplication of agency requirements, a workshop should be set up to bring all concerned parties together to discuss the project in full. In the case of this facility, a meeting was held to discuss and establish the treatment process and goals. The proposed facility design and construction parameters were compared to regulatory statutes for adequacy and compliance.

Sampling protocol and monitoring requirements, as well as regulatory concerns and comments, were addressed. The "lead" agency was established and the necessary approvals obtained.

The California State agencies involved in the project are:

CAL\EPA - Region 4 (Facility Permitting Unit)	(CAL\EPA)
CAL\EPA - Alternative Technology Division	(ATD)
Regional Water Quality Control Board	(RWQCB)
Air Pollution Control District	(APCD)
County Environmental Health Services	(EHS)
California Energy Commission	(CEC)*

* Conditions of Certification issued by the CEC required their involvement in this project. The CEC would not normally be involved in waste treatment projects.

DESIGN AND CONSTRUCTION CRITERIA

There are several factors which must be considered when determining a facility's design. While economic considerations may dictate the options selected, regulatory requirements will ultimately direct or limit those options.

The primary consideration should be environmental protection. This usually means containment features to ensure prevention of groundwater and vadose zone degradation, but may also include contaminant emissions to the atmosphere.

Regulatory requirements will dictate minimum protection standards and tolerances. The selection of materials used for containment should also consider durability, exposure to environmental elements, load factors, and the contaminant being contained and treated.

High-density polyethylene (HDPE) or similar materials are widely used for this type of application, and are easily installed and relatively inexpensive. Natural clay barriers can also satisfy containment requirements, however, they can be very expensive to install because of intensive labor requirements and import costs.

To prevent run-on and/or run-off from precipitation, the facility's containment area properly configured and the perimeter appropriately graded. In some cases, the entire facility can be covered or, at additional cost, a roof constructed over the treatment area. This may be necessary in areas where average ambient temperatures are below 65 degrees Fahrenheit for prolonged periods of time, or regions where high precipitation occurs. Cost figures for roofing applications are not considered in this paper.

Because water is applied to the facility, leachate collection and recovery systems (LCRS) must be installed directly below the treatment zone. The LCRS acts as a first line of defense against a possible release from the facility.

The LCRS allows collected fluids to be returned to the treatment zone and warns of a possible facility breach. Should fluids enter the LCRS, inspection and repair of the facility should occur immediately following confirmation that the fluid is leachate.

Installation of vadose zone and groundwater monitoring devices are often required to detect possible releases beyond the LCRS and into the unsaturated zone or water table below the facility.

Once appropriate containment and monitoring systems have been determined, facility sizing should be calculated. Facility dimensions should be sufficient to handle only the anticipated rate and volume of waste material generated. A minimal storage structure should be appropriately sized and considered as a contingency, should unusual events require temporary storage of material prior to treatment.

It may be of value to partition the treatment zone into two or three individual treatment areas to allow a staggering of start and end dates of smaller batch treatment processes.

FULL-SCALE FACILITY AS DESIGNED

This full-scale facility's design incorporates primary and secondary containment features, a triple LCRS installation, equipment access requirements and environmental control devices. The facility is 225' long, 60' wide and 2.5' deep with an annual throughput capacity of approximately 1,500 cubic yards or roughly 2,000 tons.

The facility was constructed with 7 inches of reinforced concrete as the primary containment structure. The concrete was coated with a chemically resistant sealant. An elaborate triple-liner system of HDPE was installed below the concrete. This required secondary containment is made up of two 40 mil and one 80 mil HDPE liners. There is a "geo-fabric" material between the two 40 mil liners which acts as a wick to assist in the recovery of fluids which may collect between these two liners. A LCRS exists between the concrete and the upper 40 mil liner; between the two 40 mil liners; and between the lower 40 and bottom 80 mil liners.

The area between the 40 and 80 mil liners was backfilled and compacted with 2' of native soil, and designated the lower vadose (unsaturated) zone; the third LCRS acts as the primary vadose zone monitoring system, therefore no additional subsurface monitoring devices (i.e. lysimeters, neutron probe casings, etc.) were installed below the 80 mil liner.

A broadcast watering system was installed and set up on a timing device to maintain proper soil moisture content. Soil moisture readings are taken every three days.

MONITORING REQUIREMENTS

Because of the relatively small size of this facility, it was not practical to install groundwater monitoring wells for purposes of detecting a leak from the facility. The depth to groundwater is greater than 150 feet, and contaminant pathways are not well defined. As a result, it would be virtually impossible to construct a well monitoring system that could adequately detect any degradation of the groundwater due to a leak from this facility. Hence the triple liner and LCRS system. The LCRS are monitored on a quarterly basis.

ECONOMICS

An economic comparison of various alternatives to the operation of a bioremediation facility show that it is cost-effective to construct and operate a bio-facility. This assumes, however, that either a substantial volume of waste exists, or is expected to be generated over the operating life of the project.

INITIAL CAPITAL COST

Pilot-scale testing conducted at this site cost about $15,000.00 over 18 months. The full-scale facility has thus far required agency fees totalling $85,000.00, including financial assurance for eventual facility closure.

Full-scale facility construction requirements and associated costs made up the bulk of first year capital expenses. Facility design, plan check fees, material and labor, as well as administrative oversight, has resulted in a capital expenditure of approximately $220,000.00.

Total project costs amounted to about $320,000.00. Actual costs may be higher if the purchase of earth moving and tilling equipment is required.

TREATMENT COSTS

Annual treatment costs for bioremediation are relatively low by comparison to other methods of treatment. Costs are directly related to manpower and equipment needs, as well as materials consumed (i.e. nutrients, water, etc.). Sampling and analytical costs will vary depending upon the frequency of sampling and the type and quantity of tests performed on each sample.

Overall operating costs will also be contingent upon the size of the facility and number of treatment batches completed. For this facility (which processes three 500 cubic yard batches per year), the total annual cost of operation runs approximately $35,000.00. This figure includes all of those factors indicated above.

ECONOMICS OF OPERATIONS

In deciding whether on-site bioremediation is practical, the focus is primarily on economic payback. By comparison to some of the alternatives, such as landfilling, incineration, solidification, thermal desorption, and vapor extraction, bioremediation can be very attractive.

The key questions as to whether or not on-site bioremediation is attractive or not are:

How much waste do I currently have to treat?
How much am I generating over what period of time?
Are there regulatory limitations in dealing with this waste stream?
Do I have land availability to conduct on-site treatment?
Am I under some time constraint to solve the problem?
Do I have the means in-house to attend to on-site treatment?
Is the waste stream hazardous or not? And finally,
What are my long term goals?

If the answers to the above questions are favorable towards implementing an on-site bioremediation facility, the operating costs are minimal and payback can be relatively rapid. The factors that play a role in facility operating costs are: frequency of soil aeration (labor), purchase of supplemental nutrients, water, sampling and analytical expenses, and administrative oversight.

For this particular facility, and a total first-year investment of $220,000.00 (construction), and $35,000.00 (operations), on-site bioremediation produced a per treated cubic yard cost of about $170.00, or $30.00 per yard less than the cost for landfilling the waste. In the second year, given the same volume treated, the cost drops to about $26.00 per yard without amortization of facility construction. An additional cost reduction, to about $21.00 per cubic yard, was realized once sampling and analytical parameters were reduced to minimum requirements. Experience gained over time will allow the operator to reduce sampling to the minimal requirements.

A comparison of the first year costs of selected alternatives, are generally competitive. In the second and subsequent years of operation, the cost of conducting on-site bioremediation is dramatically less on a per volume basis. For example: Treating 1,500 cubic yards of contaminated soil would result in the following first-year expenditure, using the treatment or disposal method shown in the following chart. In the second year, there is a significant difference in the cost of bioremediation compared to the other methods.

METHOD	1st year	2nd year	3rd year
Incineration	$787,500.00	NO CHANGE	NO CHANGE
Solidification	$165,000.00	"	"
Landfill	$322,500.00	"	"
Thermal Desorption	$300,000.00	"	"
Bioremediation	$255,000.00	$39,000.00	$31,500.00

These comparison figures are averages of actual quotations and information obtained from articles printed in various industry publications for the method indicated. The bioremediation figures are actual costs based on this project.

It should be remembered that the economic variables affecting individual on-site bioremediation projects will be influenced by regulatory requirements, the cost of construction materials and facility scale, the type and concentration of the contaminant being treated, the climatic conditions of the area, and the amount of waste to be treated annually. Therefore, each of these factors must be considered individually and specifically for each project.

CONCLUSION

This project and the effectiveness of bioremediation has proven itself, both environmentally and economically. In a world of tighter and tighter regulatory requirements, rising cost of hazardous waste treatment and disposal, and public awareness of environmental problems, there is no doubt that on-site bioremediation is a sound, cost-effective solution to a variety of hydrocarbon contaminated soil problems.

Biopur®

An Innovative Bioreactor for the Simultaneous Treatment of Groundwater and Soil Vapour Contaminated with Xenobiotic Compounds

TAUW Infra Consult B.V., P.O. Box 479, 7400 AL Deventer, The Netherlands

Introduction

At many places the soil, groundwater and soil vapour are contaminated with organic compounds. A bioreactor was developed to treat groundwater and soil vapour simultaneously. This system is called Biopur®. Contrary to conventional physico/chemical methods, biological treatment does not cause waste problems and is therefore an attractive method. The Biopur® system is patented.

Background

Biological groundwater treatment in fixed film reactors, has been used by TAUW Infra Consult B.V. since 1986. Trickling filters were used initially, followed by Rotating Biological Contactors (RBC). Groundwater heavily contaminated with benzene, mono-chlorobenzene and HCH could be treated. Removal efficiencies of up to 98% were obtained.
Furthermore, at in situ remediation sites, there was a need to develop a system to treat soil vapour in combination with groundwater. For these reasons the Biopur® was developed. The Biopur® is a fixed film bioreactor with polyurethane as a carrier material for the biomass. The flow of air and water is co-current to prevent the volatile compounds being stripped (see Figure 1).

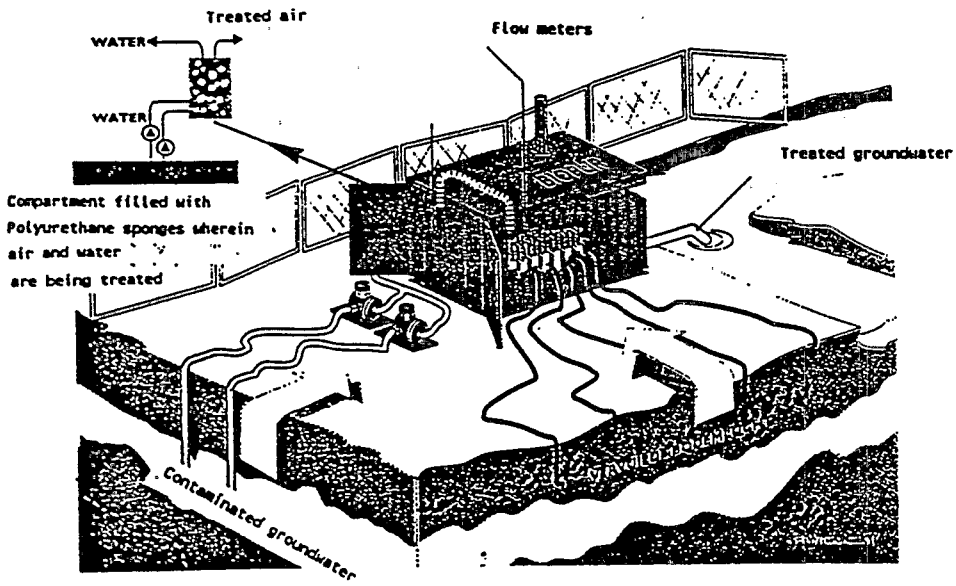


Figure 1: An Overview of an In Situ Application of the Biopur® Reactor for the Simultaneous Treatment of Soil Vapour and Groundwater

Results - Pilot Plant Scale

The Biopur® was tested for groundwater treatment at pilot plant scale, the results of one experiment are given in Table 1.

Table 1: Results of Pilot Plant Research

Site	HRT (hours)	Influent (µg/l)	Effluent (µg/l)	Stripping %
Former Gasworks				
Configuration 1	0.5			
BTEX		460	17	1
PAH (16 EPA)		930	58	0.3
Mineral Oil		9800	1000	0
Configuration 2	0.3			
BTEX		296	2.8	1.5
PAH (16 EPA)		1300	10	0
Mineral Oil		7050	250	0

At another site, a former asphalt production plant, groundwater contaminated with PAH, BTEX and phenolic compounds, was treated on site in a small Biopur® system. With a hydraulic retention time of 30 minutes, naphthalene was completely removed, BTEX 70%, 16 EPA PAH 95%, o,m,p-cresol between 68-79% and dimethylphenol 70%.

Results - Full Scale

Groundwater Treatment

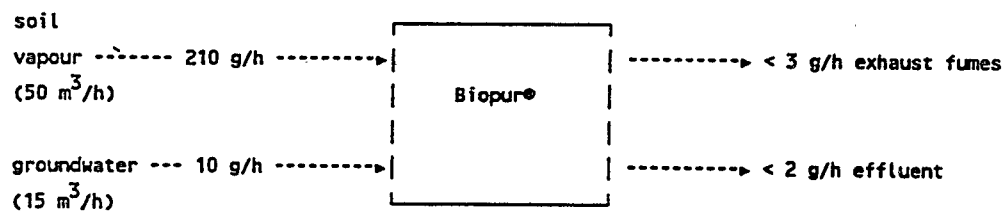
At several petrol stations, where the soil was contaminated with BTEX , volatile and non-volatile compounds and mineral oil, the groundwater was treated in a Biopur® system. Table 2 shows some of the results.

Table 2: Results of Full Scale Experiments

Site	HRT (hours)	Influent (µg/l)	Effluent (µg/l)	Removal Efficiency %
Raalte I	0.25			
BTEX		650	< 0.5	> 99.9
Mineral Oil		< 100	< 100	not applicable
Overslag	1			
BTEX		39	< 1	> 97.4
Mineral Oil		350	55	84.2
Utrecht	0.25			
BTEX		1300	3	99.7
Mineral Oil		323	36	88.8
Raalte II	1.2			
BTEX		261	< 1	< 99.6
Mineral Oil		1050	50	95.2

Results - Simultaneous Treatment of Groundwater and Soil Vapour

The Biopur® was used at a site to simultaneously treat contaminated groundwater and soil vapour. A mass balance of the system is shown below.



The mass balance shows that 5 kg of petrol was removed daily with hydraulic retention times of less than 15 minutes.

The exhaust fumes did not contain detectable organic compounds (<0.1 ppm) and could be disposed of without being treated. The treated groundwater from the site was discharged into surface water.

Treatment Costs

Related to the entire remedial action the treatment costs of soil vapour and groundwater were less than DM 0.40 per m^3 of groundwater. For calculation purposes only, the treatment of the soil vapour was free of charge.

In Table 3 a comparison of the treatment costs of four types of groundwater purifying plants is given.

Table 3: Comparison of the Treatment Costs of Four Types of Groundwater Purifying Plants

Type		Costs (DM) per m^3 of groundwater		
		10 m^3/hour	20 m^3/hour	40 m^3/hour
1	Biopur®	0.53	0.44	0.35
2	Rotating biological contactor	0.78	0.65	0.59
3	Stripper/activated carbon	0.85	0.54	0.36
4	Stripper/compost filter	1.16	0.87	0.72

Conclusions

(1) Groundwater contaminated with organic compounds, such as BTEX, PAH, mineral oil and chlorinated hydrocarbons can be treated by using the Biopur® process.

(2) The Biopur® can be used for simultaneously treating biological groundwater and soil vapour.

(3) Using the Biopur® process good removal results were obtained with relatively short hydraulic retention times.

(4) Application of the Biopur® process in groundwater/soil vapour treatment is cost effective.

We are prepared to discuss specific problems and to find a way of cooperating in complex environmental fields.

Should you require further information please contact:-

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Optimizing Bioventing in Shallow Vadose Zones and Cold Climates: Eielson AFB Bioremediation of a JP-4 Spill

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and

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Tyndall AFB, FL

[4]U.S. Air Force Center for Environmental Excellence
Brooks AFB, TX

Eielson AFB: Background

- JP-4 jet fuel contaminated unsaturated soil
- Contamination from leaks in underground fuel distribution system
- Soil contaminated from 2 to 6 ft (groundwater at 6 ft)

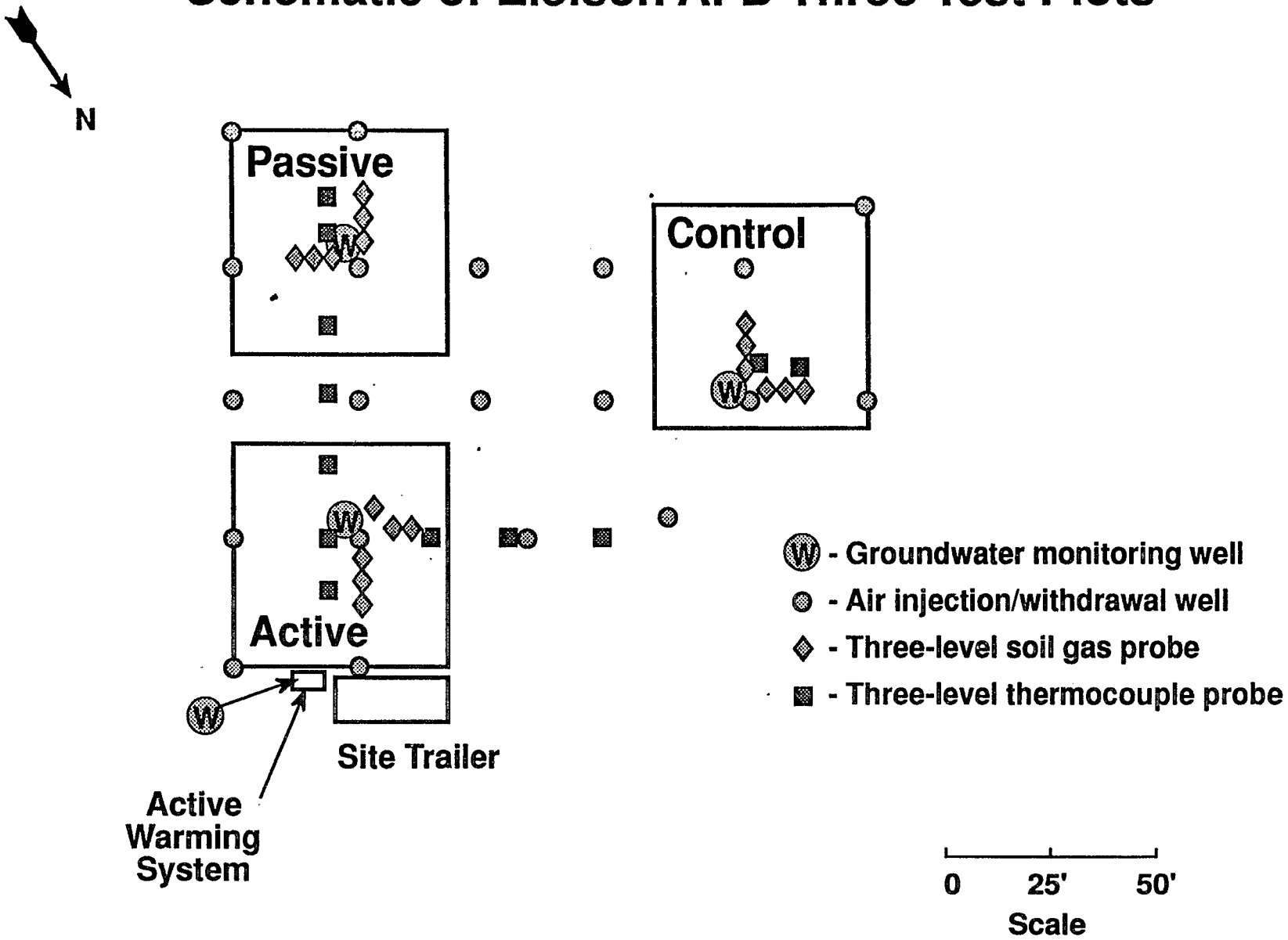
Eielson AFB: Background (continued)

- U.S. EPA, U.S. Air Force, and Battelle began work here in July 1991
- 3-year study
- Funded by
  - U.S. EPA Bioremediation Field Initiative
  - U.S. Air Force

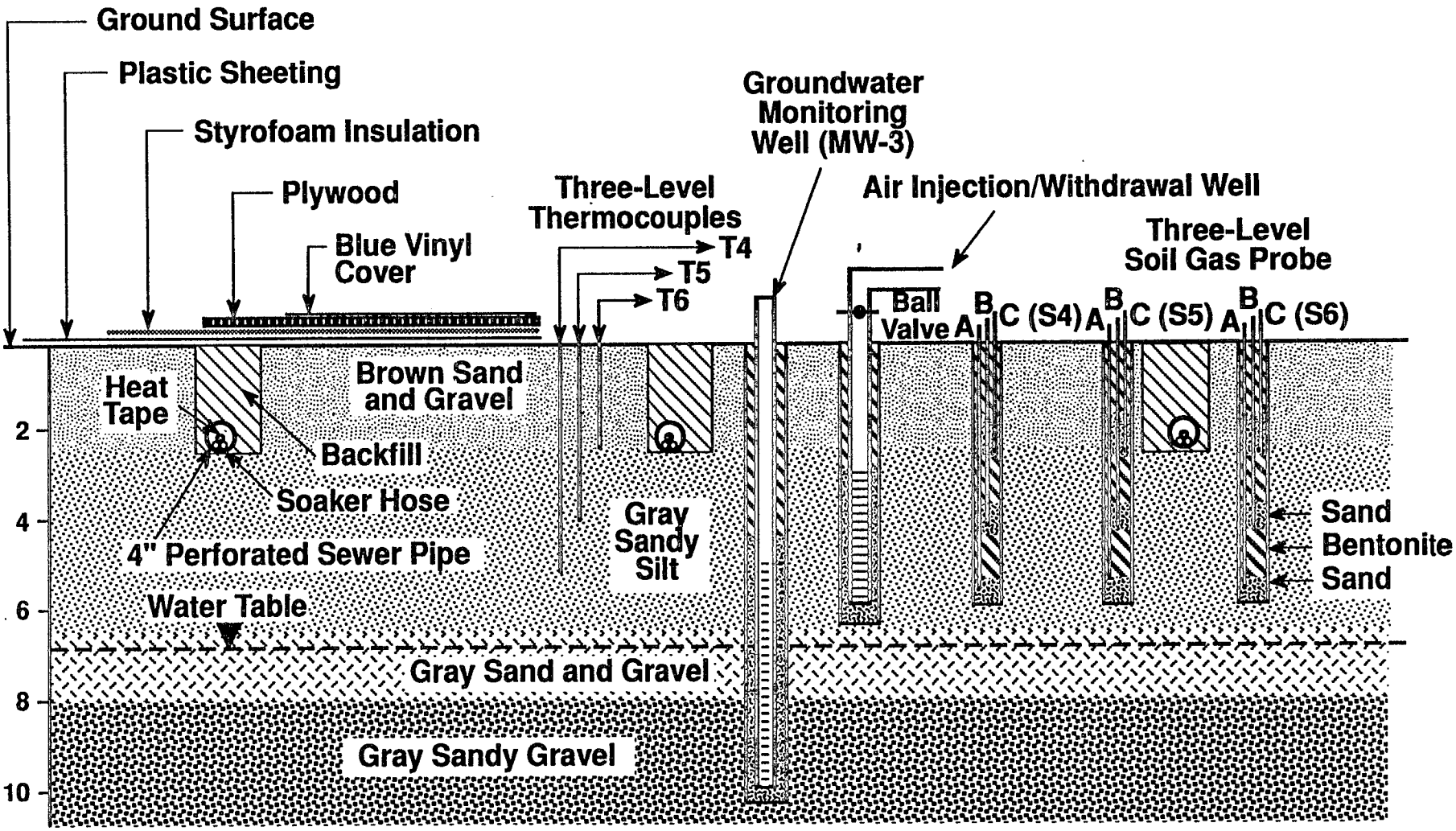
Eielson AFB: Project Objectives

- Document bioventing in a cold climate
  - average annual air temp = 0•C
- Evaluate various soil warming methods to enhance bioventing rates
  - active warming with warm water
  - passive solar warming

Schematic of Eielson AFB Three Test Plots

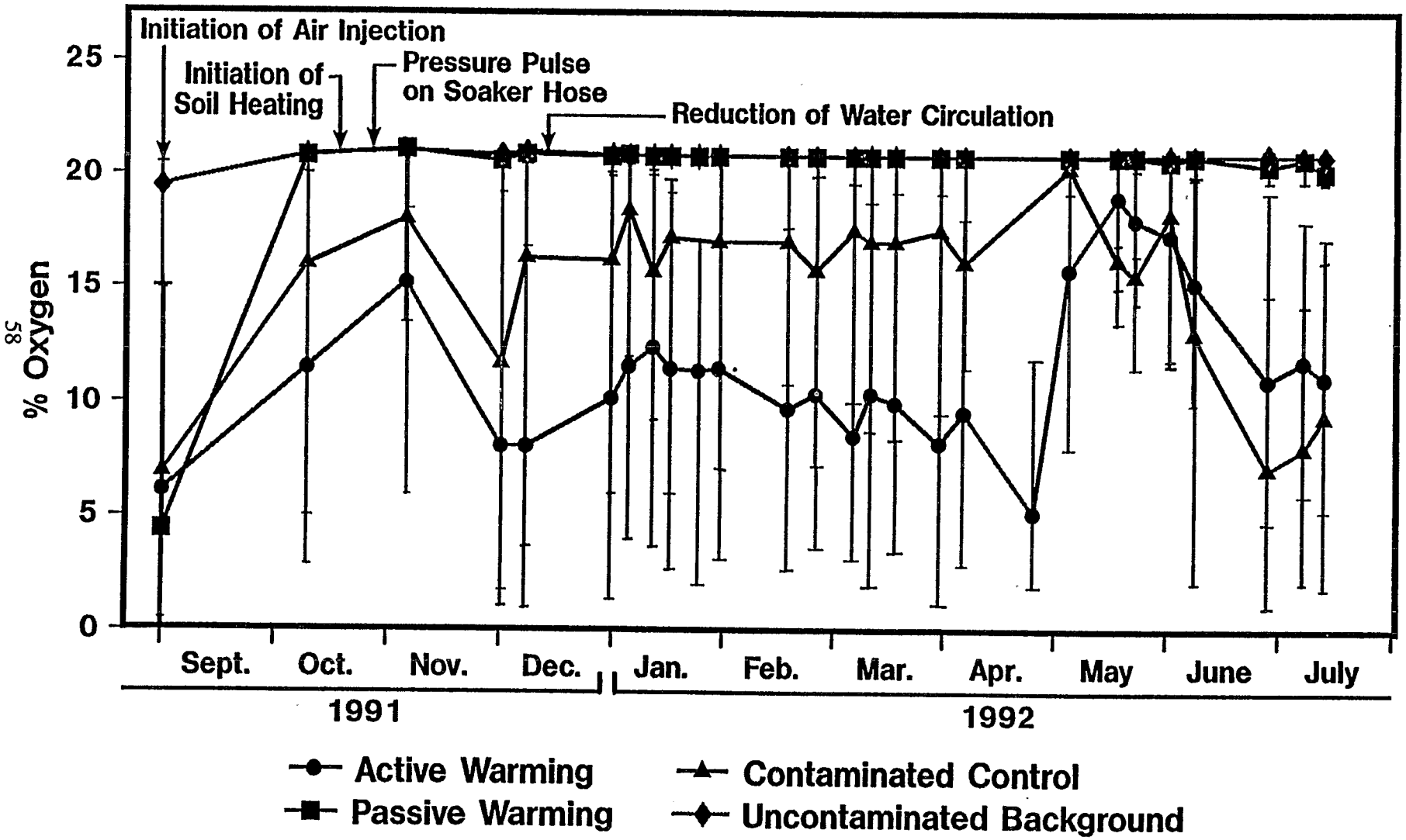


Cross-Section of EPA Active Plot Showing General Site Lithology and Bioventing System Construction Details

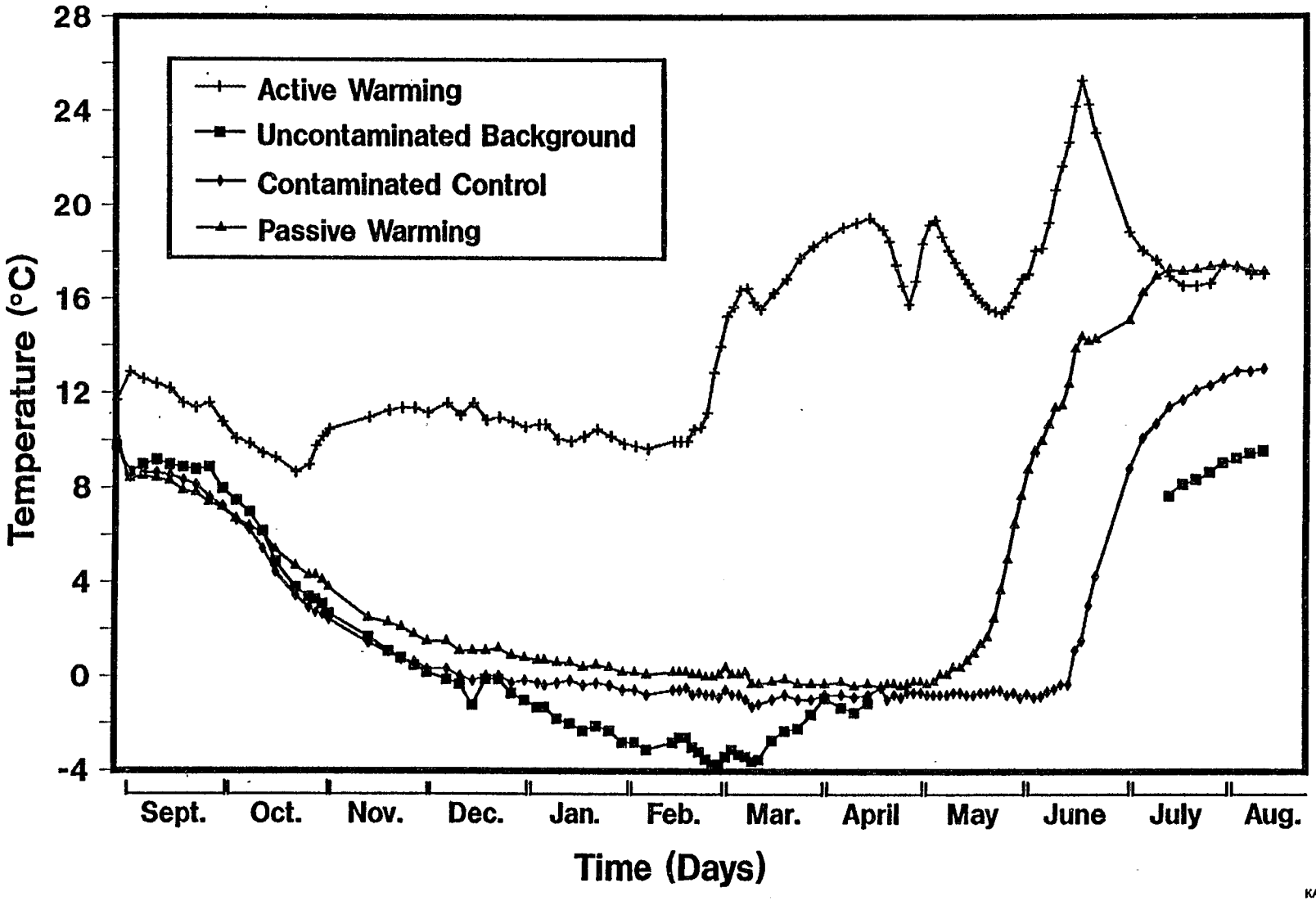


Oxygen Concentration in Three Test Plots and Background

August 22, 1991 to July 11, 1992



Soil Temperature in Three Test Plots and Background



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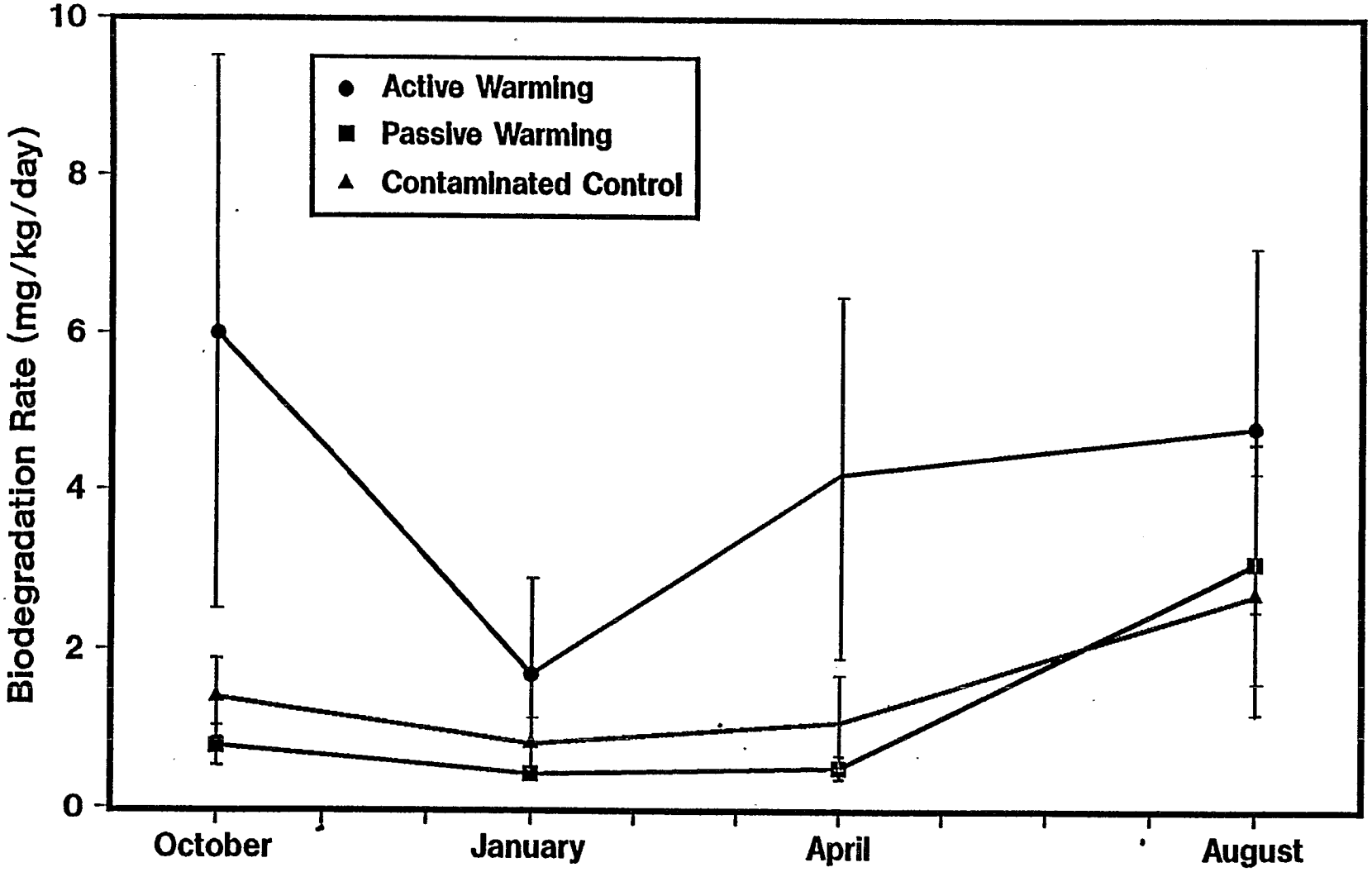
Biodegradation Rates at Eielson AFB



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Eielson AFB: Conclusions

- Active soil warming is successful
- Optimization of active heating and aeration necessary
- Passive solar heating looks very promising
- Biodegradation via bioventing is occurring year-round in all plots

BIO-REM, INC.'S AUGMENTED IN SITU SUBSURFACE BIOREMEDIATION PROCESS (TM) USING BIO-REM, INC.'S PROPRIETARY BIOCULTURES (H-10) FOR THE REMEDIATION OF JP-4 CONTAMINATED SOILS AT WILLIAMS AFB, AZ

In 1987, ten 25,000 gallon JP-4 aviation jet fuel tanks were removed from the Primary Fuels Storage Area at Williams AFB, AZ. Extensive contamination was discovered; laboratory analysis revealed contaminant levels in excess of 88,000 ppm of JP-4, and the site was closed and subsequently placed on the National Priority List (Superfund List) for future clean-up. In August of 1991, after the base had been listed for closure by the U.S. Government, an award was made for the initial clean-up of the contaminated site, designated as Operable Unit-2 of this Superfund site.

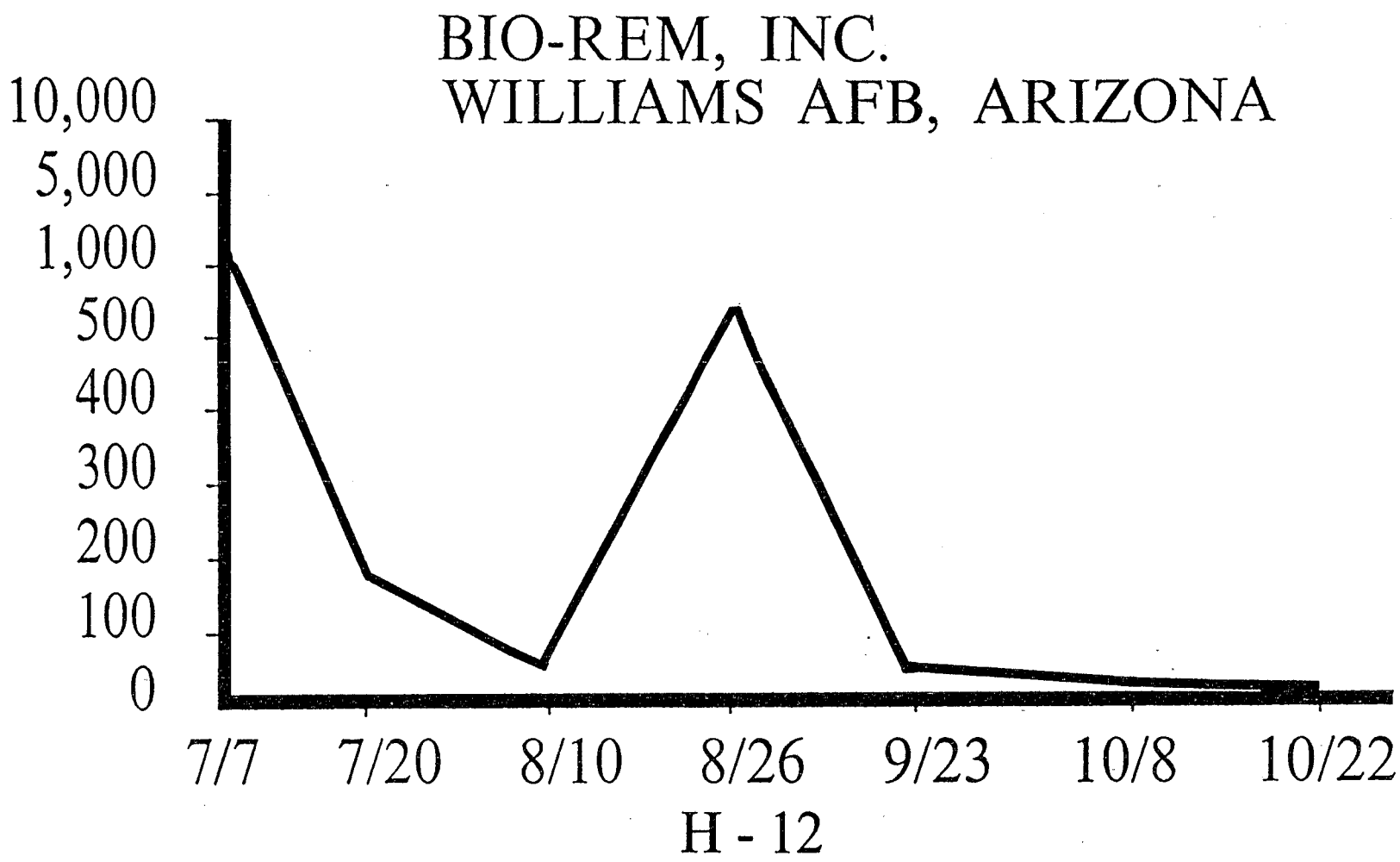
In September of 1991, the clean-up contract was awarded to a construction firm from Stockton, California to excavate and pile-remediate 16,000 cubic yards of JP-4 contaminated soil. However, due to State of Arizona and Maricopa County, Arizona Air Quality standards and regulations concerning volatile organic compound (VOCs) emissions, this methodology was rejected. The Bio-Rem's ***Augmented In Situ Subsurface Bioremediation Process (TM)*** *and* ***Bio-Rem's H-10*** *microaerophilic bacterial cultures were selected to remediate the site.*

REMEDIATION METHOD: The initial stages of the bioremediation of the Fuels Storage Area at Williams AFB, AZ began in April of 1992. Over 320 borings and monitor wells were placed on the site. Bio-Rem ***H-10*** *Product was propagated and subsequently placed into the contaminant plume, through these borings and wells, over a period of ten (10) days. Then the site was covered with plastic sheeting to reduce evaporation.*

I. Technical Information.

A. Description of Technology.

Bio-Rem, Inc.'s Process and Bioculture are commercially available and have been used in over 75 sites in 14 states. The Augmented In Situ Subsurface Bioremediation Process (TM) incorporates four (4) steps in the subsurface bioremediation of hydrocarbon contamination in soil and water. This process occurs totally underground. It utilizes Bio-Rem, Inc.'s Product "H-10", a proprietary blend of microaerophilic bacteria and micronutrients. After placement, Bio-Rem H-10 does not require additional injections of nutrients, oxygen, or oxygen-producing compounds (i.e. hydrogen peroxide). Furthermore, the by-products of the degradation process are naturally occurring elements; therefore, this process complies fully with Title I of the Clean Air Act.


BIO-REM, INC.
WILLIAMS AFB, ARIZONA
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8/10
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BIOREMEDIATION OF SOILS AT A WASTE OIL FACILITY

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U.S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OK 74820

Bioremediation of Soils at a Waste Oil Facility

The Baldwin Waste Oil site is located approximately 1.5 miles north of Robstown, a small town near Corpus Christi, Texas. Site weather is typical of Gulf Coast conditions: the summers are hot and humid, and winters are mild with frost conditions averaging about seven days each year. The site, an abandoned waste oil facility occupying slightly more than one acre, is surrounded by agricultural lands. The north half of the facility is occupied by two tank farms surrounded by earthen containment dikes and a caliche drive. The south half is a low area with vegetation and debris, bordered on three sides by a drainage ditch located just inside the property line. A small pond filled with sludge and water is located beside one group of tanks. Oil, water, and sludges were located in fifteen large storage tanks, five 55 gallon drums, numerous small containers and two containment berms surrounding the two groups of storage tanks. Areas between the tanks are covered with a sludge layer.

During operation, the facility received a large portion of its waste oil from the local navigation district ballast pits, used to store waste oil collected from slop tanks of ocean-going oil tankers. Waste oil was transported to the site and pumped into one of several mixing tanks where the oil was blended with solvents (benzene, toluene or xylene) for resale.

The native soil at the site is the Victoria clay. Characteristics of this clay material include: low permeability, high water-holding capacity, high compressibility, high to very high shrink-swell potential, poor drainage, low to depressed relief, low shear strength, and high plasticity. A particle size analysis of the Victoria clay soil indicated a sand content of 43%, a silt content of 10%, and a clay content of 46%. A caliche fill material, classified as a silty clay, is also present. Particle size analysis of the caliche material indicated a sand content of 53%, a silt content of 10%, and a clay content of 36%. Analysis of soil samples indicated levels of benzene, ethylbenzene, toluene, xylene (BTEX) of 50 ppm or less; elevated levels of lead, chromium, barium, arsenic, and total petroleum hydrocarbons.

The remedial plan for the site provided for removal of tanks, barrels, buried piping, debris and sludges. However, approximately 1500 to 2200 cubic yards of contaminated soils that had been under an oily sludge layer on the tank farm area remained to be disposed. This soil contained levels of total petroleum hydrocarbons up to 50,000 ppm. Treatment processes considered for the soil included incineration or in-situ bioremediation based on the land treatment concept. Bioremediation technology was chosen for pilot testing to determine the feasibility of the innovative use of this technology in-situ during the removal action. The treatment goals to be achieved during the removal program are concentrations of less than 1% oil and grease (O&G) and 10,000 mg/kg total petroleum hydrocarbons (TPH).

Bioremediation based on the land treatment concept involves use of natural biological, chemical and physical processes in the soil to transform organic contaminants. Biological activity apparently accounts for most of the transformations of organic contaminants in soil. Bioremediation is carried out by utilizing techniques for enhancing the development of the microorganisms and bringing them in contact with the contaminants. Conventional land treatment has been shown in a number of instances to be a viable treatment alternative for soils contaminated with oils and hydrocarbons. However, there was some concern that compounds or elements might be present at the Baldwin site which could inhibit microbial activity in a land treatment unit. Laboratory tests conducted by Dr. Alan Harker of the University of Oklahoma indicated the presence of a population of active petroleum hydrocarbon degrading microorganisms, so it was decided to conduct a pilot scale land treatment study in the field.

The pilot scale land treatment system was designed to evaluate the feasibility of utilizing in-situ remediation of the contaminated soils. Objectives of the pilot scale demonstration were to:

1) Demonstrate the efficacy of in-situ bioremediation for the oil contaminated soils at Baldwin Waste Oil site under field conditions;

2) Collect statistically defensible data on which to base conclusions of bioremediation efficacy;

3) Identify potential problems in implementing a full-scale bioremediation project;

4) Collect data which will be necessary for the full-scale implementation of in-situ bioremediation at the site.

The pilot system was constructed outside the bermed area so the system could be left in place during removal operations associated with the site tank waste disposal and demolition. A treatment plot approximately 33 feet long and 12 feet wide was constructed with the bottom sloped (about 2-4% slope) toward the middle of the area and about a 1-2% slope toward one end. A two foot berm was provided to prevent any run-on or run-off from rain or irrigation. A high density polyethylene liner was anchored within the bermed area and covered with five inches of pea gravel and eight inches of sand to allow for drainage and help protect the liner during tilling of the unit. A slotted PVC pipe was installed down the medial axis of the plot for leachate collection.

The two contaminated soil types (the native clay and caliche fill material) were kept separate in the treatment plot in order to determine the effect of soil type on treatment management and efficacy. For sampling, the plot was divided into six cells (6 ft. by 10 ft.), with three cells representing each of the two soil types. The north side of the treatment unit (cells NW, N, NE) contained the caliche material, and the south side of the treatment unit (cells SW, S, SE) contained the native clay material. An eight inch thick layer of each contaminated soil was placed on the plot, and two inches of composted chicken manure was tilled into the soil for conditioning and as a source of nutrients. The manure contained about 11,000 ppm EDTA extractable phosphate phosphorus, 30,000 ppm EDTA extractable potassium, 2.4 % total kjeldahl nitrogen (TKN), and 14% total organic carbon. Nutrient content of the amended soil is shown in Table 1. Nitrogen and phosphorus were monitored throughout the study, and fertilizer was added as needed to maintain the appropriate levels of these nutrients. A movable overhead irrigation system was used to add water as needed. Leachate from the pilot unit was collected for analysis.

Samples for the starting concentration (Week 0) were collected after the compost had been tilled into the soil. Samples taken at later sampling times were taken immediately after tilling to aid in sample homogenization. Five evenly spaced subsamples were taken within each cell. These subsamples were mixed to get one composite sample for each cell. Volatile organic compounds were measured on grab samples to minimize loss of the volatile components. The grab samples were taken at three locations in each cell using a soil coring sampler with acetate sleeves.

Week 0 soil samples were analyzed for nutrients, pH, oil and grease (O&G), total petroleum hydrocarbons (TPH), volatile organics (VOC), semi-volatile organics (SVO), polynuclear aromatic hydrocarbons (PAHs) and total organic carbon (TOC) (See Tables 1 - 3 and Figure 1). O&G, TPH, pH, and nutrients also were measured at Weeks 3, 6, 10, 21, 28, 36, 40 and 43 as operational parameters to determine the course of treatment. Once the operational parameters reached a steady state at Week 43, the full suite of analyses was performed to determine the treatment endpoints.

The project was started in November of 1991 since November is normally the beginning of the annual dry season for the Robstown area. However, the rainfall for the next ten weeks was far above normal (Figure 3). The project was proposed to end by the 12th week, but the unusually high and continued rainfall precluded tilling and other operations at the site during this period, so the project was extended. Significant degradation of O&G and TPH occurred during this period even though the LTU was saturated at times. Analyses of leachate from the pilot unit indicated TPH and O&G levels were below detection limits. Treatment levels at the 43rd week were considered acceptable since TPH and O&G concentrations approached or were below the removal program cleanup goals. Volatile organics and semivolatile organics, present at low parts per billion levels at the beginning of the study, were at nondetect levels by the end of the study. Based on reduction of TPH and O&G to cleanup goals and reduction of volatile and semivolatile organics to nondetect levels, in-situ bioremediation based on the land treatment concept has been selected as the remediation alternative for full scale clean up under the removal program.

The pilot scale demonstration study was conducted through the cooperative effort of USEPA Region VI Superfund Program and their Technical Assistance Team contractor (Ecology and Environment, Inc.), and the USEPA Robert S. Kerr Environmental Research Laboratory Subsurface Fate and Transport Technology Support Center and their technical support contractors (Dynamac Corporation).

Table 1. Status Of LTU Soil At Week 0

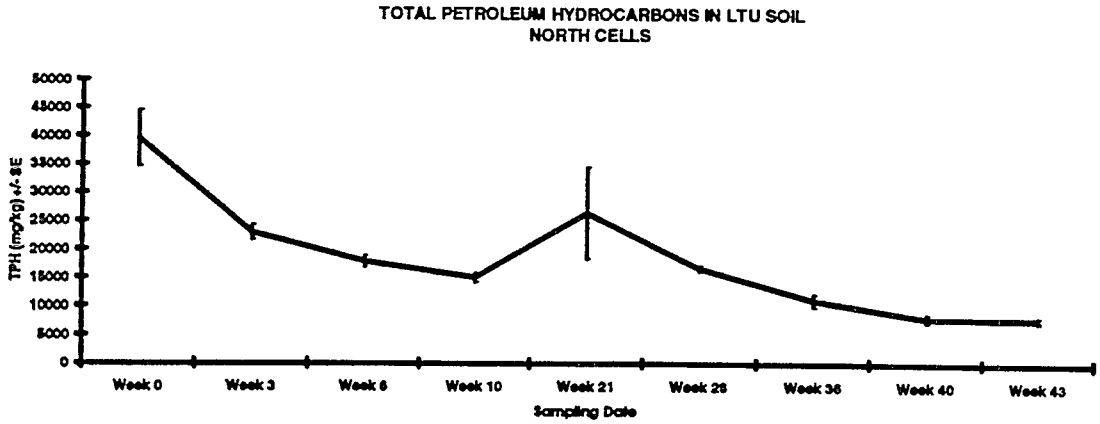
Sample Location (Cell)	Electrical Conductivity mmhos/cm	Total Organic Carbon %	Total Kjeldahl Nitrogen %	Phosphate Phosphorus ppm	Potassium ppm
SW	4.5	1.1	0.06	42.8	1250
S	5.4	2.4	0.20	76.1	1176
SE	5.2	1.1	0.05	68.5	1283
NW	5.4	1.0	0.16	42.4	1144
N	5.1	1.3	0.13	38.0	1048
NE	5.2	1.2	0.13	40.3	1175

Table 2. Total Petroleum Hydrocarbons In LTU Soil

Sample Location	Type	Total Petroleum Hydrocarbons (mg/kg) Week 0	Week 3	Week 6	Week 10	Week 21	Week 28	Week 36	Week 40	Week 43
N		31900	22300	16100	16000	40590	17570	10590	8929	6854
NW		38100	21200	17900	13400	12770	16345	9479	7415	8015
NW	D								6759	6917
NW	R								7007	8426
NE		48700	25400	19500	15600	25750	16090	13120	10240	9264
N Mean		***39567***	***22967***	***17833***	***15000***	***26370***	***16668***	***11063***	***8070***	***7895***
S		14400	7800	5800	4200	6876	6675	4248	5024	3771
SW		14300	25200	7300	4700	4292	9728	4845	4586	2233
SW	D								5761	2707
SW	R								4713	4375
SE		14500	19800	9100	9500	11390	7075	6450	9454	5361
S Mean		***14400***	***17600***	***7400***	***6133***	***7519***	***7826***	***5181***	***5908***	***3689***

Table 3. Oil And Grease In LTU Soil

Sample Location	Type	Oil and Grease (% Dry Weight) Week 0	Week 3	Week 6	Week 10	Week 21	Week 28	Week 36	Week 40	Week 43
N		5.8	2.5	3.5	5.2	5.1	2.1	1.9	1.2	1.2
NW		8.6	2.6	2.5	2.4	2.0	1.9	1.9	1.0	1.3
NW	D								0.8	1.2
NW	R								0.9	1.6
NE		8.4	4.1	2.7	3.0	3.5	2.0	2.2	1.4	1.6
N Mean		***7.6***	***3.0***	***2.9***	***3.5***	***3.5***	***2.0***	***2.0***	***1.0***	***1.4***
S		2.1	0.9	1.6	0.9	1.5	0.8	1.4	0.5	0.7
SW		3.8	2.9	1.4	2.6	1.0	1.2	1.2	0.6	0.6
SW	D								0.7	0.7
SW	R								0.5	0.9
SE		2.4	2.3	1.5	1.9	1.9	1.3	1.5	1.3	1.0
S Mean		***2.7***	***2.0***	***1.5***	***1.8***	***1.4***	***1.1***	***1.3***	***0.7***	***0.8***



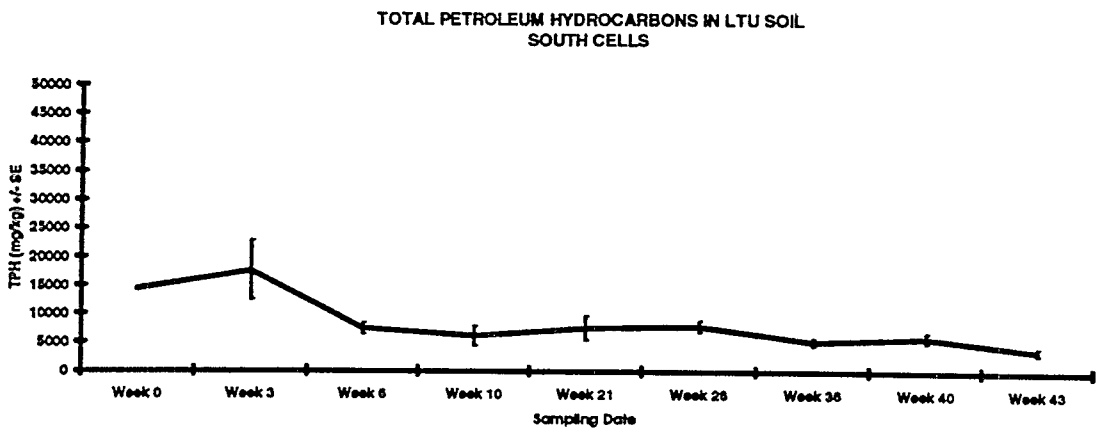
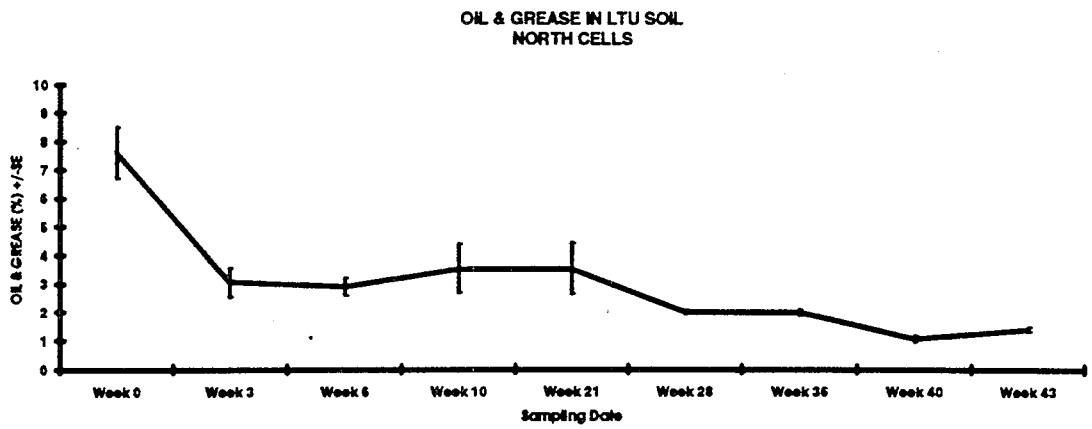


Figure 1. TPH in LTU Soil.



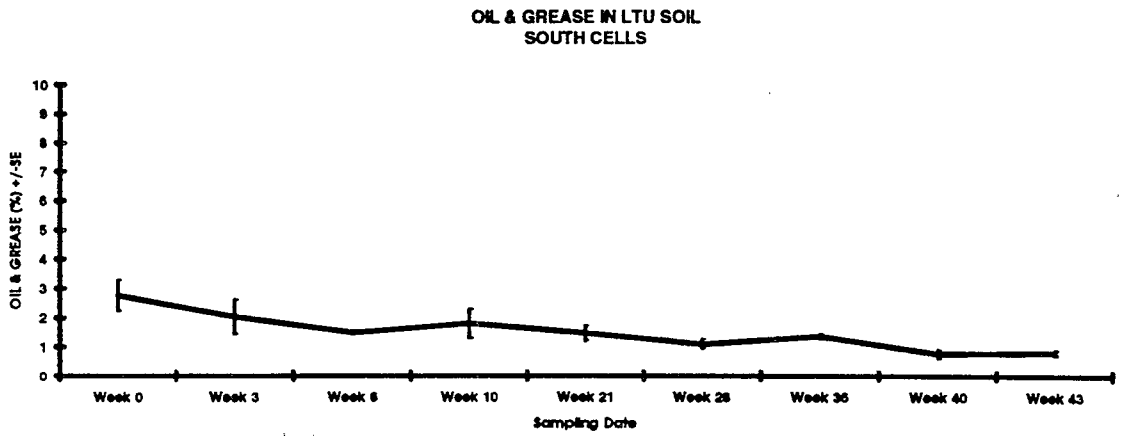


Figure 2. % O&G in LTU Soil.

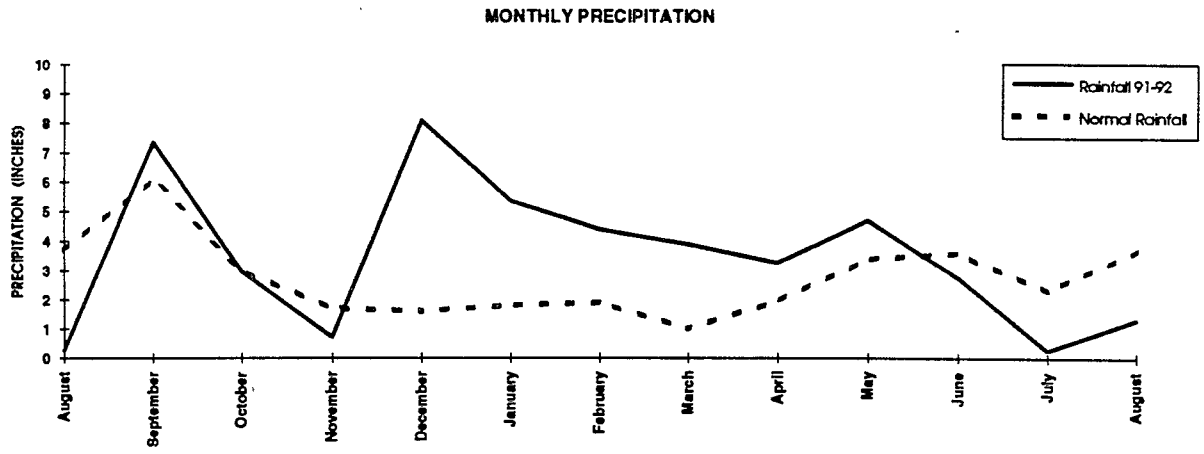


Figure 3. Rainfall During the Pilot Study.

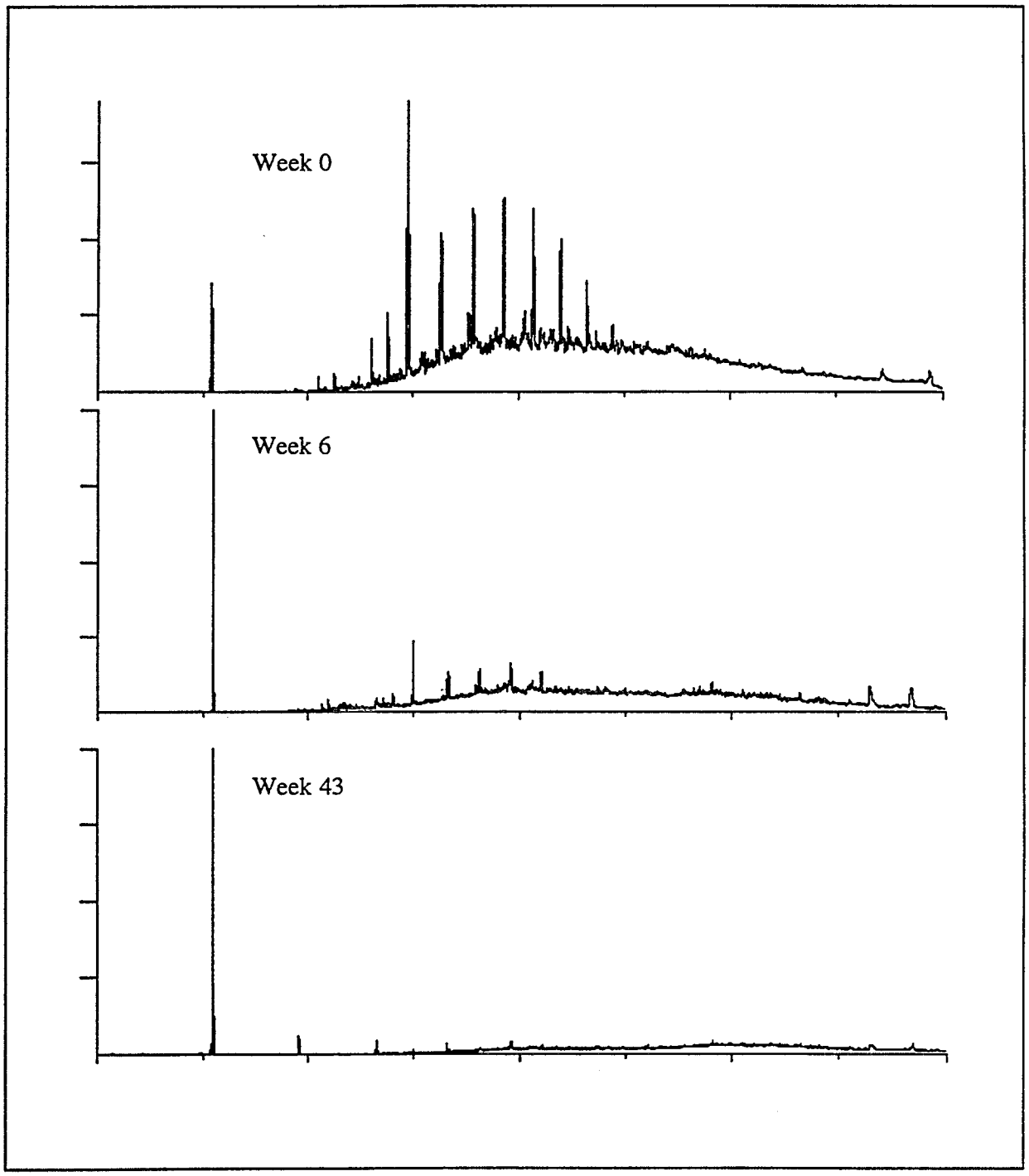


Figure 4. Gas Chromatography Chromatogram of a Hexane Extract of Treated Soil.

Low Temperature Thermal Treatment LT^3 Site Demonstration

By Michael G. Cosmos, P.E.

Roy F. Weston, Inc.

The LT^3• was used as part of a full-scale demonstration and to perform the clean up of wastewater lagoon at the Anderson Development Company Superfund Site located in Adrian, Michigan. The contaminate of concern in the lagoon was 4,4' methylene bis 2-chloroaniline commonly known as MBOCA. Roy F. Weston, Inc. (WESTON•) of West Chester, PA, was contracted by Anderson Development Company to perform the remediation of the lagoon and underlying soil. WESTON employed its patented (Patent No. 4,738,206) Low Temperature Thermal Treatment System (LT^3) to treat the material. As part of the consent order Anderson Development Company and WESTON prepared a Remedial Action Plan, Health and Safety Plan and Quality Assurance Project Plan.

Following approval of these plans by United States Environmental Protection Agency (US EPA) Region V and Michigan Department of Natural Resources, a demonstration test was conducted as part of the US EPA Superfund Innovative Technology (SITE) program. A rigorous testing program was conducted on eight process streams. The process streams were sampled and analyzed for volatile organics, semivolatile organics, metals, dioxin and furans. In addition, the stack emissions were sampled for particulate and hydrochloric acid to determine if regulatory criteria were met.

Contaminate of Concern

MBOCA is a chemical intermediate used in the production of high-tech plastics and urethane foams. MBOCA which is insoluble in water is a semivolatile with an extremely low vapor pressure. MBOCA was present as a result of previous disposal operations. The lagoon covered approximately 2 acres. The MBOCA was present in the sludge and underlying naturally occurring clay in concentrations up to 1,600 ppm. A cleanup criteria

of 1.6 ppm of MBOCA was established as the result of site specific risk analysis.

In addition to the contaminant of concern, the lagoon sludge also contained trace amounts of other organic compounds including dichlorobenzene and toluene. The sludge also contained a high concentration of manganese potassium permanganate which was added during previous operations to oxidize the organics present in the lagoon.

LT^3 System

The LT^3 process is based upon indirect thermal heat exchanger. The screw type processor is used to dry and heat the soil causing volatilization of the contaminates and moisture. The process is capable of heating of the soils up to 580°F as was demonstrated during the remedial activities at Anderson Development Company. By maintaining a constant exhaust from the processor the evaporated water and organics are removed. The vented gases are subsequently treated in a series of condensers. The condensers remove the bulk of the evaporated moisture. The vapor stream is then treated by carbon adsorption packs and exhausted to the atmosphere. The liquid phase generated in the condensers consists of water and chemicals from the soil. The condensate is treated and either recycled as quench water for the processed soil or shipped to an off-site treatment facility.

The LT^3 is divided into three main processing areas: solids processing, emissions control and wastewater treatment. A schematic diagram of the system is shown in Figure 1. The general arrangement of equipment is shown in Figure 2. The LT^3 equipment used on the Anderson Development Company was mounted on three tractor trailers. The equipment remained mounted on the trailers throughout operations.

Solid Handling System

The excavated soil and dewatered sludge from the lagoon was transported by track loader to a double deck vibrating screen to remove debris greater than 2 inches. The screened

material was then stockpiled. A wheel loader removed the screened soil from the stockpile and fed the surge hopper. The wheel loader passed over a registered weigh scale to determine total quantity of material treated. The surge hopper is maintained full to form a seal at the inlet to the thermal processor

The thermal processor is constructed of two jacketed screw conveyors. The jacket and screws are constructed with double walls that allow the circulation of a high temperature heat transfer fluid. Each screw conveyor consists of four parallel intermeshed screws. The two units are constructed in piggyback fashion. Intermeshing screws allow for improved heater transfer and breaking up of soil. The high clay content soil at Anderson Development Company did not cause balls to be formed. The screw conveyors are driven by a variable speed drive which allows adjustment in soil discharge temperature and residence time. During operations at Anderson Development Company the soil was maintained at temperatures above 540°F and residence times of 90 minutes.

The treated soil is discharged into a mixing screw conveyor. The mixing screw conveyor is a ribbon flight conveyor where water is injected to quench and wet the soil. The material is then stacked with a belt conveyor into daily storage piles.

Emissions Control

The volatilized organics and water from the LT^3 are removed and passed through the pollution control system. The exit gas which is typically maintained at 300°F. The gas is drawn through a pulse-jet type baghouse dust collector. The dust collector removes particulate matter. On a daily basis two to four drums of "fly ash" or dust are generated. The gases are then drawn into an air cooled condenser. The air cooled condenser is a tube type heat exchanger that uses force ambient air to indirectly cool the exhaust gases. Temperatures exiting the air cooled condenser ranged from 125°F in summer to 40°F in winter. The cooled exhaust gases then are drafted into a refrigerated condenser. In the refrigerated condenser the exhaust gases are indirectly cooled to 60°F by a recirculating

glycol and water solution. The glycol and water solution is maintain at 30°F by a refrigeration system. The exhaust gases are subsequently heated to 70°F by three inline electric resistance heaters. By heating the exhaust gases to 70°F the relative humidity of gas is reduced to 70% preventing condensation in process piping and enhancing carbon adsorption efficiency. The final emission control device is the carbon adsorption column. Two standard carbon rental packs are used to treat the emissions prior to release. One system is on line at all times. The second carbon pack is activated automatically if breakthrough occurs.

Monitoring of the pollution control system effectiveness is provided by a Continuous Emission Monitoring system (CEM). The CEM is used to monitor the exhaust stack for concentrations of oxygen, carbon dioxide, carbon monoxide and total hydrocarbons. The system also monitors the exhaust gases from the baghouse dust collector for oxygen and total hydrocarbons.

Wastewater Treatment

The two condensers generate a liquid stream. The liquid consists primarily of water, however, it also contains heavier organics. On the Anderson Development Project a simple overflow decanter was used to separate out heavy condensate that contained high levels of the insoluble MBOCA. The overflow was then filtered to remove entrained heavy. The water was then treated by two carbon packs in series and stored in a 6,000 gallon tank. The water at the Anderson Development project was then shipped off-site to an industrial waste waster treatment plant for disposal.

Utilities

The operation of the LT^3 requires the utilities which included 480 Volt electrical power, natural gas and potable water. At previous operations the LT^3 has used propane as a fuel.

SITE Demonstration

The SITE demonstration was conducted in December 1991 on dewatered sludge from the lagoon. The Application Analysis Report and results of the testing are currently undergoing internal EPA review and are expected to be released shortly. The emission data from this test have shown considerable control of organics and other pollutants.

The particulate emission was on average less than 1.1×10^{-4} grains per dry standard cubic feet. Similarly control of acid emissions were less than 6.0×10^{-5} pounds per hour. Exceptional control of acid gases was expected since the LT[3] is a desorption process and not expected to generated destruction or combustion of chlorinated compounds.

The emissions of volatile organics were measured by a VOST sampling train. The total non methane organic emissions were only 8.9×10^{-3} pounds per hour. Measurements of volatile organics entering and exiting the carbon column demonstrated 95% removal of the volatile organics by the carbon unit. Similar measurements on semivolatile organic compounds using a Modified Method 5 sampling train demonstrated only 3.86×10^{-5} pounds per hour of detectable semivolatile organics. The inlet and discharge streams of semivolatile organics were used to measure a 98.4% removal of semivolatiles in the carbon bed.

Stack sampling using a Method 23 sampling train was also completed to determine the emission of dioxins and furans. The emission of 2,3,7,8 TDCF and 2,3,7,8 TCDD were both less than detection at $<2.1 \times 10^{-3}$ and $<3.4 \times 10^{-3}$ ng/dscm, respectively. The total emission of TCDF was $< 3.0 \times 10^{-3}$ ng/dscm and total TCDD was determined to be $1.1 \times {}^{-1}$ ng/dscm.

For further information, please contact Michael G. Cosmos, P.E., Project Director at (215) 430-7423 or Adolfo G. Murphy, Principal Project Manager at (215) 344-3724.

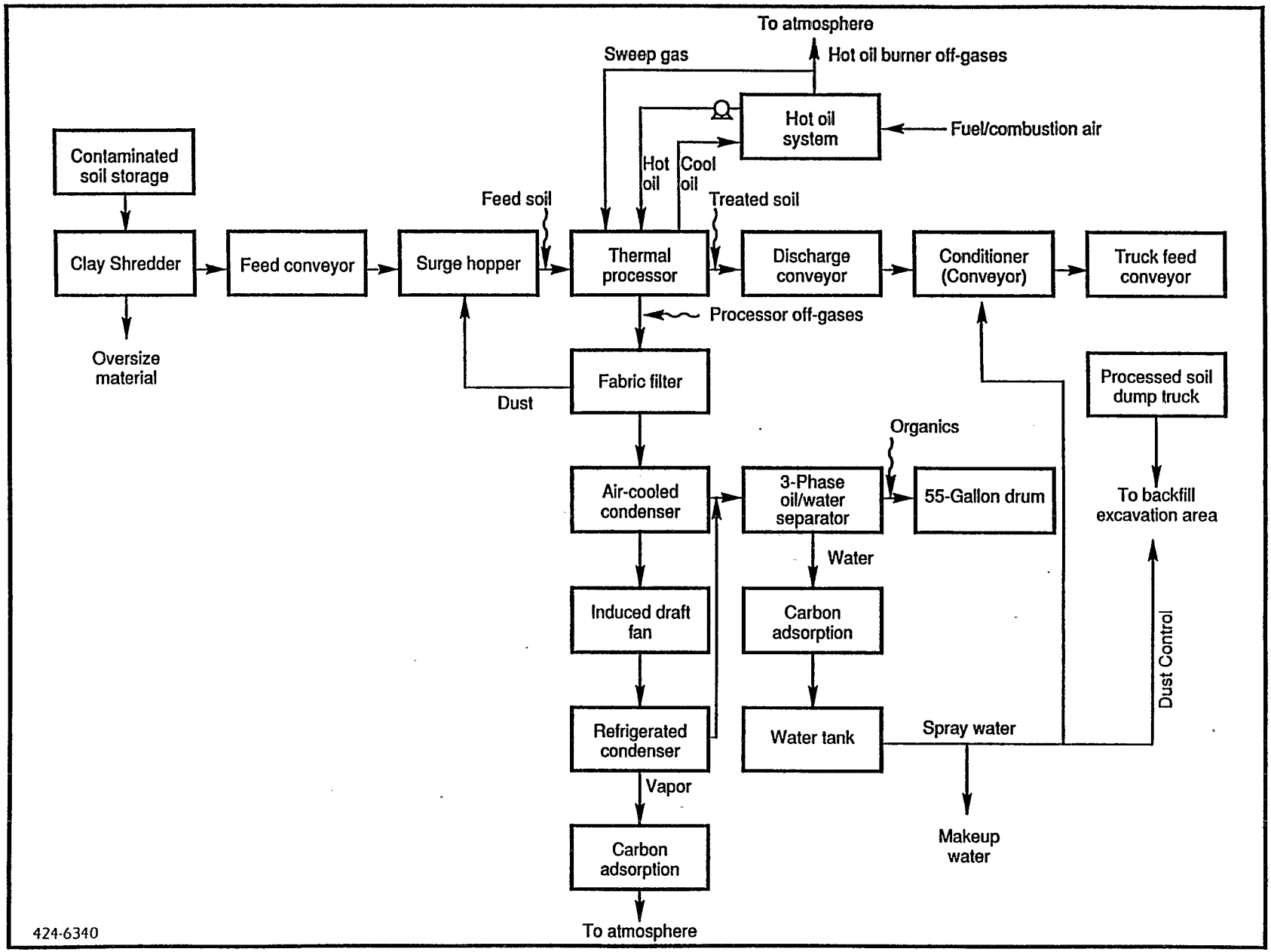
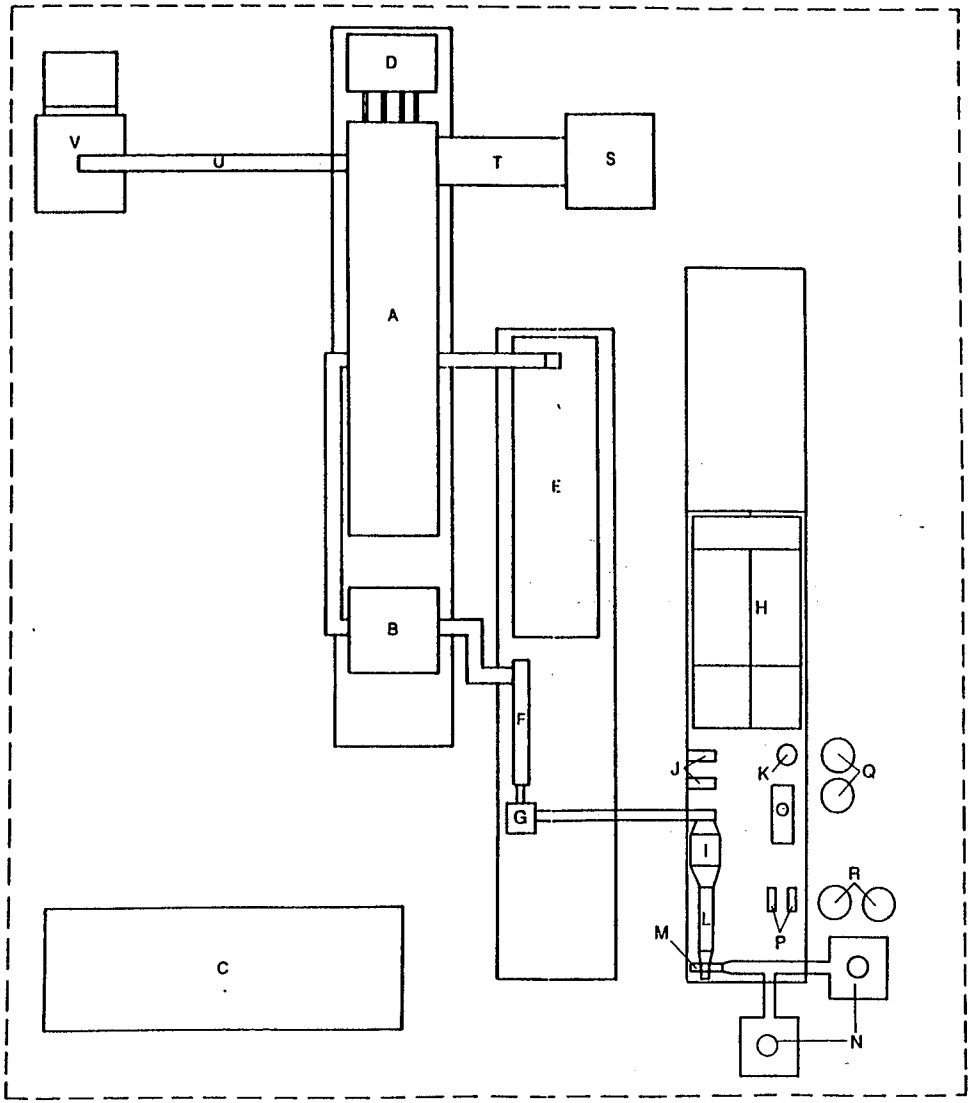


FIGURE 1 SCHEMATIC FLOW DIAGRAM OF THE LT^3® PROCESS



Equipment

A. Thermal Processors
B. Fabric Filter
C. Process Control Trailer (Office)
D. Thermal Processor Drive Units
E. Hot Oil System
F. Air-cooled Condenser
G. Induced Draft Fan
H. Refrigerated Condenser
I. Vent Condenser
J. Glycol/Water Pumps
K. Glycol/Water Reservoir
L. Heater
M. Vapor Fan
N. Vapor Phase Carbon Columns
O. Oil/Water Separator
P. Liquid Phase Carbon Pumps
Q. Organic Collection Drums
R. Liquid Phase Carbon Columns
S. Clay Shredder
T. Drag Conveyor
U. Discharge Conveyor
V. Dump Truck

FIGURE 2 GENERAL ARRANGEMENT OF LT^3® SYSTEM

PLASMA ARC VITRIFICATION

Richard C. Eschenbach, Retech, Inc.

Abstract: The paper updates results obtained with Retech's Plasma Centrifugal Furnace (PCF) process for treating hazardous waste. Data from three SITE Demonstration tests with a PCF-6 in Butte, Montana, are reported, as well as activities in Europe.

Process Concept: The Plasma Centrifugal Furnace (Figure 1) is a thermal technology that uses heat generated from a plasma torch to treat hazardous waste containing metals and/or organics. Metal-bearing solids and soil are melted by the process, and organic contaminants are thermally destroyed. The molten material forms a hard, glass-like leach-resistant mass after cooling in a mold. The major elements of the process are the feeder, plasma torch, rotating reactor well, afterburner, secondary combustion chamber, and off-gas treatment system.

The process operates as follows: contaminated soil is placed in a bulk screw feeder and gradually fed into the rotating reactor well. Solid material is retained in the well by centrifugal force while a plasma arc heats the material in an enriched oxygen atmosphere to temperatures sufficient to melt soil (typically on the order of 3000°F). At this temperature organic contamination is volatilized and burned. Any incompletely burned gases or products of incomplete combustion formed are incinerated by an afterburner located downstream of the reactor well. Once a sufficient amount of feed material has been treated, the rotating well is slowed, and the molten mass flows through a secondary chamber into a slag collection chamber.

Initial tests with a lab-size Plasma Centrifugal Furnace having an 18" diameter (=1.5 ft.) centrifuge (i.e. PCF-1.5) were conducted in the fall of 1987. Leach tests showed that the vitrified material which solidified in the tub upon run termination was extremely leach-resistant (1).

The encouraging results from the lab-size unit led to acceptance of the Retech process into EPA's second Superfund Innovative Technology Evaluation (SITE) solicitation in 1988.

In order to meet EPA's desire for a demonstration, rather than development project, Retech designed and built a larger unit with a six foot diameter centrifuge (PCF-6). In all PCF's, the centrifuge is located inside a double-walled, water-cooled shell which can withstand substantial positive or negative pressures without leakage. The PCF process is covered by two U.S. patents (2).

Test Setup at Butte, Montana

Construction of the PCF-6 was completed in March of 1989, and a preliminary test, supported by the EPA, was conducted at Ukiah April 25, 1989 with monitoring by Radian. The test disclosed problems with the feeder and SCC temperature. Modifications were made, and ten additional shakedown runs were made in Ukiah in May before the furnace was disassembled and shipped to Butte.

The Component Development and Integration Facility (CDIF) of the U.S. Department of Energy, in Butte, MT was picked as the test site for three main reasons: 1) Butte had a Superfund location with pentachlorophenol contaminated soil leaving a high content of heavy metals - this combination is readily treated with the PCF, 2) there was vacant lab space at the CDIF with good support facilities, and 3) at that time the CDIF was under the administrative supervision of the Idaho National Engineering Lab (INEL) and INEL was interested in evaluating the utility of the PCF for treating several different types of problem wastes at INEL.

About thirty shakedown tests were performed by MSE personnel between October 1989 and June 1991 (MSE, Inc. is the M&O contractor for DOE at the CDIF). Results of some of the shakedown tests have been reported (3).

During these shakedown tests, modifications were made to the original system design. These modifications included the installation of an afterburner in the secondary combustion chamber, the installation of a chiller on the gas treatment system to compensate for this additional heat input, and the elimination of the surge tank. In June the Environmental Assessment was approved by both DOE and the EPA, and the SITE tests were scheduled for the week of July 22, 1991.

The waste selected for treatment consisted of heavy metal-bearing soil from the Silver Bow Creek Superfund site mixed with 10% by weight No. 2 diesel fuel. The mixture was spiked to provide 28,000 ppm of zinc oxide and 1,000 ppm of hexachlorobenzene.

Zinc was added as a tracer to determine the leachability of the slag and the hexachlorobenzene was the Principal Organic Hazardous Constituent (POHC) used to determine organic Destruction and Removal Efficiency (DRE).

The entire process was controlled on the first level at a central control panel. Here the torch operator, aided by T.V. monitors, controlled the screw feeder and the position of the torch. Cameras were installed in viewports attached to the primary chamber. All process parameters were monitored by an automated Data Acquisition System (DAS) which collected information every 30 seconds. Auxiliary equipment was monitored by MSE personnel performing visual inspections and recording data every 30 minutes.

On Monday, 22 July 1991, furnace preheat started at 9:05 a.m. and feeding of the first load commenced at 1:10 p.m. Four loads were fed, a pour was made (277 pounds) and operations were shut down. On Wednesday, 24 July 1991, furnace preheat started at 8:20 a.m. and feeding of the first load commenced at 11:20 a.m. Exhaust fan problems limited the number of soil loads to three (265 pounds of slag poured). On Friday, 26 July 1991, furnace preheat started at 8:20 a.m. A water leak from the torch protective sleeve interrupted the preheat; repair required three hours. Preheat was again initiated at 12:40 p.m. and feeding of the first load started at 3:50 p.m. Five loads were fed; feeding of the fifth load was completed at 9:06 p.m. The melt was poured (595 pounds) starting at 9:23 p.m.

As part of the SITE Program, a sampling strategy was designed and employed to evaluate the performance of the Plasma Centrifugal Furnace technology developed by Retech, Inc. Samples were collected in accordance with the "Demonstration Plan for Plasma Centrifugal Furnace Technology" (4). Minor changes to the original sampling plan were made. Figure 2 presents a schematic of the sampling locations for the Demonstration Tests.

A somewhat more complete summary of the test procedure and the result was given at the 1992 Incineration Conference (5). The detailed final report appeared in two volumes (6, 7). An Applications Analysis Report has also been issued by the EPA (8).

After the three SITE tests were completed, the PCF-6 at Butte was used to treat surrogates of wastes now at INEL. These tests have been summarized by MSE (9).

Test Results at Butte

The Destruction and Removal Efficiency (DRE), used to determine organic destruction, was determined by analyzing the feed soil and the stack gas for the Principle Organic Hazardous Compound (POHC). For these tests, the POHC was hexachlorobenzene, which is harder to destroy than PCB's. The estimated mean level of hexachlorobenzene, based on all the feed soil samples for the three tests was 972 ppm. The 95% confidence interval for the estimated mean was 864 to 1,080 ppm. No hexachlorobenzene was detected in the stack gas; therefore, all DREs determined are based on the detection limit from the appropriate tests. Table 1 gives the 95% confidence interval for the DREs based on the confidence interval of the feed soil and the detection limit for the particular test.

Table 1

DRE Results for Demonstration Tests

Hexachlorobenzene	Test 1	Test 1 Duplicate	Test 2	Test 3
Lower 95% Confidence Interval	>99.9964	>99.9982	>99.9990	>99.99989
Mean	>99.9968	>99.9984	>99.9991	>99.99990
Upper 95% Confidence Interval	>99.9971	>99.9986	99.9992	99.99991

As can be seen from Table 1, the estimated average DRE values for these tests ranged from >99.9968% to >99.9999% for a highly chlorinated compound, hexachlorobenzene. It can be reasonably assumed that this level of DRE (if measurable) can be achieved for most chlorinated or halogenated compounds.

Throughout each of the three Demonstration Tests, CO, CO_2, O_2, NO_x, and total hydrocarbons (THC) were monitored continuously to present a real time image of the combustion process and to determine if regulatory standards were being exceeded. MSE, Inc. also monitored the same combustion products for DOE during shakedown tests and other testing of the PCF.

Since the installation of the afterburner in the secondary combustion chamber, the level of total hydrocarbons exiting the system has been low (<4 ppm) even with at least 10% organics in the feed soil.

This gives a good indication that effective thermal destruction of the organic compounds is occurring. Another indication of the ability of the process to treat organic contaminated media is the low level of CO in the exhaust (approximately 1.4 ppm) and the level of CO_2 (approximately 8%). O_2 monitors show significant variation throughout the treatment process as pure O_2 is fed to the primary chamber at approximately 18 scfm while waste is being fed to the furnace.

The PCF is designed to encapsulate inorganic compounds in the vitrified slag and render the treated soil nonleachable. Testing activities have demonstrated that the process can effectively bind inorganic compounds into the treated soil. The Toxicity Characteristic Leaching Procedure (TCLP) was performed on both the feed soil and the treated soil (i.e. slag). The feed soil was tested to ensure that the material was leachable for organic and inorganic compounds. The vitrified slag underwent TCLP to meet the testing objectives.

TCLP analysis of the feed soil for metals showed that the only elements which exhibited significant leachability characteristics were calcium and the spiked zinc. The results of the TCLP metals analysis of the feed soil are summarized in Table 2. The presence of sodium in the leachate is not unexpected because of its high concentration in the soil and the fact that, unlike other metals, it will have an affinity to go into solution. If the solution is even slightly acidic (as in the TCLP) this phenomenon is enhanced. None of the eight RCRA characteristic metals found in the feed soil leachate were above the regulatory limit, therefore, the evaluation of the leachability of the vitrified slag was based on calcium and zinc.

Calcium was chosen, in addition to zinc, because of its tendency to leach from the feed soil. During the Demonstration Tests, sodium was not used in evaluating the soil leachability because it is not typical of regulated TCLP metals.

The treated soil TCLP metals analysis is also shown in Table 2. None of the metals, with the exception of sodium, show any strong characteristic for leaching. Sodium is probably present in the leachate for the reasons stated above and is not considered in this evaluation. Both tracer metals, calcium and zinc, showed significant reductions in leaching properties in the treated soil as compared to the feed. In fact, all of the metals with the exception of aluminum and iron showed reduced leaching characteristics. The leachability for the aluminum in both feed and treated soil is low and the values reported for the treated soil are only estimates (less than the quantity limit).

Therefore, it is quite probable that the leachability of aluminum from the feed soil to the treated soil did not change. The apparent increase in leachability of iron in the treated soil occurred is because approximately 100 pounds of mild steel was placed in the furnace to aid in initiating the arc. This considerably increased the iron content of the slag in comparison to the feed soil.

The only organic constituents that were found to be leachable from the feed soil were 2-methylnaphthalene and naphthalene. Although the feed soil was spiked with a high level of hexachlorobenzene (1000 ppm), it did not leach from the soil. No organic compounds were found to leach from the treated slag.

The Toxicity Characteristic Leaching Procedure requires samples to be ground into small particles. In this manner, a large amount of surface area is available for leaching. Since the PCF produces a monolithic slag after treatment, the surface area per pound of treated soil is much smaller than that for the TCLP test. The TCLP results, therefore, present a conservative assessment of the actual leachability of the monolithic slag.

Table 2

TCLP Results for Demonstration Tests

Compound	Average Feed Soil Leachate Concentration (mg/L)	Treated Soil Leachate Concentration			
		Test 1 (mg/L)	Test 2 (mg/L)	Test 3 (mg/L)	Regulatory Limit* (mg/L)
Metals:					
Aluminum	0.23 J	0.45 J	0.41 J	0.32 J	NR
Barium	0.14	0.08	0.08	0.07	100.0
Cadmium	0.07	ND	ND	ND	1.0
Calcium	175	2.1 J	2.5 J	2.05 J	NR
Copper	4.6	0.15	0.35	0.3	NR
Iron	0.06	2.5	2.95	31.1	NR
Magnesium	8.12	ND	ND	ND	NR
Manganese	4.82	0.06	0.06	0.24	NR
Nickel	0.02	ND	0.01 J	0.1	NR
Potassium	4.57	ND	ND	ND	NR
Sodium	1475	1500	1400	1400	NR
Vanadium	0.1	ND	ND	ND	NR
Zinc	982	0.45	0.36	0.3	NR
Semivolatiles:					
Napthalene	0.397	ND	ND	ND	NR
2-Methylnaphthalene	0.282	ND	ND	ND	NR
Hexachlorobenzene	ND	ND	ND	ND	0.13

ND - Not Detected
NR - Not Regulated
* - 40 CFR (07/01/90 Edition) §261.24, Table 2
J - Estimated result (less than five times the detection limit)

Note that slightly less than half the zinc was captured in the slag. If the scrubber had been effective, the zinc not captured when charged could have been subsequently re-charged.

The post-test scrubber liquor did not contain any significant quantities of organic compounds. Nitrated compounds and phthalates were the only compounds present. The nitrated compounds were most likely produced from the high levels of NO_X in the exhaust gas reacting with the water from the scrubber and any organic compounds present.

The phthalates and volatile organic compounds probably entered the scrubber sump from the scrubber make-up liquor.

The lack of organic compounds in the scrubber liquor and, as stated earlier, the absence of volatile or semivolatile organic compounds in the exhaust gas, indicates that combustion of the organic compounds was complete.

The scrubbing unit was very inefficient in the capture of the inorganic compounds. The scrubber did capture some of the volatile metal elements but not at the levels that would typically be expected from a well-designed system. As stated previously, the exhaust gas contained a variety of metals that should have been captured by the scrubbing unit. The types of metals found in the scrubber liquor were similar to those found in the stack gas; that is, arsenic, iron, and zinc were the elements in abundance. High sodium levels found in the liquor were probably a consequence of the scrubber make-up (sodium hydroxide).

Results of the tests run by MSE for DOE after the SITE tests again showed excellent TCLP results. Cerium was added as a surrogate for radioactive compounds found in some INEL wastes; the mass balance for cerium was inconclusive since less than half the feed cerium was accounted for (9). Additional tests are planned.

Other Applications

In 1989 a Swiss firm, MGC Plasma ordered a PCF-8 furnace which was installed in the summer of 1990 in Muttenz, a suburb of Basel (10). A gas cleanup system built by Ceilcote was installed to permit the effluent to meet the very strict Swiss standards. The furnace has a very unique charging system: whole drums are inserted, five at a time, into a drum-feeder chamber. A drum manipulator clamps the lid of the lead drum and holds the drum in the furnace while an auxiliary cutting device opens up the drum to dump the contents gradually into the furnace. There have been some problems with this feeder and a different feed system is under construction.

Retech is currently designing three more systems for three European customers. One is a PCF-8 for treating soil contaminated with military wastes. Most of the PCF feed in this application will arrive from a soil-washing process which will enable at least 90% of the contaminated soil to be returned as "clean" soil.

The second is a PCF-8 for treating low/intermediate level radioactive wastes. In this application, three categories of feed will be charged to the furnace - organic liquids, combustible solids and metal waste. All three categories will come to the furnace in 200 liter drums.

The third project is a smaller furnace, a PCF-2, which will be used to test first radioactive surrogates, then radioactive mixed wastes. Figure 3 is a schematic of this lab-size furnace.

Acknowledgments
Much of the detail in this report came from the Butte SITE tests, and special thanks are due to the co-authors of the paper summarizing this work: Rob Haun of Retech, Corry Alsberg and Dan Battleson of MSE and Trevor Jackson of SAIC. I am also grateful for the support of the EPA SITE Demonstration Program which is conducted by the Risk Reduction Engineering Laboratory. Ms. Laurel Staley was the Technical Project Manager for the SITE tests.

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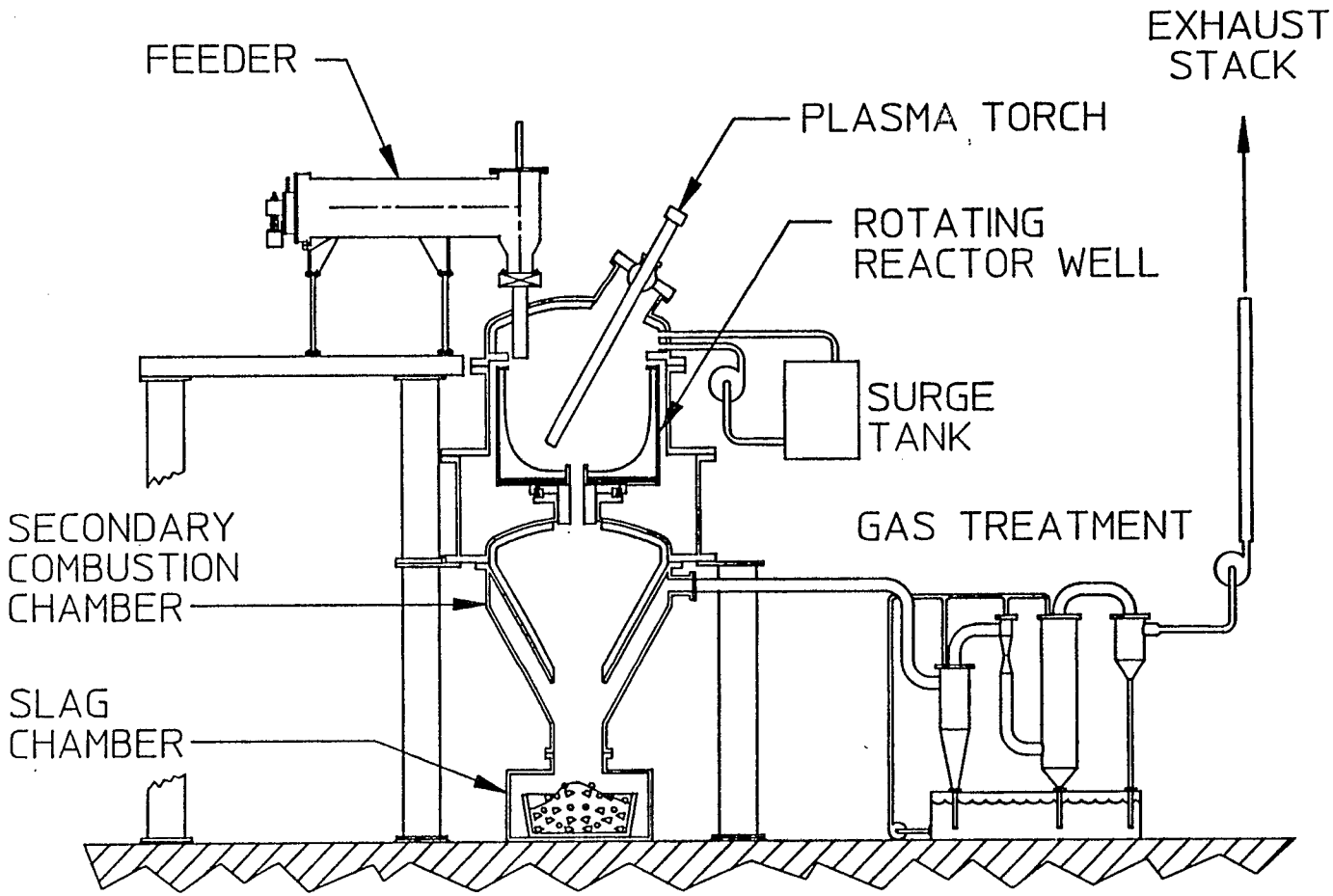

FIGURE 1: COMPONENTS OF PCF SYSTEM

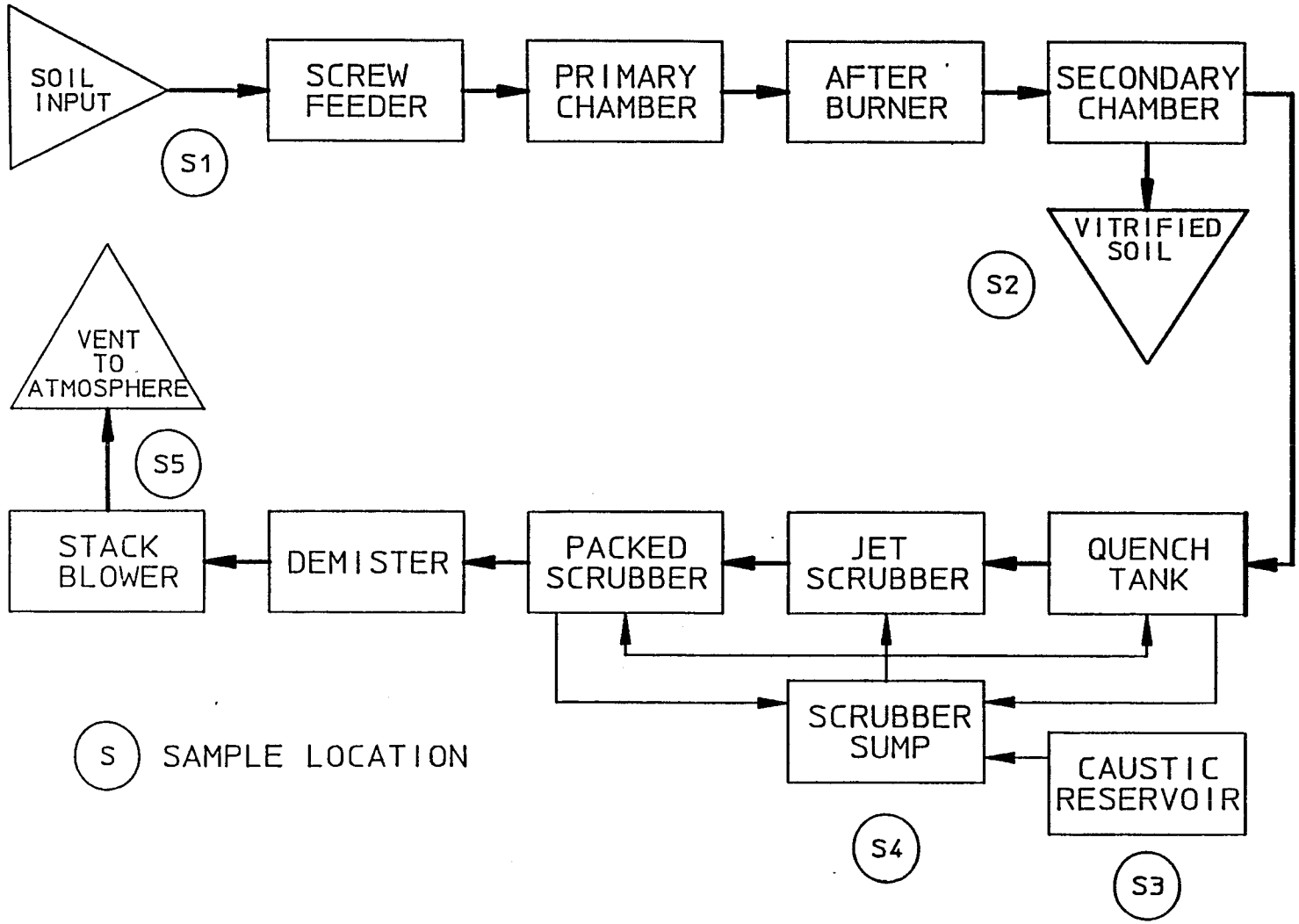

FIGURE 2: SCHEMATIC OF SAMPLING LOCATONS FOR THE DEMONSTRATION TESTS

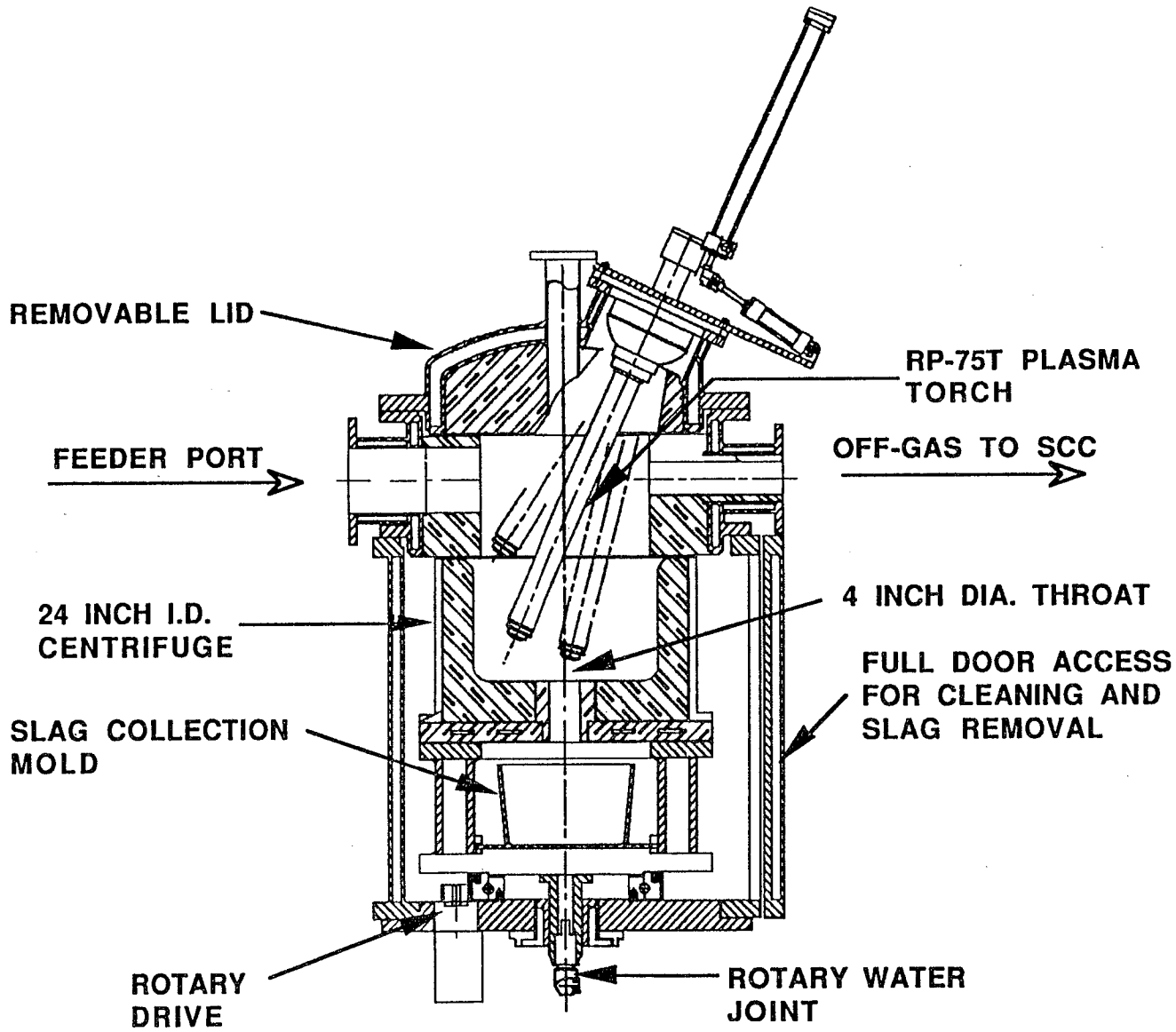

FIGURE 3: SCHEMATIC OF PCF-2

THERMAL DESORPTION OF PCB-CONTAMINATED WASTE AT THE WAUKEGAN HARBOR SUPERFUND SITE (A CASE STUDY)

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Abstract

In June 1992, SoilTech ATP Systems, Inc. (SoilTech) completed the soil treatment phase of the Waukegan Harbor Superfund Project in Waukegan, Illinois, after approximately five months of operation. SoilTech successfully treated 12,700 tons of polychlorinated biphenyl (PCB)-contaminated sediments using a transportable SoilTech Anaerobic Thermal Processor (ATP) System nominally rated at 10 tons-per-hour (tph) throughput capacity. The SoilTech ATP Technology anaerobically desorbs contaminants such as PCBs from solids and sludges at temperatures over 1,000 degrees Fahrenheit (°F). Principal products of the process are clean treated solids and an oil condensate containing the hydrocarbon contaminants.

At the Waukegan Harbor Superfund site, PCB concentrations in the sediments excavated and dredged from a ditch, lagoon and harbor slip averaged 10,400 parts per million (ppm) (1.04 percent) and were as high as 23,000 ppm (2.3 percent). Treated soil contained less than 2 ppm PCBs and was backfilled in an on-site containment cell. The removal efficiency of PCBs from the soil averaged 99.98 percent, relative to the project performance specification of 97 percent. Approximately 30,000 gallons of PCB oil, desorbed from the feed material, were returned to the potentially responsible party (PRP) trust for subsequent off-site disposal. After modifications to the emissions control equipment, compliance with the 99.9999 percent destruction and removal efficiency (DRE) for PCBs in stack emissions required by the United States Environmental Protection Agency was achieved. SoilTech demonstrated compliance with the DRE requirement in eleven consecutive stack sampling events. Feed rate averaged 8 tons-per-hour at a mechanical availability of 85 percent. SoilTech revenues for the project were $700,000 in fixed costs and $185 per ton of soil processed.

THERMAL DESORPTION OF PCB-CONTAMINATED WASTE AT THE WAUKEGAN HARBOR SUPERFUND SITE (A CASE STUDY)

By

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1.0 INTRODUCTION

This technical paper outlines SoilTech's role in the Waukegan Harbor Superfund Project. SoilTech was responsible for the soils processing phase of the project using its unique rotary kiln known as the SoilTech Anaerobic Thermal Processor (ATP) Technology to remediate the PCB-contaminated soils and sediments. The Waukegan Harbor Project is the second commercial application of the SoilTech ATP Technology. 42,000 tons of PCB contaminated soils were successfully treated to nondetect levels at the Wide Beach Superfund site in western New York in 1990 and 1991. The ATP distills organic contaminants out of a solid matrix in an oxygen-free environment. Oxidative degradation of contaminants such as PCBs into more harmful reaction products is therefore prevented. Contaminants are collected in an oily condensate which can then be economically disposed of.

Section 2.0 of this paper describes the technology and Section 3.0 discusses treatment costs. Section 4.0 summarizes SoilTech's activities at the Waukegan Harbor site.

2.0 SOILTECH ATP TECHNOLOGY DESCRIPTION

The ATP Technology was originally conceived as a means to perform primary refining of tar sands and oil shales to crude oil in the early 1970s. UMATAC Industrial Processes (UMATAC) developed and tested the technology over a period of more than 15 years with funding from the Alberta Oil Sands Technology Research Authority (AOSTRA). The technology has been further developed to handle a wide range of organic contaminants such as PCBs. In 1988, Canonie Environmental Services Corp. (Canonie) entered into an exclusive license agreement to utilize the technology for waste treatment in the United States. Together, Canonie and UMATAC, as equal partners, formed SoilTech. The technology, now known as the SoilTech ATP Technology, is described below. Specific fundamental elements of an ATP plant include the ATP System, the vapor handling equipment, the air pollution control equipment, and the control room. Each of these elements is described below.

2.1 Anaerobic Thermal Processor

The central element of the ATP Technology is the processor itself which resembles a rotary kiln from its exterior. However, inside the processor are three physically distinct zones and four zones characterized by different physical processes. The four process zones are described as the following:

1. Preheat zone;
2. Retort zone;
3. Combustion zone; and
4. Cooling zone.

Figure 1 is a cross section of the ATP which depicts each of the four zones. The form and function of each of the zones are described below.

2.1.1 Preheat Zone

As indicated on Figure 1, the preheat zone is the first zone of the ATP into which feed material is conveyed. The preheat zone is charged with feed material by a system of variable-speed material conveyors and feed hoppers as indicated on the process flow diagram shown on Figure 2. The preheat zone is a cylindrical compartment oriented centrally along the axis of the ATP. It is indirectly heated by conduction of thermal energy from hot treated material exiting the processor through the cooling zone.

The material fed to the preheat zone is raised from ambient temperature to approximately 500°F as the material travels through the preheat zone. Any light hydrocarbons and moisture present are distilled out of the feed material and evacuated through a vapor pipe mounted in the fixed endframe of the preheat zone (see Figure 1). The blowers and dampers used to evacuate the vapors from the preheat zone are configured to maintain a negative pressure of approximately 0.10-inch water column relative to atmospheric pressure.

When material reaches the end of the preheat zone, it exits by passing through a circumferential grizzly and entering the proprietary sand seals before being conveyed into the retort zone. The proprietary sand seals allow conveyance of solid material while prohibiting the passage of vapors. This allows the retort zone to be maintained in an anaerobic condition.

2.1.2 Retort Zone

The ATP retort zone is a cylindrical chamber oriented along the axis of the processor at the discharge end of the preheat zone. Material enters the retort zone from two sets of sand seals. The first set conveys preheated material from the preheat zone into the retort zone, as previously described. The second set conveys treated material from the combustion zone back into the retort zone. This hot recycled material

provides the necessary thermal energy to raise the temperature of the bulk solid mixture in the retort zone to temperatures of 950°F to 1,150°F. The sand seals prevent the passage of oxygen into the retort zone and also prevent contaminated vapors from passing into the combustion zone from the retort zone.

Solid material exits the retort zone through a third set of sand seals into the combustion zone, as indicated on Figure 1. Heavy hydrocarbons, which enter the retort zone on the material entering from the preheat zone, are quickly vaporized, producing hot, decontaminated, inert solids. The distilled hydrocarbon vapors are evacuated from the retort zone through a vapor pipe mounted through the stationary endframe at the combustion end of the processor. The evacuated vapors are conveyed to a system of condensing equipment. The blowers and dampers employed to evacuate vapor from the retort zone are configured to maintain a negative pressure of approximately 0.12-inch water column relative to atmospheric pressure.

2.1.3 Combustion Zone

The combustion zone of the ATP makes up the annular space between the inner wall of the processor and the outer wall of the retort zone bordered by the stationary combustion endframe and the cooling zone. As shown on Figure 1, there is no physical barrier between the combustion zone and the cooling zone.

Treated material enters the combustion zone from the discharge sand seal of the retort zone. Accelerator flights reverse the direction of material flow back toward the feed end of the ATP unit. Lifting elements lift and drop the treated soil into the combustion flue gases. Temperatures of around 1,400°F are maintained by two natural gas/propane burners that are fired into the combustion zone through the processor endframe. A portion of the heat requirements of the system are provided by the oxidation of any coke present on the decontaminated solids and light, noncondensable hydrocarbons returned to the combustion zone from the vapor condensing systems.

As the hot treated material nears the entrance to the cooling zone, a fraction is diverted back into the retort zone through the recycle sand seals described previously. This recycled treated material provides the thermal energy necessary to achieve the required desorption temperatures in the retort zone. The material that is not diverted into the retort zone passes through to the ATP cooling zone.

2.1.4 Cooling Zone

The cooling zone is a continuation of the combustion zone. It is the annular space between the inner wall of the processor and the outer wall of the preheat zone. In the cooling zone, treated material continues to be lifted and dropped into the flue gases and onto the exterior wall of the preheat zone. Thermal energy is thereby transferred by conduction through the preheat zone wall to the incoming feed material in the preheat zone while cooling treated material in the cooling zone. When material reaches the end of the cooling zone, it falls through a stationary grizzly into a screw conveyor.

2.2 Auxiliary Systems

The ATP is supported by various auxiliary systems which employ well-established technology, most of which have been proven over many years in a wide range of industrial applications. A simplified process flowsheet for the ATP Technology is provided on Figure 2. A more detailed process flowsheet is included as Figure 3.

Each of these auxiliary systems is described in detail below.

2.2.1 Vapor Handling Equipment

The ATP plant contains two separate gas-handling trains to process the vapors generated in the preheat and retort zones. The basic function of each of the trains is to remove particulate matter and cool the vapors such that water and hydrocarbons are condensed.

2.2.2 Preheat Vapor Handling Equipment

Steam and light hydrocarbons are removed from the preheat zone through a cyclone separator to remove particulate matter and then through a water-cooled shell and tube heat exchanger. The liquids condensed in the shell and tube heat exchanger gravity drain into an oil/water separator. Water collected in the separator is pumped to storage and subsequent treatment. Oil collected in the separator is pumped to storage for subsequent disposal off-site or can be used for reflux in the retort zone's vapor handling equipment. Any noncondensable gases are passed through activated carbon and then into the combustion zone.

2.2.3 Retort Zone Vapor Handling Equipment

The hydrocarbon vapors and contaminants, such as PCBs, are removed from the retort zone and pulled through a vapor scrubber which removes particulate material too fine for removal in the upstream cyclones and cools the vapors from over 1,000°F to approximately 400°F. The vapor scrubber is a direct-contact condensing tower which relies on closed-circuit pumping to circulate oil countercurrent to the vapor flow. The condensed oils and contaminants are pumped to storage for subsequent disposal off-site. Most of the PCBs are condensed in the vapor scrubber.

Vapors exiting the vapor scrubber are pulled through the fractionater. The fractionater is identical to the vapor scrubber but operates at lower temperatures and cools the

vapors to approximately 250°F. Condensed oil can either be pumped to the vapor scrubber or directly to storage.

The vapors which exit the fractionater are pulled through a water-cooled shell and tube heat exchanger identical to the one used in the preheat system. The condensed liquids gravity drain into a two-phase separator. The water phase is pumped from the separator to storage for subsequent treatment. The oil phase is pumped into the fractionater or vapor scrubber as a means of temperature and oil level control. Noncondensable vapors are passed through activated carbon to remove residual heavy hydrocarbons and then onto the combustion zone of the ATP through the combustion endframe.

2.2.4 Air Emissions Control Equipment

The combustion gases are pulled under vacuum from the cooling zone by two induced-draft fans through a cyclone separator, a quench tower, two baghouses operated in parallel, and an activated carbon bed. The relatively low gas flow rate and temperature assure thorough removal of particulates and residual hydrocarbons.

2.2.5 Material Handling Systems

The ATP Plant includes two independent solid handling systems for feed handling and treated soil handling.

The feed handling system is designed to provide solid feed material to the ATP during steady-state waste treatment operations and to provide clean sand feed to the ATP during startup, shutdown or upset conditions. As indicated on Figure 3, the feed system consists of two hoppers equipped with apron belt conveyors, either of which can feed a belt conveyor that transports contaminated feed or clean sand into the preheat zone.

The treated soil handling system conveys treated soil from the base of the cooling plenum via a soil conditioner equipped with water sprays and onto a conveyor belt.

2.2.6 Process Wastewater Treatment System

The ATP Plant produces aqueous condensate at a rate equal to the rate that moisture enters the processor with the feed soil. At the Waukegan Harbor site, the ATP System produced 6 gallons-per-minute (gpm) or less of aqueous condensate which required treatment. The water was pumped from the phase separators into storage tanks and then through the on-site treatment system operated by Canonie. The treatment system is designed to process up to 25 gpm.

The treatment system relies on filtration, oxidation, and adsorption operations to remove contaminants from the aqueous condensate. Specific treatment steps include sand filtration, Klensorb® filtration, ultraviolet enhanced oxidation, cartridge filtration to 0.5 microns, and activated carbon filtration through multiple beds in series. The treated water can be pumped to the process water storage tanks for subsequent use in the plant. However, at Waukegan Harbor treated water was discharged to the sanitary sewer.

2.2.7 The Control Room

The plant control systems and electrical hook-ups are housed in the control room trailer. Extensive use of microprocessor technology for process control and logic functions allows one lead operator to run and monitor the plant from the control panel with the assistance of two technicians in the field. All process parameters such as temperatures, flowrates, pressures, tank levels, equipment current draws, and flue gas quality are monitored and recorded.

2.3 ATP Plant Utility Requirements

The ATP Plant requires electricity, fuel (natural gas or propane) and nitrogen in addition to process water. Specifically, the plant consumes an average of 210 KVA electricity, eight million BTU-per-hour of fuel, and 15,000 cubic feet-per-week of nitrogen.

2.4 Staffing

The ATP System runs on a three-shift, 24-hour-per-day basis with an operating crew of three or four people comprised of one lead operator and two or three assistant operators working in the field. Three or four maintenance personnel work day shift five days a week. A Project Superintendent, Project Engineer, Site Safety Officer, and Receptionist are also on-site during day shift hours.

2.5 Health and Safety

At the Waukegan Harbor site the ATP System was located inside the exclusion zone. Level D personal protective equipment (PPE) was used during plant set-up. An upgrade to Level C was required as soon as processing began. The control room was positioned in the support zone adjacent to the exclusion zone, allowing the lead operator to work in street clothes.

3.0 TREATMENT COSTS

Costs for treatment using the 10-tph SoilTech ATP System can vary depending on the character of the waste material, ranging from $150 per ton to $250 per ton. Costs depend mainly upon the following variables:

- Moisture content of feed material;
- Particle size;
- Hydrocarbon content;
- Material handling characteristics; and
- Chemical characteristics.

Mobilization and demobilization costs for the 10-tph SoilTech ATP System range from $700,000 to $1.5 million.

As illustrated on Figure 4, the smaller 5-tph SoilTech ATP is generally more cost-effective for projects of 5,000 tons or less, while the larger 25-tph ATP System is more cost-effective for project of greater than 45,000 tons.

3.1 Moisture Content of Feed

Feed moisture content is a rate-limiting parameter related linearly to plant throughput and therefore to the price of treatment. Ideal moisture content in feed material is in the range of 5 to 10 percent. At lower moisture contents, entrained dust can create problems in the vapor condensing systems. At moisture contents above 10 percent, the latent heat required to distill the moisture from the feed in the preheat zone of the

ATP System can become rate limiting. SoilTech evaluates, and when appropriate, incorporates predrying of feed material into a project work plan when waste moisture content might affect treatment economics.

3.2 Particle Size

Material should be smaller than 2 inches; if not, pre-screening and/or crushing may be necessary. Where a material contains a high percentage of very fine material such as clay, co-feeding of coarse material may be necessary. Fine material tends to reduce the efficiency of the sand seals and will be drawn out of the processor with the flue gases, reducing the quantity of material available for heat transfer in the combustion and cooling zones.

3.3 Hydrocarbon Content

The SoilTech ATP System is designed to handle feed materials containing up to 10 percent hydrocarbons. With higher levels or where a substantial proportion of those hydrocarbons have a high molecular weight and amenable to cracking, the amount of coke formed in the retort zone may be excessive. Elevated levels of carbon monoxide in the flue gas stream may then result. Reducing feed rate or incorporating an additional flue gas treatment step, such as catalytic oxidation, mitigates the problem but increases treatment costs.

3.4 Chemical Characteristics

A feedstock exhibiting unusual reactivity, corrosivity or toxicity may require pre-treatment or special handling precautions. Treatment cost would therefore be affected adversely.

3.5 SoilTech Bench-Scale Unit

SoilTech is able to accurately predict treatment performance and costs based on bench-scale testing results. The bench test unit accurately simulates conditions in the full-scale system. Over 2,000 bench-scale tests have been conducted on a variety of contaminated materials. Strict procedures and protocols have been developed and are rigorously applied.

4.0 WAUKEGAN HARBOR SUPERFUND PROJECT DESCRIPTION

The Waukegan Harbor Superfund site was listed on the EPA's Superfund Priority List. Contamination resulted from leakage of PCBs - used as an aluminum casting lubricant and machine tool lubricant - through floor drains from a major manufacturing facility into an adjacent stream and Waukegan Harbor. PCB concentrations in excess of 20,000 ppm were found in the harbor sediments and stream bed. Remediation of the site was complicated by the fact that the harbor was being used for both commercial and recreational boating activities and was adjacent to a public beach. The client insisted that operations not impact the day-to-day activities of the local community. It was therefore necessary for Canonie, the prime contractor, to build a new boat slip prior to isolating the old one. Sediments with PCB concentrations greater than 500 ppm were hydraulically dredged from the old slip and pumped to a containment cell where dewatering was achieved before they were blended with soils from the contaminated stream bed.

The 1984 Record of Decision (ROD) called for stabilization of these soils and sediments. However, SoilTech and the PRPs were able to convince the EPA that the use of SoilTech's ATP Technology offered a more environmentally acceptable and cost-effective solution. The EPA accepted that the SoilTech ATP System was an innovative treatment technology that provided a significant and permanent reduction in the toxicity and volume of PCB wastes at the Waukegan Harbor site. SoilTech's approach fulfilled the requirements of the Superfund Amendments and Reauthorization Act (SARA). Under the 1984 ROD, there would have been a potential future liability posed by stabilized stored wastes.

SoilTech was contracted by Canonie to process the soils and sediments for $700,000 in fixed costs and $185 per ton of material processed. SoilTech was not responsible for providing utilities (water, gas and electricity). Site preparation and excavation of contaminated material were carried out by Canonie. The PRPs took full responsibility

for disposing of the PCB condensate produced. Had SoilTech been responsible for any or all of these additional activities, the unit price for soils processing would have been correspondingly higher.

The project clean-up criteria called for a treated soil residual PCB level of 500 ppm, or 97 percent removal efficiency from the soils, whichever was more stringent. The average target clean-up level turned out to be approximately 310 ppm. Total soils requiring treatment amounted to about 12,700 tons. Treated soils were to be placed in one of two containment cells along with untreated soils containing less than 500 ppm PCBs before being closed with a Toxic Substances Control Act (TSCA)-approved impermeable cap. PCB-contaminated oils extracted from the soils were returned to the PRPs for subsequent disposal.

Since no applicable air emissions standard exists for thermal desorption, the EPA required that SoilTech meet the 99.9999 percent (6 nines) destruction and removal efficiency (DRE). SoilTech was also required to meet the municipal waste incineration standard of 30 nanograms per dry standard cubic meter (ng/dscm) total dioxins and furans applied to incineration of PCB-contaminated wastes. Discharged water was to be less than 15 parts-per-billion (ppb) PCBs.

4.1 Sequence of Events

SoilTech arrived at the Waukegan Harbor Superfund site in the last week of November 1991. Modification and repair of key process components continued at a shop in Indiana while the site was prepared, and support equipment was assembled and erected. Shakedown and troubleshooting of the SoilTech ATP System was conducted in mid-January. SoilTech began treating contaminated soils and sediments on January 22, 1992. This date also marked the start of the 30-day proof-of-process period.

Between startup and March 6, 1992, the SoilTech ATP System averaged a feed rate of 10 tph, outperforming initial projections of 9 tph. Net plant availability was over 85 percent. PCB concentrations in the feed averaged 14,000 ppm and treated soil concentrations less than 2 ppm PCBs were attained. The average removal efficiency from the treated soil was 99.96 percent.

During this time period, SoilTech performed seven stack tests. Although the emissions criteria for dioxins and furans were met, SoilTech was unable to meet the 6 nines DRE for PCBs and consequently stopped operations at the direction of the EPA.

During the next two months, SoilTech operated the ATP System intermittently to test various modifications to the ATP and to the emission control system. Specific modifications included:

- Increasing the volume of carbon in flue gas carbon bed;
- Removing the wet scrubber from the flue gas handling system;
- Adding carbon beds to internal gas recycle streams;
- Testing of continuous addition of powdered activated carbon upstream of the baghouses to facilitate adsorption of PCBs;
- Reducing flue gas carbon bed temperature; and
- Testing of continuous addition of sodium bicarbonate in the combustion zone of the ATP in an attempt to induce catalytic destruction of residual PCBs.

In the latter phase of this period of intermittent operation and testing, SoilTech discovered a gap in the flue gas carbon bed seal which was allowing 70 percent of the flue gas stream to bypass the carbon bed. SoilTech corrected the poor seal before stack testing on May 12, 13, and 14, 1992.

Each of four stack tests conducted on those three consecutive days demonstrated performance superior to the 6 nines DRE required. A summary of the stack testing conducted throughout the project is given in Table 1.

It appeared that the final three tests, using powdered activated carbon in the baghouse and then soda ash in the combustion zone, produced slightly better results than the test conducted without these additives. The results are, however, statistically inconclusive.

With EPA's approval SoilTech was then able to resume processing the contaminated soils and sediments having met all of the project performance criteria.

To insure that this performance was maintained, SoilTech instituted several new procedures and operating conditions.

- Soda ash was fed to combustion zone at 200 lbs/hour;
- Stack temperature was maintained at 170°F with automatic waste feed shut off at 190°F;
- The stack gas carbon bed was sampled on a daily basis. The plant was to be shut down and the carbon bed changed when the PCB concentration exceeds 10 ppm;
- Weekly stack testing were performed by Clean Air Engineering. Failure to meet 6-nines DRE would necessitate immediate shutdown until the cause had been identified and remedied; and
- The pressure drop across the stack carbon bed was maintained. The bed was to be inspected if it drops below 5-inches water column.

4.2 EPA Site Demonstration

On June 16, 1992 the EPA began a Superfund Innovative Technology Evaluation (SITE) demonstration of the SoilTech ATP System. This involved three days of rigorous sampling and testing. The test runs were conducted at typical operating conditions. The fourth and final test was, however, run without the addition of soda ash to the combustion zone. The other three tests were run while 200 lbs/hr of soda ash was added to the combustion zone. Each test run consisted of 8.5 hours of solids and liquids sampling and 8 hours of stack sampling. During the site demonstration, 224 tons of PCB-contaminated soils and sediments were processed. In addition to sampling, data on critical operating parameters were collected during each test.

Based on the preliminary results at the site demonstration, the EPA concluded the following:

- PCB concentrations were reduced from an average of 9,761 ppm in the untreated soil and sediment to an average concentration of 2 ppm in the treated soil and sediment.
- Approximately 0.12 milligram (mg) of PCBs was discharged from the ATP System's stack per kilogram of PCBs fed to the ATP.
- The majority of PCBs removed from the untreated soil and sediment were accumulated in the waste oil discharge from the vapor cooling system.
- No dioxins, other than a low concentration 0.1 ng/dscm of octachlorinated dibenzo-p-dioxin in one stack gas sample, were detected in the stack gas from the ATP System. Tetrachlorinated dibenzofurans were found in both the untreated soil and sediment (88 ng/g) and treated soil and sediment (5 ng/g) and the stack gas (0.07 ng/dscm).
- Leachable volatile organic compounds, semivolatile organic compounds, and metals in the treated soil and sediment were below Resource Conservation and Recovery Act (RCRA) toxicity characteristic standards.

- No operational problems affecting the ATP's ability to treat the contaminated soil and sediment were observed.

Selected results provided by the EPA are presented in Table 2. As expected, the results confirm that SoilTech met all of the project performance criteria. Removal efficiency for PCBs in the treated soil averaged 99.98 percent. DRE for the stack emissions exceeded the 6 nines criteria in each test and bettered 7 nines in two of the tests.

The results also demonstrated that dioxins and furans are not produced in the ATP. Trace amounts detected in the waste oil, the treated soil and stack gas can be traced back to the untreated soils and sediments.

The highest DRE for PCBs in the stack was achieved for the test in which no soda ash was added to the combustion zone of the ATP. This indicates that the addition of soda ash provides no reduction in the flue gas emissions produced by the SoilTech ATP System. Further bench testing might, however, provide a more statistically conclusive evaluation.

Processing of soils and sediments at the Waukegan Harbor site continued without further incident and was successfully completed on June 23, 1992 when a total of 12,700 tons had been processed. A summary of production data is provided in Table 3. Approximately 30,000 gallons of PCB-contaminated oil was desorbed from the soils and sediments and returned to the PRPs for subsequent off-site disposal. An average plant throughput of 8 tph had been achieved with a mechanical availability of 85 percent.

Process water generated during operations was discharged to Canonie's water treatment system at approximately 5 gpm and released to the sewer at a PCB concentration of less than 15 ppb PCBs.

5.0 CONCLUSIONS

The Waukegan Harbor Superfund Project was the SoilTech ATP Technology's greatest challenge to date due to the high concentrations of PCBs in the feed material. System modifications allowed the strict project performance criteria to be met and surpassed. The SoilTech ATP Technology has demonstrated the capability to:

- Provide a significant and permanent reduction in the toxicity and volume of PCB wastes at Waukegan Harbor,
- Reduce PCB concentrations in the soils and sediments from as high as 2.3 percent to below 2 ppm,
- Achieve a 7-nines PCB DRE in the stack gases,
- Meet or exceed all project performance criteria, and
- Provide a cost-effective and more environmentally favorable alternative to established technologies.

References

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TABLE 1

STACK TEST SUMMARY
WAUKEGAN HARBOR

Date	Feed PCBs (#/hr)	Stack PCBs (#/hr)	PCB DRE (%)
01-28-92	192.50	0.0144000	99.9925195
02-04-92	215.50	0.0932000	99.9567517
02-11-92	213.40	0.0690000	99.9676664
02-18-92	155.70	0.0087600	99.9943738
03-04-92	105.60	0.0039700	99.9962405
03-05-92	100.80	0.0012700	99.9987401
03-05-92	100.80	0.0007720	99.9992341
03-18-92	174.90	0.0009890	99.9994345
04-09-92	148.60	0.0034500	99.9976783
04-10-92	298.50	0.0009430	99.9996841
05-12-92	230.40	0.0002000	99.9999132
05-13-92	264.60	0.0000735	99.9999722
05-13-92	183.00	0.0000464	99.9999746
05-14-92	205.70	0.0000448	99.9999782
06-02-92	167.40	0.0000942	99.9999437
06-02-92	213.60	0.0001850	99.9999134
06-09-92	159.15	0.0000432	99.9999729
06-16-92	140.80	0.0000050	99.9999964

NOTE:

1. PCB Destruction Removal Efficiency (DRE) criterion is 99.9999 percent.

TABLE 2

EPA SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION DRAFT RESULTS

Waste Feed Contaminant Concentrations

Contaminant	Average Concentration
Total PCBs	9231 ppm
Dioxin/Furan:	
TCDF	86 ppb
PeCDF	16 ppb

Treated Soil Contaminant Concentrations

Contaminant	Average Concentration
Total PCBs	1.972 ppm
Dioxin/Furan:	
TCDF	5.4 ppb

Waste Discharge Oil Contaminant Concentrations

Contaminant	Average Concentration
Total PCBs	32%
Dioxin/Furan:	
TCDF	136 ppb
PeCDF	14 ppb

TABLE 2

EPA SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION DRAFT RESULTS (Continued)

Stack Gas Contaminant Concentrations

Contaminant	Average Concentration	Output (lbs/hr)	Emissions Criteria
Particulates	0.0039 μg/dscm	0.071	8.7 lb/hr
Total PCBs	0.8330 μg/dscm	1.7E-5	
Total TCDF	0.0790 ng/dscm	1.4E-9	30 ng/m^3
HCL Gas	23.000 μg/dscm	0.00042	0.2 lb/hr
Total Hydrocarbons	ND	0	

Stack Gas Emissions Destruction and Removal Efficiencies

Test Run No.	PCBs Fed to ATP (lb/hr)	PCBs Exiting Stack (lb/hr)	DRE (%)
1	140.60	18.9E-6	99.999987
2	136.87	14.27E-6	99.999990
3	153.73	17.15E-6	99.999989
4	181.71	8.09E-6	99.999996

NOTE:

1. Project emissions criteria for PCBs is 99.9999% DRE.

TABLE 3

PRODUCTION DATA
WAUKEGAN HARBOR

Week Ending	Production (tons)	Average PCB in Feed Soil (ppm)	Average PCB Removal Efficiency (%)
1-25-92	561	15,500	99.97
2-01-92	1,476	9,243	99.95
2-08-92	1,202	11,657	99.98
2-15-92	1,205	13,143	99.98
2-22-92	1,493	9,571	99.98
2-29-92	606	7,025	99.98
3-07-92	841	7,060	99.99
3-21-92	245	9,950	99.97
4-11-92	483	8,350	99.97
4-18-92	592	13,740	99.99
5-16-92	377	8,800	99.99
5-30-92	46	12,000	99.99
6-06-92	1,284	10,486	99.98
6-13-92	1,000	9,450	99.98
6-20-92	887	9,917	99.99
6-27-92	402	9,300	99.95
TOTAL	12,700	10,400	99.98

NOTE:

1. Soil treatment criterion is 97 percent removal efficiency.

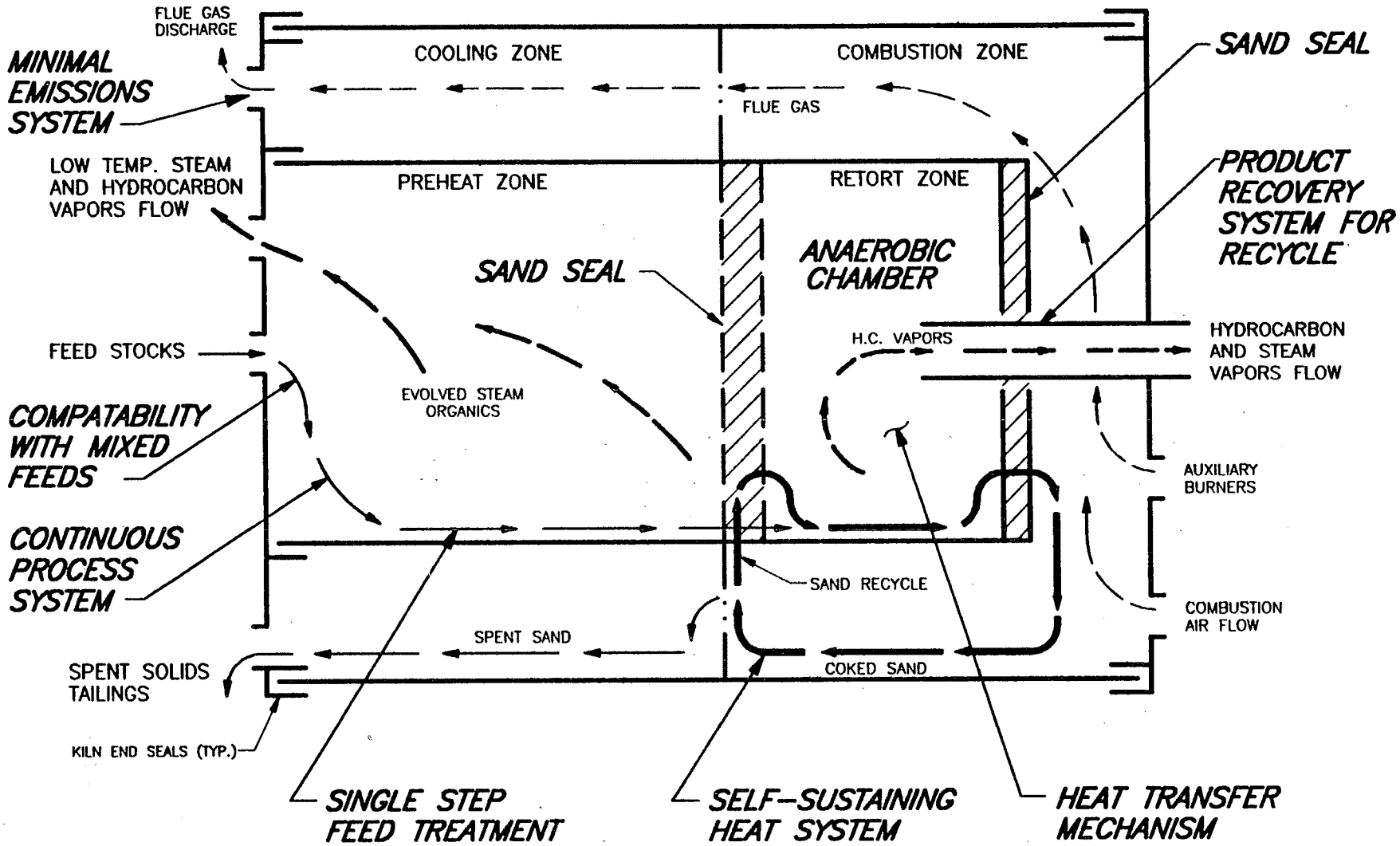

FIGURE 1

SOILTECH ATP CROSS SECTION

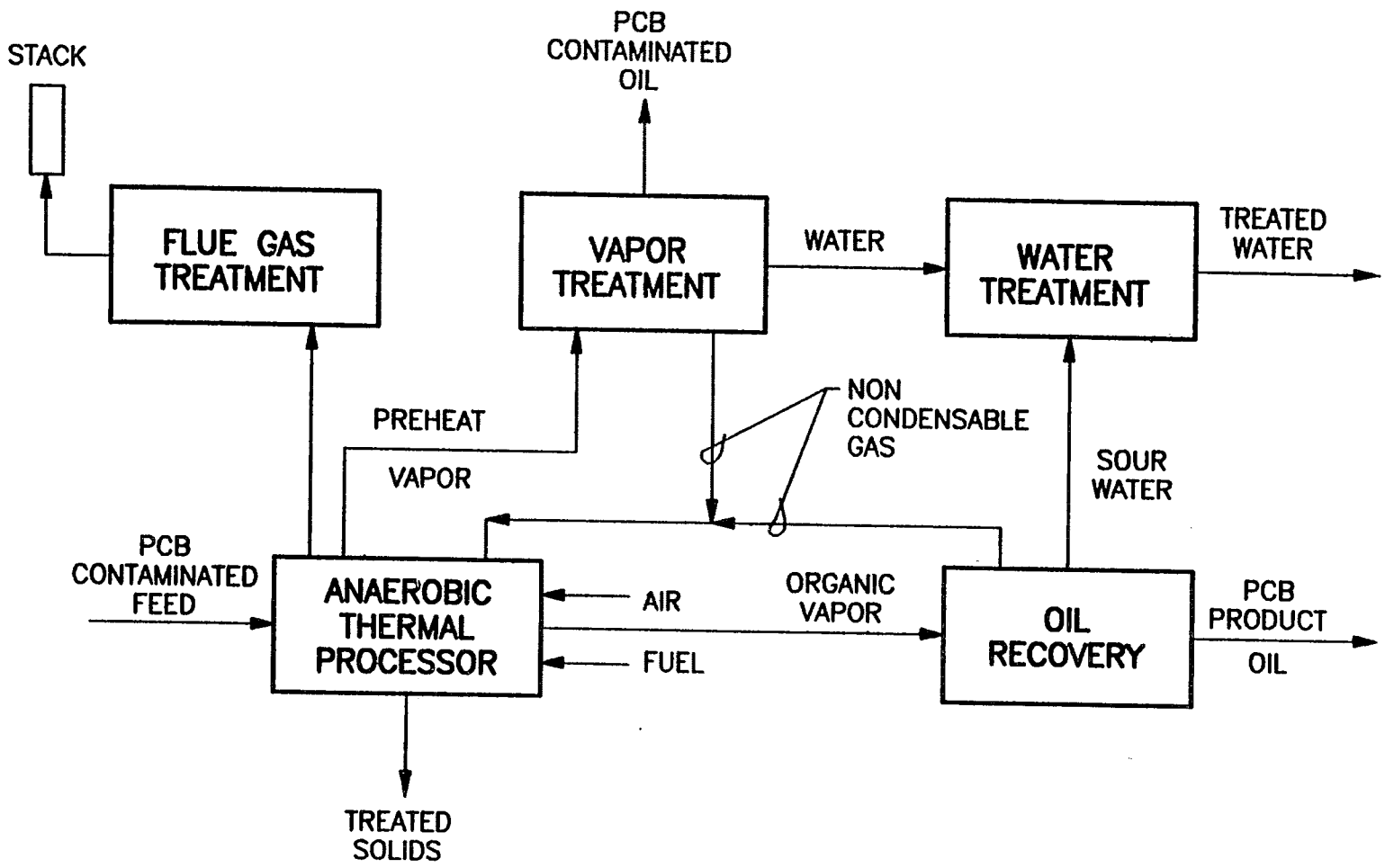

FIGURE 2
SOILTECH ATP TECHNOLOGY SIMPLIFIED FLOW DIAGRAM

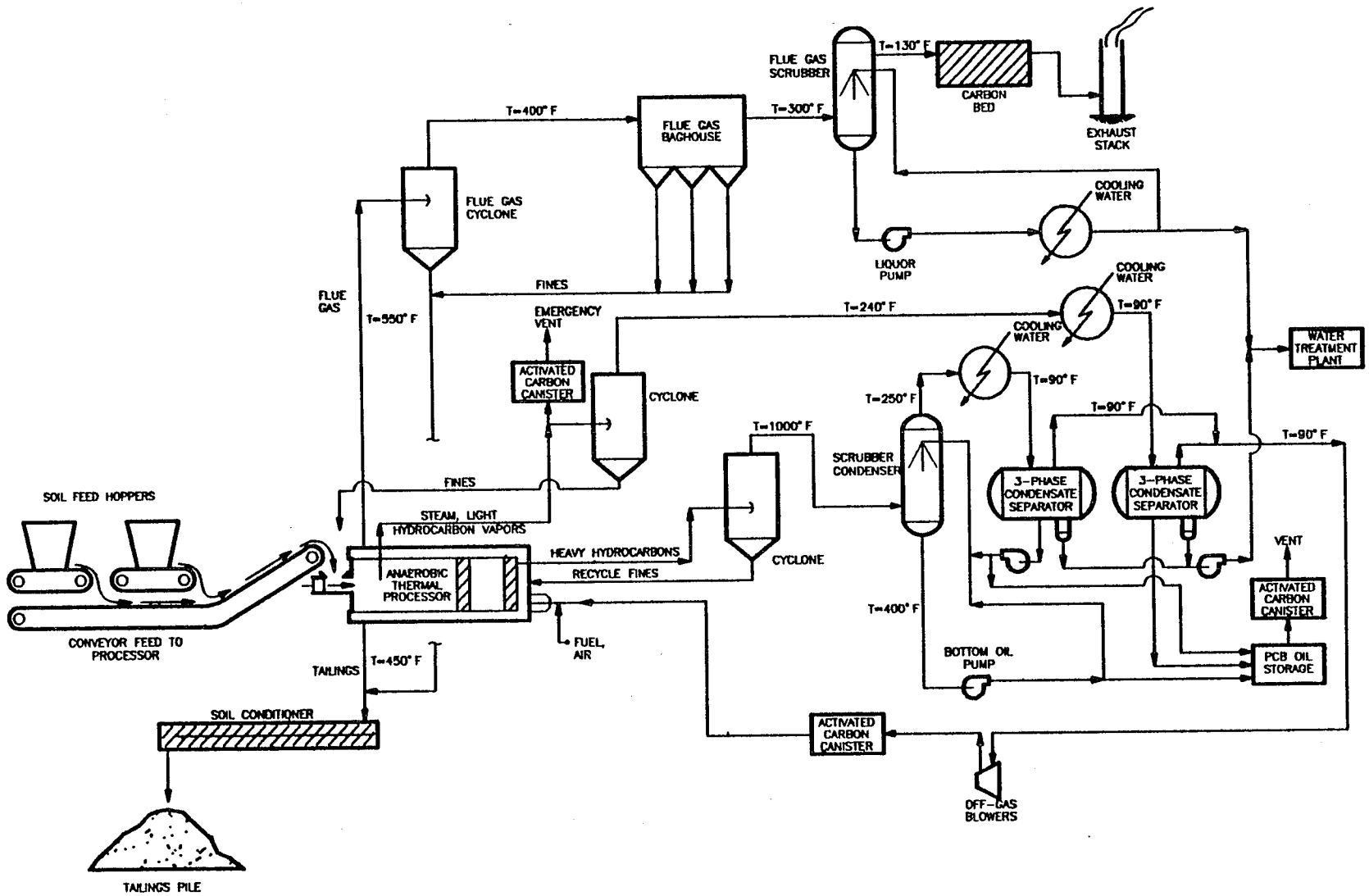

FIGURE 3

SOILTECH ATP TECHNOLOGY PROCESS FLOW SHEET

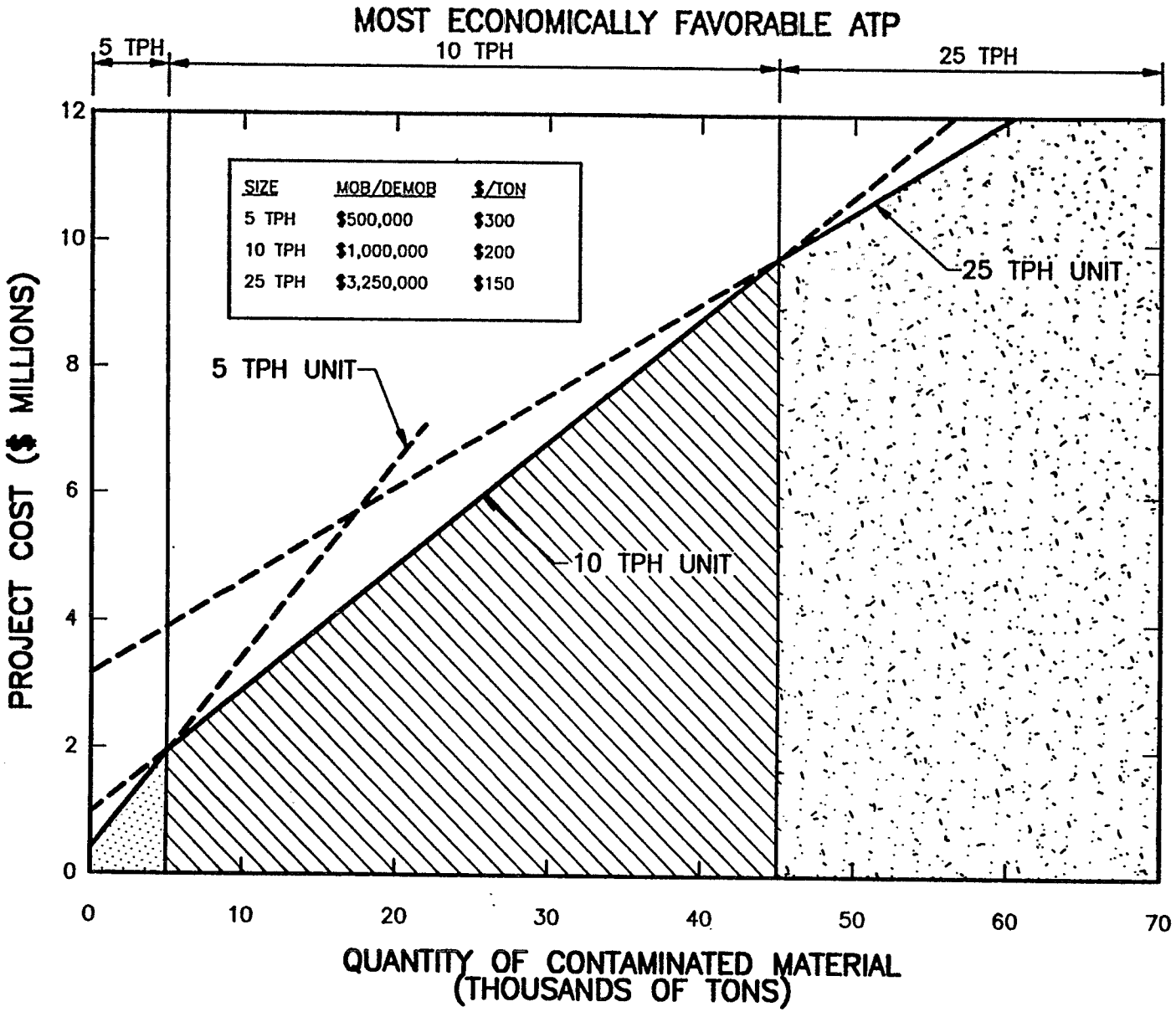

FIGURE 4

EVALUATION OF OPTIMUM SIZE ATP UNIT

THE BABCOCK & WILCOX CYCLONE VITRIFICATION TECHNOLOGY FOR CONTAMINATED SOIL

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INTRODUCTION

Technology Development at Babcock & Wilcox

The Babcock & Wilcox cyclone furnace is a well-established design (over 26,000 MW installed electrical capacity) for the combustion of high inorganic (ash) coal. The combination of high heat release rates (450,000 Btu/cuft for coal) and high turbulence in cyclones assures the high temperatures required for melting the high ash fuels. The inert ash exits the cyclone furnace as a vitrified slag.

Taking advantage of the ability of the cyclone furnace to form a vitrified slag from waste inorganics, the cyclone furnace was used in a research and development project to vitrify municipal solid waste (MSW) ash containing heavy metals. The cyclone furnace produced a vitrified MSW ash which was below EPA leachability limits for all 8 RCRA metals. The successful treatment of MSW ash suggested that the cyclone vitrification technology would be applicable to high inorganic content hazardous wastes and contaminated soils that also contain organic constituents. These types of materials exist at many Superfund sites, as well as sites where petrochemical and chemical sludges have been disposed. Our approach for establishing the suitability of the cyclone vitrification technology relies on the premise that for acceptable performance in treating contaminated soils containing organic and heavy metals constituents, the cyclone furnace must melt the soil matrix while producing a non-leachable slag and must achieve the destruction and removal efficiencies (DREs, currently 99.99%) for organic contaminants normally required for RCRA hazardous waste incinerators. The high temperature (>2,500 to 3,000°F), turbulence, and residence time in the cyclone and main furnace are expected to result in high organics destruction and removal efficiencies (DREs).

Process Description

The Babcock & Wilcox four to six million Btu/h cyclone furnace located in Alliance, Ohio, was used to perform all pilot-scale vitrification tests. The furnace is water-cooled and simulates the geometry of B&W's single cyclone, front-wall fired cyclone coal-fired

boilers. This cyclone facility has been proven to simulate typical full-scale cyclone units in regard to furnace/convection gas temperature profiles and residence times, NO_x levels, cyclone slagging potential, ash retention in the slag, unburned carbon and flyash particle size.

The pilot cyclone furnace, shown in Figure 1, is fired by a single, scaled-down version of a commercial coal combustion cyclone furnace. The furnace geometry is a horizontal cylinder (barrel). A summary of the process is illustrated in Figure 2. For the present application, natural gas and preheated primary combustion air (820°F) enter tangentially into the cyclone burner. In dry soil processing, preheated secondary air (820°F), the soil matrix, and natural gas enter tangentially along the cyclone furnace barrel. For wet soil processing, an atomizer is used to spray the soil paste directly into the furnace. The soil is captured and melted and organics are destroyed in the gas phase or in the molten slag layer formed and retained on the furnace barrel wall by centrifugal action. The soil melts, exits the cyclone furnace from the tap at the cyclone throat, and is dropped into a water-filled slag tank where it solidifies. A small quantity of soil also exits as flyash with the flue gas from the furnace and is collected in a baghouse. In principle, this flyash could be recycled to the furnace as indicated in Figure 2 to increase the capture of metals and to minimize the volume of the potentially hazardous waste stream.

Particulate control is achieved by way of a baghouse. To maximize the capture of metals, a heat exchanger is used to cool the stack gases to approximately 200°F before entering the baghouse. Although the cyclone facility is equipped with an acid gas scrubber, it was not used for these tests because acid gas generation (e.g., HCl) from the vitrification of the SSM was expected to be low.

Applicable Wastes and Soils and Possible Technology Configurations

An advantage of vitrification over other thermal destruction processes is that in addition to the destruction of organic constituents, the resulting vitrified product captures and does not leach heavy metals or radionuclides. The cyclone vitrification technology would be applicable to high inorganic content hazardous wastes, sludges and contaminated soils that contain heavy metals and organic constituents. The wastes may be in the form of solids, a soil slurry (wet soil) or liquids. To be treated in the cyclone furnace, the ash or solid matrix must melt and flow at cyclone furnace temperatures (2400 to 3000°F). Because of the technology's ability to capture heavy metals in the slag and render these non-leachable, an important application of the technology is contaminated soils which contain non-volatile radionuclides (e.g., strontium, transuranics).

The cyclone furnace can be operated with gas, oil or coal as the supplemental fuel. The waste may also supply a significant portion of the required heat input. Additional air pollution control devices, such as NOx reduction technologies, can be applied as

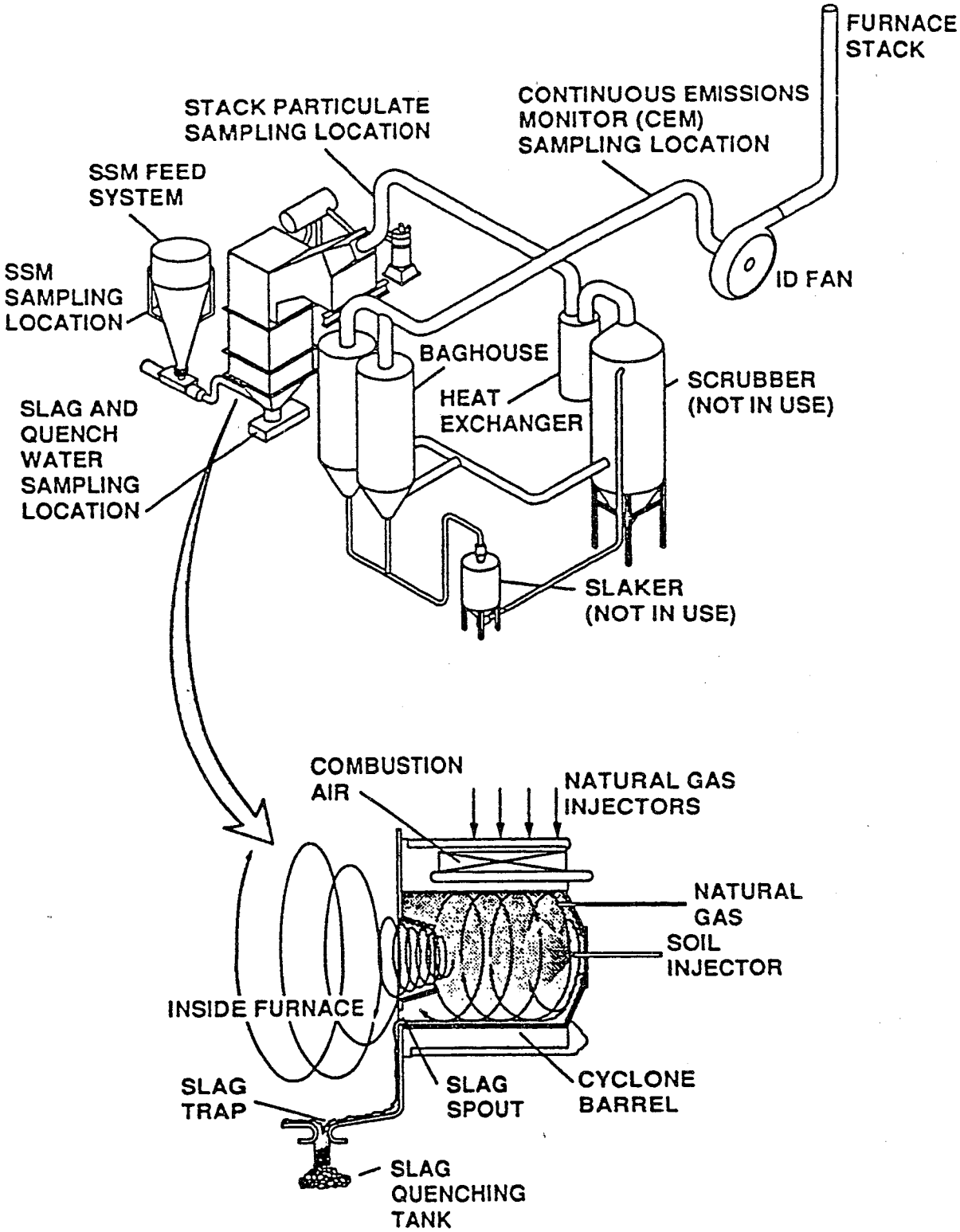

FIGURE 1. The pilot cyclone test facility at the Babcock & Wilcox Research and Development Division. The insert of the furnace shows the wet soil feed configuration.

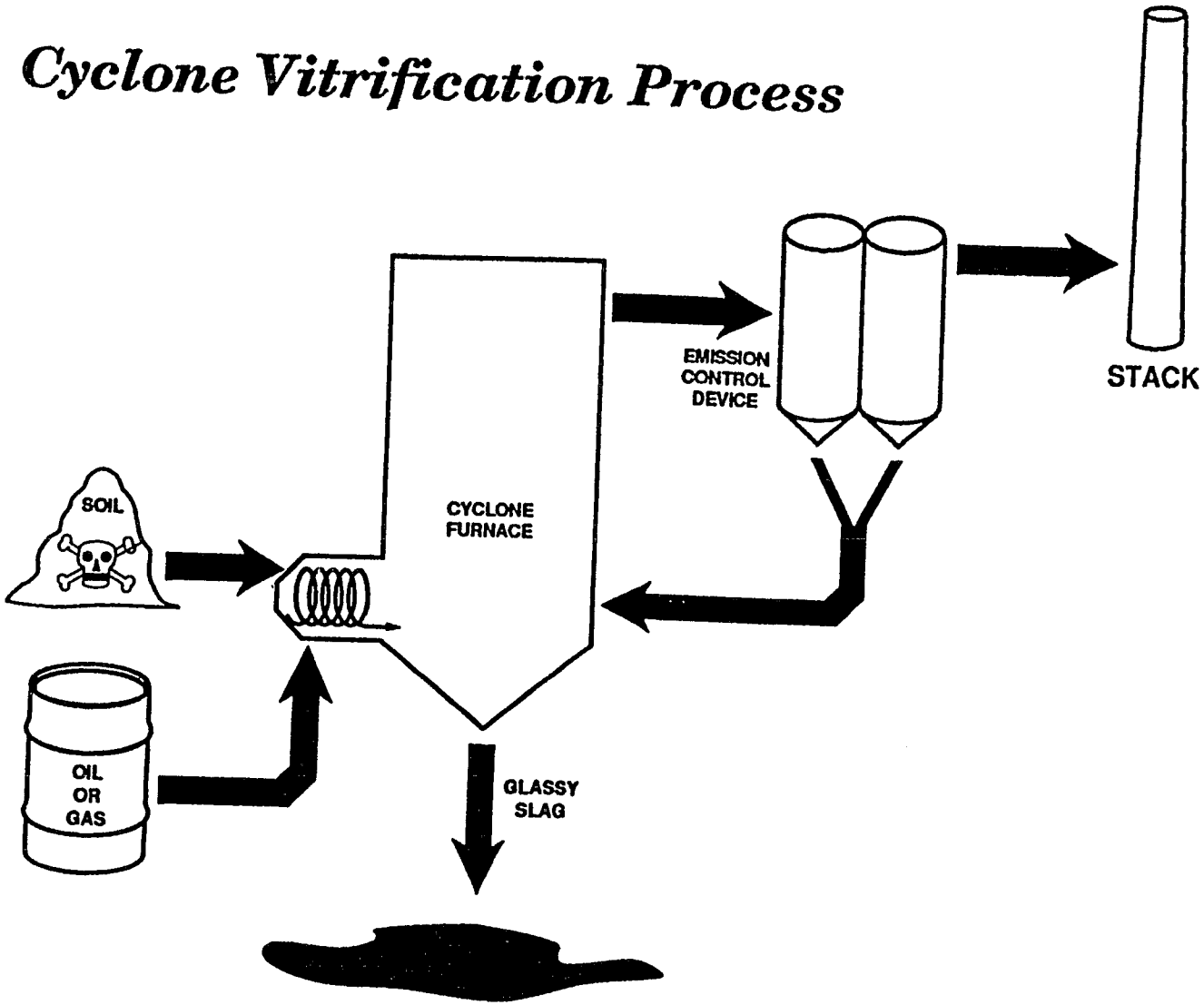

FIGURE 2. Schematic of the cyclone vitrification process. The emission control devices may include scrubber and baghouse. Ash recycling to the furnace to increase metals capture is possible, but was not demonstrated during this project.

needed. An acid gas scrubber would be required, for example, when chlorinated wastes are treated.

Description of the B&W SITE Emerging Technologies Project

The EPA Office of Solid Waste and Emergency Response and the Office of Research and Development established a formal program called the Superfund Innovative Technology Evaluation (SITE) Program to accelerate the development and use of innovative cleanup technologies at hazardous waste sites across the country. This project was sponsored under the SITE Emerging Technologies Program.

The goal of the SITE Emerging Technologies project, is to perform a pilot-scale test of the Babcock & Wilcox 6 million Btu/h cyclone furnace for vitrification of an EPA-supplied synthetic soil matrix (SSM) spiked with three heavy metals (lead, cadmium and chromium).

This paper will present the results of both the Phase I (1990-1991) and Phase II (1991-1992) Emerging Technologies efforts. Both Phase I and II used an EPA synthetic soil matrix spiked with lead, cadmium and chromium. The most important goal for both Phase I and II was to produce a vitrified soil that passes the Toxicity Characteristic Leaching Procedure (TCLP) limits for lead, cadmium and chromium. Secondary goals were the measurement of volume reduction after treatment and heavy metals mass balance. The most significant difference between the Phase I and II is the use of dry and wet soil feed system, respectively. The wet soil feed system was used for the SITE Demonstration, and thus this paper emphasizes the results for this final system configuration.

Measurement of organics destruction efficiencies, thought to be less of a technical challenge compared with metals capture, was reserved for a SITE Demonstration performed in November 1991.

The SITE Demonstration

A SITE demonstration was performed on the pilot cyclone furnace in November of 1991. An EPA-supplied synthetic soil matrix spiked with heavy metals (cadmium, chromium and lead), organics (anthracene and dimethyl phthalate), and simulated radionuclides (cold strontium, bismuth, and zirconium) was used.

The demonstration was designed to test the performance of the cyclone furnace in (1) producing a non-leachable slag for metals and simulated radionuclides; (2) destruction and removal efficiencies for the organics, (3) producing a greater than 10 to 1 ratio of slag to flyash; (4) capturing at least 60 percent of the least volatile metals; and (5) reducing the volume of the treated waste by at least 25%. Results from the demonstration are expected to be published by EPA in fall of 1992, but preliminary results are summarized here.

MATERIALS AND METHODS

Typical Run Conditions

Typical run conditions for the Phase I and Phase II tests are given in Table I, below. The SITE Demonstration was run under conditions similar to those of Phase II.

Table I. Typical Cyclone Furnace Tests Conditions.

Condition	Typical Range of Values
Heat Input (natural gas fuel)	5 Million Btu/h
SSM Feed Rate	50 to 300 lb/h
Excess Oxygen	1.0%
1° and 2° Air Temperature	830°F
Total Air Split-Phase I	
Primary Air	25%
Secondary Air	72%
Feed Air	3%
Total Air Split-Phase II	
Primary Air	not used
Secondary Air	96.5%
Soil Atomizer Air	3.5%
Slag Temperature	2370-2460°F
Cyclone Furnace Gas Temperature	2800-3000°F
Flue Gas Exit Temperature	2100-2200°F
Baghouse Temperature	200°F

RESULTS: SITE DEMONSTRATION VENDOR'S CLAIMS

The effectiveness of the B&W Cyclone Furnace Vitrification Technology at destroying organics and immobilizing heavy metals and simulated radionuclides in a non-leachable slag was evaluated during the SITE Demonstration. To perform this evaluation, the following critical and non-critical Vendor's Claims were developed by Babcock & Wilcox, based on discussions with the U.S. EPA, for evaluation in the Demonstration (see below).

These claims are compared with performance data for the cyclone vitrification technology below.

Parameter	Claim
Critical Claims	
TCLP	Produce a vitrified slag that does not exceed Toxicity Characteristic Leaching Procedure (TCLP) regulatory levels for cadmium (i.e., <1 mg/L), lead (<5 mg/L), and chromium (<5 mg/L).
Slag to Flyash Ratio	Achieve at least a 10 to 1 ratio (dry weight basis) of slag to flyash.
Non-Volatile Metals Capture (Cr) in the Slag	Capture at least 60% (by weight) of the non-volatile metal chromium from the dry, untreated SSM in the vitrified slag.
Volume Reduction	Achieve at least a 25 percent volume reduction in solids when comparing product solid to untreated SSM.
DREs	Achieve a 99.99% destruction and removal efficiencies DREs for each organic contaminant spike (anthracene and dimethylphthalate).
CO, THC, Particulates	Comply with emission limits for CO, total hydrocarbons (THC), and particulates from the stack as stipulated by 40 CFR 264 (i.e., CO of <100 ppm, THC of <20 ppm, and particulates of <0.08 gr/dscf at 7% oxygen).
Non-Critical Claims	
ANS 16.1 Simulated Radionuclide Leachability	Produce a slag that immobilizes (passes leaching standards) radionuclides as measured by the American Nuclear Society test (ANS) 16.1 (i.e., ANS 16.1 calculated leachability index (LI) >6).
Non-Volatile Radionuclide Capture in the Slag	Capture at least 60% (by weight) of the non-volatile metals strontium and zirconium in the vitrified slag.

COMPARISON OF PERFORMANCE RESULTS FROM THE TWO SITE EMERGING TECHNOLOGY PROJECTS WITH THE VENDORS CLAIMS

Synthetic Soil Matrix and Feed Conditions

Two Superfund Innovative Technology Evaluation (SITE) Emerging Technology projects were conducted prior to the SITE Demonstration. These two projects, Phase I and Phase II, were conducted to establish the feasibility of the cyclone vitrification process for dry soil (Phase I) and wet soil (Phase II) treatment. In each project, measurements were made to evaluate TCLP leachabilities, volume reduction, and materials and heavy metals mass balances.

A synthetic soil matrix formulated by EPA was used for all cyclone testing. Both clean and spiked SSM were obtained from the EPA Risk Reduction Engineering Laboratory (RREL) Releases Control Branch in Edison, NJ. SSM, used by EPA for treatment technology evaluations, has been well-characterized in previous studies [1]. Clean soil was used for furnace conditions optimization. The spiked SSM used in the Emerging Technologies projects contained 7,000 ppm (0.7%) lead, 1,000 ppm (0.1%) cadmium, and 1,500 ppm (0.15%) chromium.

In Phase I, dry SSM was processed at feed rates of 50 to 150 lb/hr. In Phase II, wet SSM was processed at feed rates of 100 to 300 lb/hr (dry basis). Approximately 11 tons of spiked and unspiked SSM were processed during each of the two project Phases.

Performance Results

A comparison of Phase I and II results against the Vendor's Claims developed for the Demonstration is presented below. Not all of the Demonstration claims were tested during these projects (e.g., DRE, ANS 16.1 were omitted). All claims tested were met or exceeded during these Emerging Technology projects (the Claims were finalized on the basis of these results).

Parameter	Performance Criterion in Vendor's Claim	Performance Measured in Phase I*	Performance Measured in Phase II*
TCLP-Cadmium	1.0 mg/L	0.13 mg/L	0.07 mg/L
TCLP-Lead	5.0 mg/L	0.20 mg/L	0.20 mg/L
TCLP-Chromium	5.0 mg/L	0.11 mg/L	0.04 mg/L
Slag to Flyash Ratio	10:1	14.6:1	34:1
Non-Volatile Metal (Cr) Capture in the Slag	60%	80-95%	78-95%
Volume Reduction	25%	35%	25%

*Average results where several measurements were made.

COMPARISON OF PERFORMANCE RESULTS FROM THE SITE DEMONSTRATION WITH THE VENDORS CLAIMS

Synthetic Soil Matrix and Feed Conditions

On the basis of the Phase I and II Emerging Technology projects, Babcock & Wilcox was asked to perform a SITE Demonstration. For the Demonstration, a wet SSM was used. Demonstration goals included the vendor's claims given above.

The SSM used in the SITE Demonstration contained 7,000 ppm lead, 1,000 ppm cadmium, and 4,500 ppm chromium; 6,500 ppm anthracene; 8,000 ppm dimethylphthalate; and the three simulated radionuclides: 4,500 ppm bismuth, 4,500 ppm strontium, and 4,500 ppm zirconium. The rationale for B&W's choice of radionuclide surrogates is as follows: Bismuth was used as a surrogate for volatile radionuclides important at DOE/DOD sites such as cesium (cold cesium was originally proposed but found to be excessively expensive). Cold strontium was used as a surrogate for radioactive strontium (the cold version of the radionuclide is the best possible surrogate). Zirconium was considered an excellent surrogate for radioactive thorium and uranium from the standpoint of both volatility and chemical behavior (all are oxophillic and tend to be in the +4 oxidation state).

A total of 3 tons of SSM were processed during the Demonstration at a feed rate of 170 lb/hr.

Performance Results

A comparison of the Demonstration results against the Vendor's Claims developed for the Demonstration is presented below. All claims tested were exceeded during the Demonstration.

SUMMARY

The Babcock & Wilcox 6 million Btu/hr pilot cyclone furnace met or exceeded all critical and non-critical Vendor's Claims. Because these performance results were measured on a pilot cyclone furnace configured as a utility boiler, and by no means optimized for soil vitrification, a unit designed for dedicated soil vitrification may improve process performance and throughput.

REFERENCE

1. P. Esposito, J. Hessling, B. Locke, M. Taylor, M. Szabo, R. Trumau, C. Rogers, R. Traver, and E. Barth, "Results of Treatment Evaluations of a Contaminated Synthetic Soil," JAPCA, 39: 294 (1989).

Parameter	Performance Criterion in Vendor's Claim	Performance Measured in Demonstration*
TCLP-Cadmium	1.0 mg/L	0.12 mg/L
TCLP-Lead	5.0 mg/L	0.29 mg/L
TCLP-Chromium	5.0 mg/L	0.30 mg/L
Slag to Flyash Ratio	10:1	15.6:1
Non-Volatile Metal (Cr) Capture in the Slag	60%	76%
Non-Volatile Metal (Sr) Capture in the Slag**	60%	88%
Non-Volatile Metal (Zr) Capture in the Slag**	60%	96%
Volume Reduction	25%	28.1%
DRE-Anthracene	99.99%	>99.996%
DRE-Dimethylphthalate	99.99%	>99.998%
CO	<100 ppm	4.8-54.1 ppm
THC	<20 ppm	<5.9-18.2 ppm
Particulates	0.08 gr/dscf***	0.001 gr/dscf***
ANS 16.1 Leachability-Bismuth**	LI > 6	LI = 13.4
ANS 16.1 Leachability-Strontium**	LI > 6	LI = 13.1
ANS 16.1 Leachability-Zirconium**	LI > 6	LI = 8.7

*Average results where several measurements were made.
**Non-critical parameter.
***Corrected to 7% oxygen.

THE ECO LOGIC PROCESS

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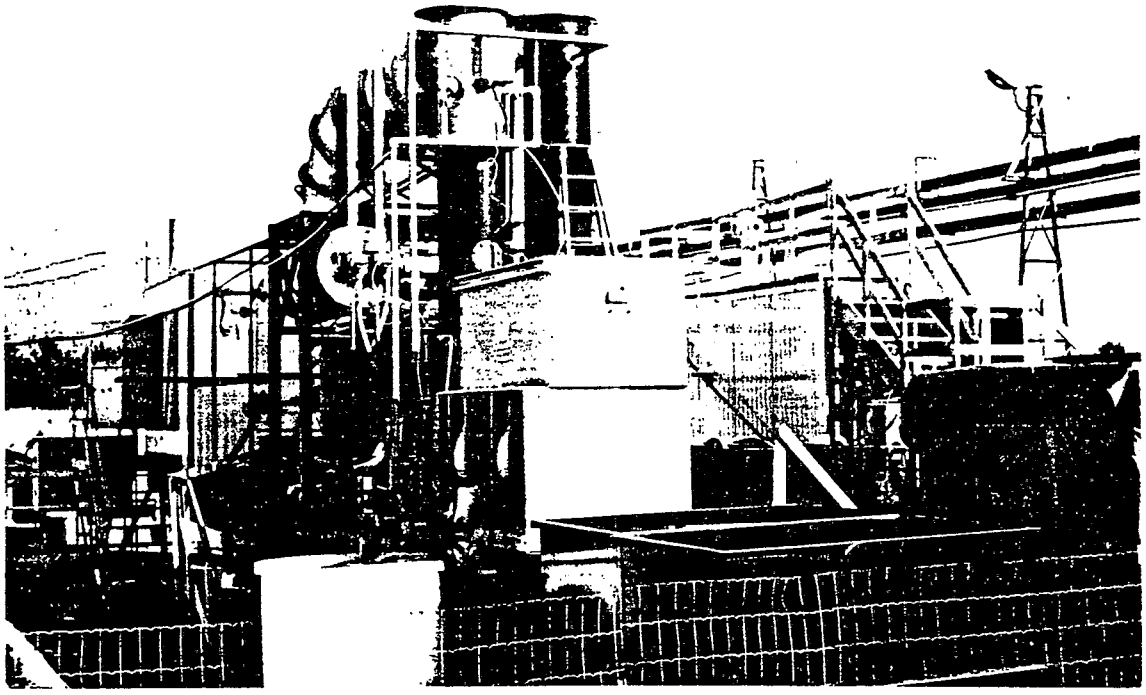

THE ECO LOGIC PROCESS

Douglas Hallett, Ph.D.
Kelvin Campbell, P.Eng.

The ECO LOGIC Process is a high-efficiency destruction alternative to incineration which is particularly suitable for hazardous wastes with a substantial water content. The process is based on the gas-phase thermo-chemical reaction of hydrogen with organic and chlorinated organic compounds. At 850°C or higher, hydrogen combines with organic compounds in a very efficient reaction known as reduction to form smaller, lighter hydrocarbons, primarily methane. For chlorinated organic compounds, such as PCBs, the reduction products include methane and hydrogen chloride. This reaction is enhanced by the presence of water, which can act as a reducing agent and a hydrogen source. Bench-scale, lab-scale, and pilot-scale testing has shown that destruction removal efficiencies (DREs) of 99.9999% can be achieved.

The main features of the patented ECO LOGIC Process include:

1. High destruction efficiency
2. No possibility of dioxin or furan emissions
3. Continuous monitoring and process control suitability
4. Suitability for aqueous wastes
5. Mobility
6. Reasonable cost

The high efficiency of the process has been demonstrated with PCBs, PAHs, chlorobenzenes, and organochlorine pesticides. During the demonstration testing of the pilot-scale system at Hamilton Harbour in the summer of 1991, coal-tar PAHs at levels of 30% (dry basis) in the harbour sediment were effectively eliminated. DREs of 99.99999% were calculated (see Table 1), based on the total organic input and the PAHs analysed in the stack emission. During one test, the liquid waste input was spiked with 500 ppm PCBs, with the result that there were no detectable levels of PCB in the air emission, the processed solids, or the liquid effluents. Based on detection limits for the stack sampling trains, a PCB DRE of at least 99.9999% was achieved.

HAMILTON HARBOUR SEDIMENT

ANALYTICAL RESULTS SUMMARY

3% ORGANIC COAL TAR

Run	Target Analyses	Waste Influent Conc. (ppm)	Decant Water Conc. (ppb)	Grit Conc. (ppm)	Sludge Conc. (ppm)	Stack Gas Conc. ($\mu g/m^3$)	Destruction Removal Efficiency * (%)
P1	PAHs	21,000	483	1.67	32.8	0.27	99.99999
P2	PAHs	30,000	680	7.76	56.1	0.23	99.99999
P3	PAHs	30,000	423	0.37	4.3	0.14	99.99999
P3	PCBs	500	ND	ND	ND	ND	99.9999

* DRE = (Total Input - Stack Emissions) / (Total Input)

One of the distinct differences between the ECO LOGIC Process and incineration processes is that there is no possibility of dioxin or furan formation with the reduction process. These compounds can be formed by the incomplete oxidation of PCBs, but in an actively reducing atmosphere with an abundance of free hydrogen and no free oxygen, the possibility of their formation is eliminated.

The use of hydrogen as an active reducing agent in the process also creates a product gas of low molecular weight without the formation of heavier hydrocarbons common to pyrolysis processes. This product gas is suitable for continuous monitoring, and ECO LOGIC has included in the process control design a very sophisticated on-line mass spectrometer which can monitor organic compounds continuously in the parts per billion range. This allows the operator and the process control system to effectively monitor destruction efficiency by selectively analyzing for trace concentrations of known breakdown products of the hazardous waste.

Another feature of the ECO LOGIC Process is its ability to process aqueous wastes. Water does not inhibit, but actually enhances the reduction process, and also provides a source of hydrogen through the water shift reaction with methane. After the destruction of the organic contaminants in the reduction reactor, the water and the HCl produced are removed in a scrubber and the clean, dry product gas can be recirculated back to the reactor or used as supplementary fuel in the propane boiler. At Hamilton Harbour, approximately 97% of the product gas was recirculated to take advantage of the hydrogen content, and about 3% was sent to the boiler. The boiler produced steam which was used to pre-heat the waste prior to injection into the reactor.

Other features of the ECO LOGIC Process are the high degree of mobility and the reasonable operating cost. The process is mounted on two standard drop-deck highway trailers and is easily set up and taken down. The relatively small size and capital cost help keep the operating cost per tonne fairly low. The price for processing high moisture-content matrices such as contaminated soils, sludges, and sediments is projected to start at $400 per tonne for the first 100-tonne/day commercial unit. High-strength PCB liquids can be processed at the same time as environmental wastes with only a limited price increase.

WASTES SUITABLE FOR DESTRUCTION

CHEMICALS:

Non-halogenated / halogenated biphenyls
Non-halogenated / halogenated benzenes
Non-halogenated / halogenated phenols
Non-halogenated / halogenated cycloalkanes
Non-halogenated / halogenated alkanes
Non-halogenated / halogenated dioxins
Non-halogenated / halogenated dibenzofurans
Polyaromatic hydrocarbons

* Note: Halogenated means: Chlorinated
Brominated
Fluorinated

TYPICAL WASTES:

PCBs
Pulp mill wastes
Chlorinated solvent waste
Contaminated coal tars
Solvent still bottoms
Chlorophenols / Wood treatment waste
Pesticide wastes
Landfill leachates
Lagoon bottoms

The ECO LOGIC Process has been accepted into the US EPA Superfund Innovative Technology Evaluation (SITE) Program, following the successful demonstration at Hamilton Harbour last summer. A demonstration program in the autumn of 1992 at a landfill site in Michigan will be funded by ECO LOGIC, Environment Canada, and Environment Ontario, and the evaluation will be performed by the US EPA. The site is contaminated by a dense oil containing approximately 40% PCBs. This oil will be processed along with contaminated groundwater and contaminated soil, in separate streams, as in Table 2.

ECO LOGIC began operation in 1986 when Dr. Hallett proceeded to patent the gas phase thermo-chemical reduction process for the destruction of high hazardous organic chemicals. Research has led to subsequent inventions in on-line continuous emission/process monitoring using chemical ionization mass spectrometry, and computerized process control systems and software for hazardous waste. The company's mission is to manufacture, supply, operate, and service high technology for the destruction or control of hazardous chemicals and the remediation of hazardous waste landfills, lagoons, soils, and sediments.

ECO LOGIC will enter the market to supply hazardous waste destruction services itself with its own machines, and to license and sell equipment to companies that already supply services, or to licence and sell to large chemical producers or users where ownership is economically advantageous. The service market is the initial focus in order to demonstrate the machine and obtain approvals in jurisdictions where units will be licensed and sold when the technology has buyer (versus user) acceptance.

We would encourage interested parties with organic hazardous waste problems to contact our offices in Rockwood and Ann Arbor.

This offers potential clients the opportunity to obtain direct information on the application of this technology to the resolution of their hazardous waste problems.

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Jim Nash, B.A.
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Sales and Business Development
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During September and October, 1992, The U.S. Environmental Protection Agency, in co-operation with the City of Bay City, Environment Canada, and the Ontario Ministry of the Environment will sponsor a demonstration and evaluation of the ELI Eco Logic Process at Bay City's Middleground Landfill. This demonstration will occur under the auspices of the U.S. EPA's Superfund Innovative Technology Evaluation (SITE) Program.

HAZARDOUS WASTE DESTRUCTION DEMONSTRATION
BAY CITY, MICHIGAN

1. OILY WATER (7 T/DAY)

- 5 kg/min contaminated water (TCE)
- .05 kg/min PCB oil (40% PCBs)

  (feed concentration of 4000 ppm PCBs)

2. SOIL (15 T/DAY)

- 10 kg/min contaminated soil (1000 ppm PCBs)
- 1 kg/min contaminated water (TCE)

3. OIL/WATER (3 T/DAY)

- 1 kg/min PCB oil (40% PCBs)
- 1 kg/min contaminated water (TCE)

  (feed concentration 20% PCBs)

4. 72-HOUR RUN OF 1 OR MORE OF 3 CASES ABOVE

BioGenesis℠ Soil Washing Process
Technology Summary

GENERAL DESCRIPTION

- The BioGenesis℠ soil remediation technology is capable of extracting volatile and non-volatile oils including crude oil, chlorinated hydrocarbons, pesticides, and other organics from most types of soil and clay. A single "Soil Remediation Unit," using a complex bioremediating surfactant and water, washes 25 to 30 tons of soil an hour, depending on the pollutant, contamination level, and soil type.

DEVELOPMENT STATUS

- Being introduced to the United States as part of the EPA's Superfund Innovative Technology Evaluation (SITE) Program.
- First commercial use in October, 1992, removing crude oil from contaminated soil at mid-west refineries; work in progress to complete cleaning of over 5,000 cubic yards by early 1993.

SPECIAL FEATURES

- Wastes are reduced to recyclable oil, treatable water, and active soil suitable for onsite backfill.
- Treats both volatile and non-volatile oils.
- Complex surfactant used is safe, 100% rapidly biodegradable, and has low toxicity.
- Processing rate is 25-35 tons per hour for one washer unit.
- Organics do not combine with the surfactant.
- Surfactant enhances the biodegradation of residual contamination.
- Potentially effective on broad range of chlorinated hydrocarbons, pesticides, PCBs, and other organic pollutants.
- Treats soils with high clay content and heavily weathered soils.
- No air pollution except that connected with excavation.
- No toxic by-products produced besides the contaminant removed.

PLANNING FACTORS

- *Variables.* Contaminant, amount of contamination, soil type, job size, and cleanup target.
- *Effectiveness.* Heavy hydrocarbons, one wash-95%, two washes-99%+; light hydrocarbons, one wash-97 to 99%. Residuals polished through biodegradation.
- *Cost.* $40-180 per ton depending on the variables; average range $60-100 per ton.

EQUIPMENT & MANPOWER

- *Equipment.*
  - Earth moving equipment.
  - Truck mounted washer unit, 20 cubic yards capacity.
  - Hydrocyclones, centrifuge, and flotation units for the separation of fines.
  - Gravity separators and coalescing filters for oil water separation.
- *Manpower.* The mobile system is operated by five personnel: a system supervisor, a test director, two operators, and a materials handler.

BioGenesis Enterprises, Inc.

CHICAGO, ILLINOIS • TEL (708) 827-0024 • WASHINGTON, DC • TEL (703) 250-3442

FULL SCALE FIELD RESULTS

3% CRUDE OIL CONTAMINATION, MINNESOTA REFINERY, ONE WASH, METHOD 9073 TESTING, mg/kg			
Soil Fraction	TRPH Level Before	TRPH Level After	Extraction Percent, One Wash
Large Particles > 40 Mesh	30,800	1,620	**95%**
Fines < 40 Mesh	30,800	4,520	85%

BIODEGRADATION OF RESIDUAL CONTAMINATION AFTER ONE WASH, METHOD 9073 TESTING, mg/kg		
Days After Washing	TRPH, Fines < 40 Mesh	Cumulative Effectiveness, Fines
Zero	4,550	85%
Seven	2,200	93%
Fourteen	1,300	**96%**

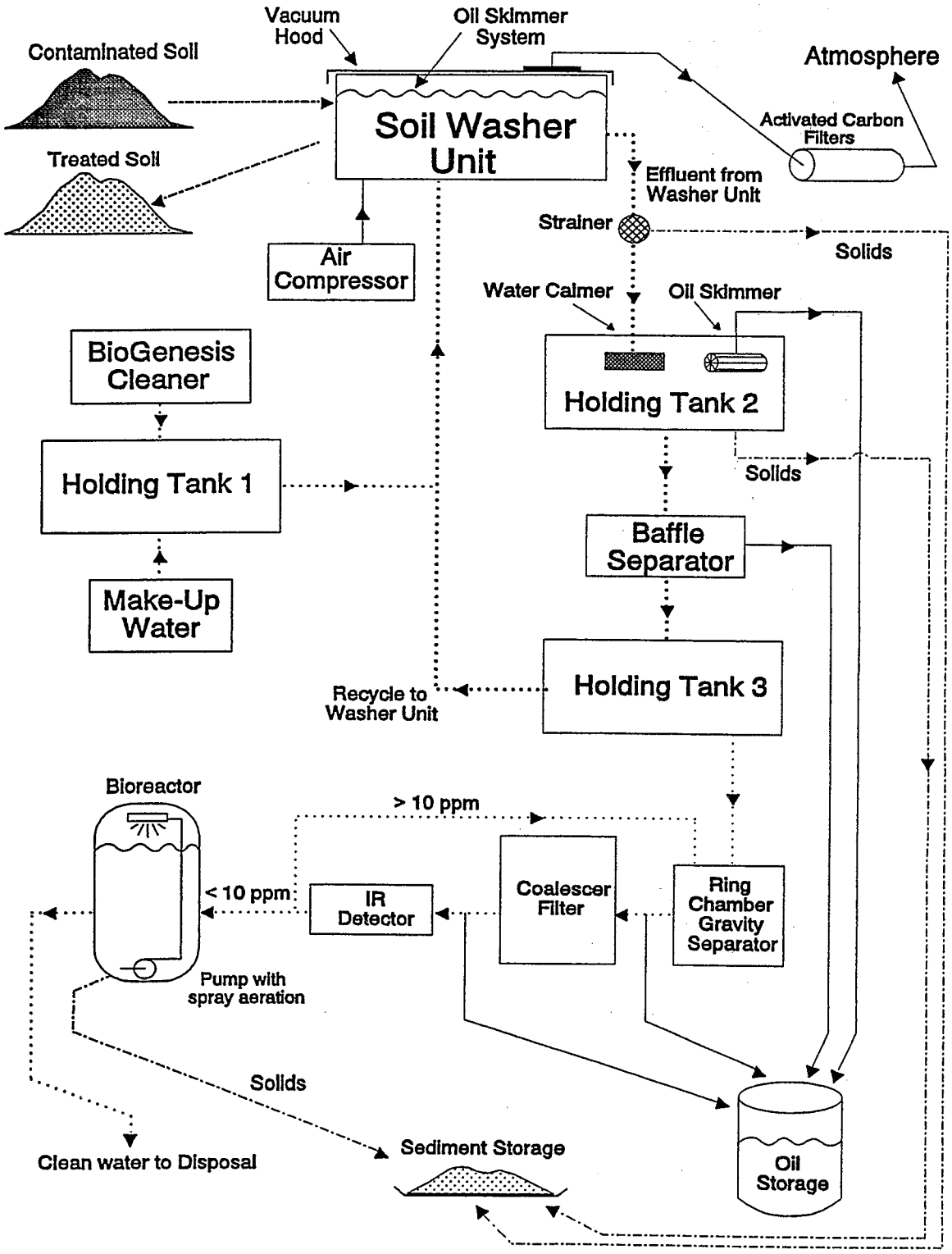
BTEX REMOVAL EFFECTIVENESS, FINES < 40 MESH, ONE WASH, METHOD 8020 TESTING, mg/kg			
Contaminant	Unwashed Soil	Fines < 40 Mesh	Removal Effectiveness, Fines, One Wash
Benzene	< 0.24	< 0.024	90.0%
Toluene	< 0.25	0.034	86.4%
Ethylbenzene	1.2	< 0.016	98.7%
Xylenes	4.3	0.073	98.3%
Total BTEX	5.99	0.147	**97.6%**

SIEVE ANALYSIS, UNWASHED SOIL AND FINES				
Percent Passing →→→	10 Mesh	40 Mesh	120 Mesh	200 Mesh
Unwashed Soil	72	18	4	3
Fines	100	94	33	11

CONTACT POINT

- Charles Wilde, TEL: (703) 250-3442, FAX: (703) 250-3559

BioGenesis℠ Soil Washing Process

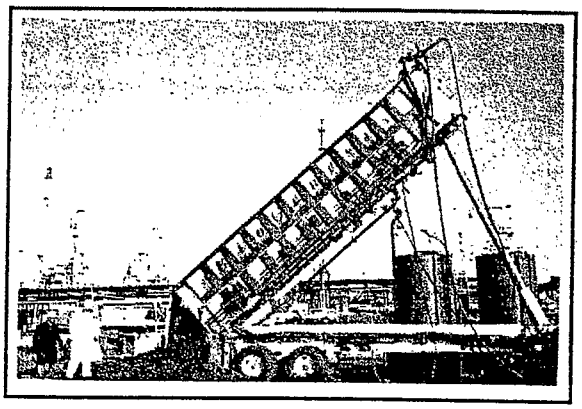


BioGenesis℠ Soil Washing Process

The BioGenesis℠ process is designed to treat soils and other types of solids contaminated with organic compounds, including volatile and non-volatile hydrocarbons. The treatment is a two-stage process; first, extract contaminants from soil using water and BioGenesis℠ cleaner; second, accelerate the biodegradation of residual soil contamination and contaminant-rich wastewater.

The major components of the treatment system include the following:

- *Soil washing unit.* This is the principal component of the treatment system. The unit holds 20 cubic yards, about 25 tons. The washer has a perforated bottom to introduce air for mixing and to drain wastewater. A poly-canvas hood with vacuum extraction covers the top of the wash unit to collect any organic compounds volatilized during treatment.



- *Oil skimmers.* Oil is skimmed from the surface of the soil and water mixture. Oil can be skimmed two ways. A manual method requires workers to skim oil from the top of the water to the Baffle Separator. A mechanical method uses rising water to push the oil/water into a system that runs through an elastometer belt. Oil clings to the belt while water flows through.

- *Strainers.* Strainers are located at the ends of the oil skimmer troughs on the wash unit. The strainers prevent floating debris from damaging the transfer pump.

- *Two 7.5-horsepower (hp) transfer pumps.* These pumps are used to transfer wastewater from the wash unit to the baffle separator.

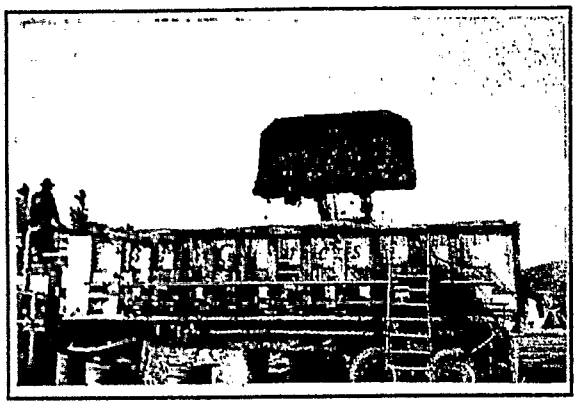
- *Baffle Separator.* This unit is used as a primary separator to separate oil from the waste water through a series of baffles.

- *Gravity Separator and Oil Coalescer.* These units are used as a secondary separators to separate the oil phase from the wastewater. The unit is equipped with an infrared (IR) detector. The detector controls a diversion valve that depending on oil concentration in the water, either returns the water to the influent line and to the gravity separator or to the bioreactor.

- *Bioreactor.* The bioreactor is a cylindrical shaped tank with a holding capacity of approximately 5,000 gallons. At the end of operations, wastewater from the oil/water separators is transferred to the bioreactor. A specially formulated BioGenesis℠ solution is added to the bioreactor to stimulate biodegradation of residual contamination in the wastewater. Within the bioreactor, water is mixed by pumping it through a spray aerator fitted above the liquid phase. The bioreactor is covered with an activated charcoal filter to minimize losses due to volatilization.

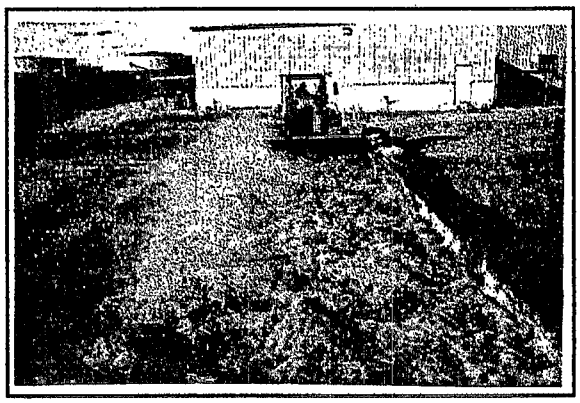
- *One 48-foot flat bed trailer.* This trailer houses a 200-ampere (amp), 480 VAC,

cooled air compressors; a vacuum source; and a gravity separator and oil coalescer.

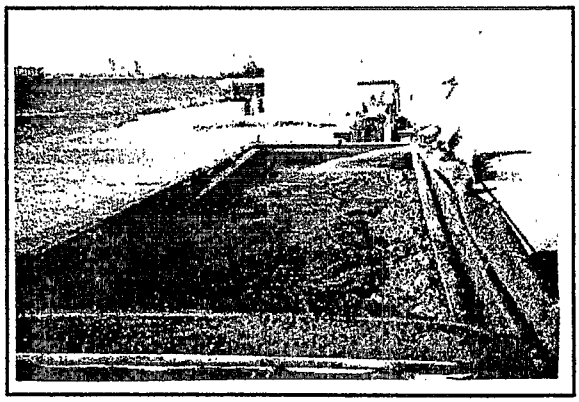


The BioGenesis℠ process begins by introducing approximately 1,000 gallons of water into the wash unit. Next, contaminated soil is added to the wash unit, normally with a front-end loader. The wash unit is capable of treating 20 cubic yards per batch. If volatile organic compounds (VOC) are present, the wash unit is covered with a retractable canvas cover. A positive air flow is drawn through the back of the wash unit, creating a negative pressure within the unit. Air flow is directed to strip away any VOCs. Volatile emissions, if any, are passed through a granular activated carbon filter before being vented to ambient air.

Water and BioGenesis℠ cleaner are premixed in a 4,800-gallon holding tank (Holding Tank 1) and pumped into the wash unit. A typical wash requires approximately 2,500 gallons of water and 8 gallons of BioGenesis℠ cleaner. The resulting slurry is agitated by a series of aerators in the bottom of the wash unit. After the soil slurry is mixed for a period of time, air is turned off, and water is added to raise the fluid level to allow floating oil product to flow out of the unit via ports located 8 inches from the top of the unit into a holding tank (Holding Tank 2). After the floating product is removed, the soil slurry is agitated again for a period determined by the operator. The fluid level is again raised to allow for oil/water to be removed through the ports. Soil settles to the bottom of the wash unit.

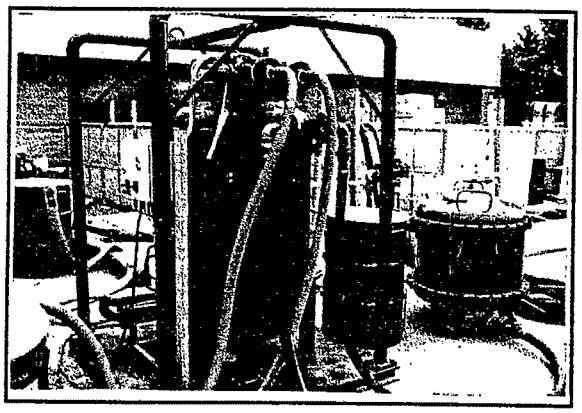


Wash water from the bottom of the wash unit and oil/water exiting through the ports are pumped to Holding Tank 2 which is equipped with an oil skimmer. After the water has drained from the treated soil, the operator inverts one end of the wash unit, dumping the soil onto the ground whence it is moved by front loader to a clean soil holding area pending test and final clearance.



In Holding Tank 2, the oily material removed by the skimmer is pumped to 55-gallon drums. Material not removed by skimming is pumped to a baffle separator. The use of the baffle separator is optional based on the operator's discretion. Any oily material recovered from

the baffle separator is pumped to 55-gallon drums. Water from the baffle separator is then directed to a 4,800-gallon holding tank (Holding Tank 3) for storage prior to reuse in the wash unit. Approximately 15 percent of the wash water is retained in the soil; therefore, make-up water and BioGenesis℠ cleaner must be added to the recycled water as needed. Any make-up water for the next batch of soil is supplied from Holding Tank 1.



Once all runs are complete, the water in Holding Tank 3 is processed through the oil/water separation unit, which includes a ring chamber gravity oil/water separator and an oil coalescing filter. Water from the coalescer is monitored by an infrared (IR) detector and is directed to a bioreactor if the oil concentration is below 10 ppm. If the oil concentration is above 10 ppm, the water is recycled through the gravity separator and coalescer until the oil concentration is below 10 ppm. Oily material from the gravity separator and the coalescer is pumped to 55-gallon drums. Sediments from the wash unit, Holding Tank 2, the baffle separator,and the bioreactor are stored in storage bins and covered with plastic sheets. Samples from the sediment storage and treated soil storage are collected over a period of time and analyzed for chemical composition.

Soil washing, the BioGenesis℠ method, excavates soil with earth-moving equipment, separates contaminants in a washing process, and returns the soil to the excavated area. It positively removes the contaminant, works on-site, and produces no toxic byproducts except the contaminant removed.

Historically, difficulties with washing chemicals, equipment efficiency, and inability to treat soils with more than 30% clay have impeded implementation of soil washing. BioGenesis℠ solves these problems with its complex surfactant mixtures and efficient washing equipment. BioGenesis℠ soil washing is competitive with other technologies in almost all situations. The determining factors of price are soil type, contaminant type, dirtiness, job size, and cleanup target.

Steam Enhanced Recovery Process (SERP)

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ABSTRACT

In-situ steam enhanced recovery, utilizes formation tailored injected low pressure steam to establish temperature and pressure gradients to improve the migration of hydrocarbons through the soil. Vapor, free-liquid hydrocarbons and condensate are removed using specially designed vapor extraction wells. Steam enhances removal of hydrocarbons and allows extraction of heavier petroleum products by elevating the vapor pressure and reducing the viscosity, thereby inducing greater hydrocarbon mobility. The time required to remove hydrocarbon vapors and liquids is reduced and removal efficiency is increased, with consequent reductions in project cost. Vapors and liquids are treated at the surface using thermal oxidation and waste water treatment respectively.

INTRODUCTION

Steam injection remediation was a diversification of the Enhanced Oil Recovery (EOR) process in use by the petroleum industry since the 1950's (Hong 1989). Brought to the environmental industry by the Dutch firm of Heidemij Reststoffendiensten, laboratory studies, research and pilot projects in the United States (Hunt, et al, 1988/1989) followed. As a result of available data and site requirements, the Steam Enhanced Remediation Process was selected for use at a large industrial site in Southern California (Dablow, 1991). This paper addresses unique aspects of the project as well as provided an update of the current status.

PROJECT SITE

The Rainbow project resulted from the inadvertent puncture of a diesel fueling manifold during construction activities. Undiscovered

for about two years, estimates of 20,000 - 100,000+ gallons of fuel leached down to the groundwater and migrated offsite to the north and west. Sediments of the contaminated formation consists of several feet of fill material, partially cemented sands, and clayey silts with lenses of fine to medium sand. The fuel leak formed a column approximately 100 feet in diameter that migrated downward, spreading laterally as less permeable mud's were encountered. Upon penetrating the mud's, downward migration continued, stopping where ground water was encountered.

The plume of greater than two acres was located primarily under a trash recycling and transfer station. Expansion requirements required an accelerated remediation, as did the need to prevent further offsite migration. A high volume of traffic (500 - 700 trucks per day/6 days, two shifts) required an in-situ process that did not impede operations or interfere with traffic. Construction was completed and all operating permits received to commence remediation in April 1992.

SYSTEM DESIGN AND DEVELOPMENT

System design was based upon soil characteristics, estimated soil volume, well spacing and quantity, and temperature/pressures necessary for vaporization. The design was selected to accelerate the remediation of the large area impacted. Extensive sampling and characterization of the site were combined with bench scale testing and modeling to determine injection and extraction well influence radius and well placement. 37 injection wells were placed to totally surround the plume to stop offsite migration and to move contaminant towards the center of the plume. Oversized boilers were specified to provide the capacity for rapid heating of the entire site. 39 extraction wells were designed and installed for the dual purpose for vapor and product/condensate recovery. It was anticipated that 90% of the contaminant recovered would be liquid phase which would be treated by an oily water separator, micron filtration system and polished by activated carbon. Vapor treatment utilized a packed bed thermal oxidizer. 80% of the injection wells, extraction wells and system piping were placed in trenches and covered. All work on the trash transfer station site was accomplished on the third shift Monday through Saturday or on Sundays.

PROJECT STATUS

Remediation is in full swing. Significant delays were encountered as a result of under estimations of the permitting processes and the need to throttle down key injection wells while an alternative for the underground fueling system was designed, permitted and installed. At this point only small traces liquid phase hydrocarbons have been recovered. Four thousand four hundred gallons of free product were recovered and fourteen thousand gallons have been recovered by the vapor extraction system in five months of effective system operation. Approximately 1200 CFM of vapor are flowing into the thermal oxidizer with Total Petroleum Hydrocarbons (TPH) gradually increasing from 700 ppm to a current level of about 3,000 ppm. As a result more than two thousand gallons per month are being recovered.

CONCLUSIONS

The Steam Enhanced Recovery Process appears to be effectively removing diesel fuel from the soil and perched aquifer. The plume has been reduced to 20-30% of its original volume. System design has allowed monitoring, control and manipulation of pressure and vacuum gradients to protect underground tanks and to focus on specific areas to be remediated. Monitoring wells have not detected unwanted migration of hydrocarbons offsite or into lower aquifers. To date no interruption of site operation has occurred.

The use of the steam enhanced recovery process when applied to appropriate substances, offers the following advantages over other techniques:

- Enhances removal of volatile and semivolatile hydrocarbons
- Effective for heavy hydrocarbons
- Not limited by soil concentrations
- Process easily monitored and verified
- In-situ process with minimal surface impact

The following disadvantages of steam enhanced recovery process should be considered:

- Capital costs
- A cap may be necessary for remediation on sites with high vertical permeability surface conditions
- Extensive permitting maybe required

- Trained boiler technicians may be needed as part of the O&M team

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Hong, K.C., 1989 "Recent Advances in Steamflood Technology",. represented at the 1989 Indonesian Petroleum association Convention.

Hunt, J.R. Sitar, N. and Udell, K.S., 1988 "Non aqueous Phase Liquid Transport and Cleanup", Water Resources Research, volume 24.

Udell, K.S., and Stewart, L..D., 1989 "Mechanism of In Situ Remediation of Soil and Groundwater Contamination by Combined Steam Injection and Vacuum extraction", Paper No. 119d presented at the Symposium on thermal Treatment of Radioactive and Hazardous Waste at the AICHE annual meeting, San Francisco, California, November 6, 1989.

SOIL VENTING TO REMOVE DBCP FROM SUBSURFACE SOIL: A CASE HISTORY

M.B. Bennedsen, F. Gomez, C.R. Kneiblher, J.D. Dean, J. Scott
Woodward-Clyde Consultants

ABSTRACT

Dibromochloropropane (DBCP) was widely used as a soil fumigant for the control of nematodes during the 1970s. In 1979, the EPA restricted its use, primarily because of its toxicity to mammals. In the early 1970s, a spill of about 3,100 gallons of DBCP occurred at an agricultural chemicals distribution facility in the San Joaquin Valley of California. Groundwater at the site is at a depth of about 100 feet. The vadose zone soils are alluvial, moderately stratified, and vary from silty fine sands to coarse sands with some gravel. In the 1980s DBCP was detected in the area groundwater, and investigations in the vicinity of the spill found DBCP throughout the soil column above the water table. Because of the depth of the soils contamination, and the existing facilities at the surface, only in situ remedial technologies were considered feasible. DBCP has a melting point of 6.7°C and low vapor pressure at ambient soil temperatures. However, the decision was made to try soil venting for removing the vapor phase component and possibly stimulating biodegradation of the liquid phase component of the material. The system installed for the purpose has been operating since January 1992, and at this time has removed several hundred pounds of DBCP plus many thousands of pounds of CO_2 from the area soil. The focus of this paper is to provide additional information on the design and operation of the installed soil venting system. The project is considered of interest to this conference because of the nature of the contaminant, the use of an on-line G.C. to provide a continuous and current record of system performance, relatively low costs for operations and because it does not interfere with on-going facility operations.

During the 1970s an estimated 3,100 gallons, or about 60,000 pounds, of 1,2-dibromo, 3-chloropropane (DBCP) were accidentally released onto the ground surface during a rail tank car unloading operation. The material is known to be toxic to mammals. The release occurred at an agricultural chemicals distribution facility, in the Central Valley of California. Soils in the area of the spill are alluvial, varying from silty fine sands to coarse sand with some gravel, and some stratification. Soil samples, collected in the late 1980s from throughout the vadose zone, contained detectable DBCP concentrations. Also, DBCP has been detected in the area groundwater, which is at a variable depth, but generally in the range of about 90 to 110 feet below the ground surface. Limiting or preventing further migration of DBCP from the soil to the groundwater was clearly desirable.

Because of the depth of the soils contamination, and the physical constraints created by existing facilities surrounding the spill site, only in situ remedial techniques were considered applicable. In consultation with the State of California, Environmental Protection Agency, Department of Toxic Substances Control, Alternative Technologies Division, and with the concurrence of the California Regional Water Quality Control Board-Central Valley Region, it was agreed that soil venting might be an appropriate technology in this instance. A short term venting test (a few hours) demonstrated that venting could remove DBCP from the soils at a significant rate. Based on the test results, and a proposed venting system design that would prevent discharge of extracted DBCP to the atmosphere, the Department of Toxic Substance Control granted a Variance From Permit Requirements, for a two-month, trial program operation. At the conclusion of the trial program operation, and based on the results of the operation, an Extension of the Variance From Permit Requirements was granted to allow an additional year of operation. The venting process was considered experimental in this application because the vapor pressure of DBCP, at ambient soil temperature, is about 1 mmHg, and near the lower limit generally considered appropriate for soil venting.

Three soil borings had been drilled in the area of the spill to assess the extent of the contamination. The borings were located within the areas of maximum contamination as determined by a soil gas survey. One of the borings was completed as a groundwater monitoring well. For the short-term venting test, three vapor extraction/soil venting wells were installed with 2-inch-diameter PVC casing and with screened intervals extending from 20 to 40 feet, 40 to 60 feet, and 60 to 80 feet, respectively, below the ground surface. Figure 1 presents simplified stratigraphic data for the soils penetrated by these wells, and data on contaminant concentrations in soil samples collected during the drilling of the wells.

The borings were on a line paralleling, and about 10 feet from the rail spur on which the tank car was set when the spill occurred. The in-line separations between the wells were about 13 feet and 40 feet, respectively. The borings were advanced using dual-tube reverse-circulation drilling techniques, and the boring diameters were about 10 inches. Because of the toxic properties of DBCP, the drill crew worked in Level B protective equipment — i.e., fully covered and with supplied air.

To make a preliminary assessment of the applicability of soil venting at this site, and to obtain design information in case the technique was judged applicable, the short term test, mentioned above, was performed. The test demonstrated that it was possible to extract at least 100 cubic feet per minute (cfm) of soil gas from each of the three wells, at an applied well head vacuum of about one inch, mercury gage (1 in. Hg). Also, based on the soil gas extracted during the test, it was estimated that a production VES would initially extract a gas containing 10 to 15 parts per million, volumetric (ppmV) DBCP. This extraction rate was considered sufficient to justify installation and operation of a production type soil venting system. Again, it is noted that the short-term test was performed with the test crew utilizing Level B protective equipment.

Based on the results of the short-term test, a vapor extraction system was designed and installed at the site. The major system components, in the order of flow were: wells, valved manifold, air/water separator drum (knockout tank), two carbon tanks in series, blower, silencer, and discharge stack. To monitor the system performance, an on-line gas chromatograph (GC) was included. The GC was equipped with an electron capture detector and an automatic, programmable sampling pump and a multiport sampling valve connected to the gas stream at the inlets to the first and second carbon canisters, the discharge from the second canister, and to the atmosphere as a reference point for system blanks. The carbon canisters were located upstream from the blower, where they would operate under negative pressure relative to atmospheric. The objective was to prevent the possible release of untreated, extracted soil gas to the atmosphere.

In November 1989 the system was initially operated. However, it operated for only about 100 hours before excessive pressure drops occurred in the flow through the carbon canisters, and the lid of the number two canister collapsed. Investigation of the cause of failure revealed that ammonia salts had plugged the carbon. Low ambient temperatures — about 30° to 40°F — at the time of the operation, probably contributed to solids formation. During the initial operation, a strong ammonia odor was noticed in the gas discharged from the system. It is known that large quantities of ammonia based fertilizers are handled at this facility, and it is expected that leaks or spills thereof resulted in ammonia being present in the extracted soil gas. Because all work associated with installing the VES wells, and performing the initial short-term test, had been done with the workers in Level B protective equipment, they had had no opportunity to smell the presence of ammonia in the area soils, or in the gas extracted from the wells during the test. In addition, the laboratory analyses on the associated soil and gas samples were not programmed for, nor capable of, detecting ammonia. Therefore, the initial system design included no provisions for accommodating ammonia.

Following this initial failure, the system was modified by addition of an air stream heater, installed between the water knockout tank and the carbon tanks. Regulatory approval of the revised design was received and authorization to operate was based on the original Variance From Permit Requirements. A schematic diagram of the system following the modification is included in Figure 1.

SCHEMATIC OF SOIL VENTING SYSTEM FOR REMEDIATING DBCP CONTAMINATED SOIL

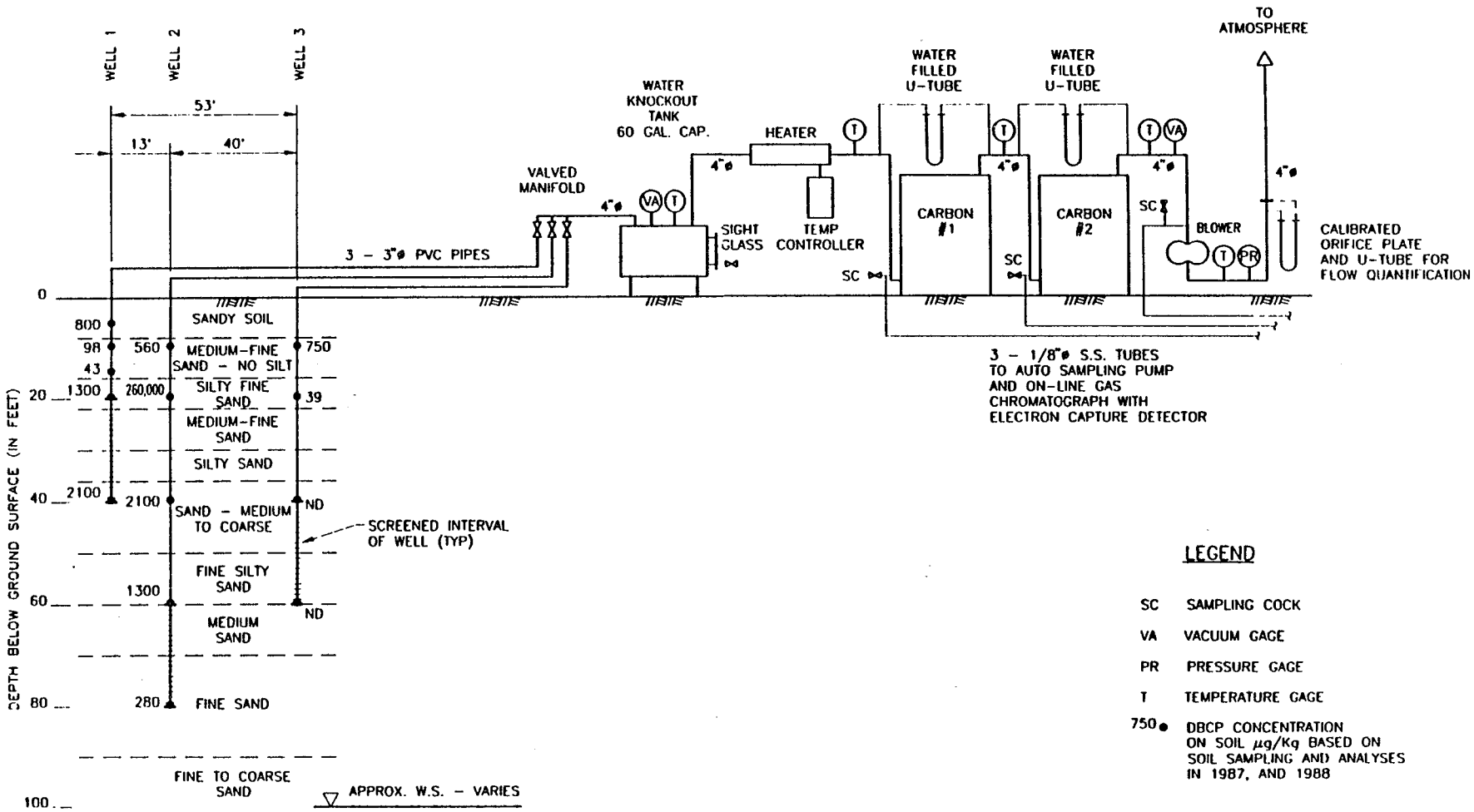


Figure 1

The addition of an electric heater, immediately downstream from the knockout tank, was intended to maintain the gas stream at a temperature above the point at which water could accumulate or solids form in the carbon. Also, the revised design included addition of water filled, U-tube manometers for monitoring the pressure drops through the carbon canisters. Start-up of the reconfigured VES occurred January 14, 1992, and the operation has been essentially continuous since then. The balance of this report is devoted to the information learned from the continued operation.

PROPERTIES OF DIBROMOCHLOROPROPANE

The compound 1,2-dibromo-3-chloropropane (DBCP) formerly was widely used in California, in the fruit and vegetable growing industry, as a soil fumigant for the control of nematodes. However, since 1979, its use has been restricted to Hawaii, for cultivation of pineapples only, primarily because of its toxicity to mammals. Acute toxicity studies have identified the kidneys, liver, and testes as the primary target organs of DBCP. Other properties of DBCP are:

Melting point	6.7°C
Boiling point	195.5°C
Molecular weight	236.33
Specific gravity at 20°C/20°C	2.5
Solubility in water at 19°C	<1 mg/ml

When used as a fumigant, DBCP is considered to have a half-life in the soil of about 2 years, but of course, this factor is a variable, depending in large measure on site specific conditions, such as soil texture and climate. Probably it is not appropriate to extrapolate this half-life value to concentrated releases, such as occurred at this site, and where the material has penetrated tens of feet below the soil surface. It is likely that the material has been toxic to all or most soil bacteria, at least in the areas where it is or was most concentrated. However, it is noted that, based on data from investigations conducted at the site in the late 1980s, it was possible to account for only about 1,000 pounds of DBCP in the site soils. It is further noted that the time that has elapsed since the spill occurred (about 20 years), the quantity spilled (about 60,000 pounds), and the residual contamination accounted for in the soil (less than 1,000 pounds) are qualitatively consistent values for a material having a half-life of 2 to 3 years and a time frame corresponding to about 6 half-lives ($64{,}000 \div 2^6 = 1000$).

PERFORMANCE MONITORING

To assess the performance of a vapor extraction system it is necessary to measure the quantity of gas extracted from the soil and the concentrations of target compounds in the extracted gas. On this project, flow quantification is accomplished by monitoring differential pressures across a calibrated orifice plate inserted in the system discharge-to-atmosphere stack. Differential pressures are measured, in inches water column (in. H_2O) using a U-tube manometer connected to the pressure taps provided with the orifice plate. A calibration

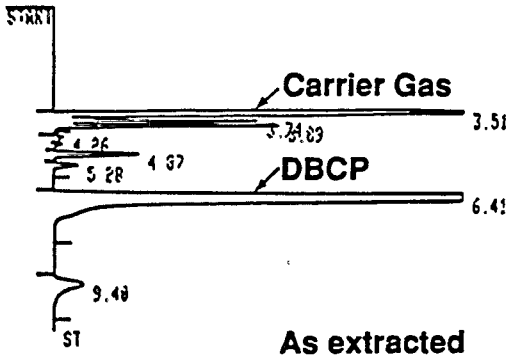
curve, provided by the plate manufacturer, indicates flows, in cubic feet per minute, as a function of differential pressures. The VES is equipped with a positive displacement blower and operated at constant speed. The only significant changes in flow occur as a result of adjusting the control valves on the pipelines to the extraction wells and thereby the vacuum against which the blower operates. System flow to date has been within the range of 220 to 260 ambient cubic feet per minute (acfm). The estimated average flow is approximately one million cubic feet every three days.

The concentration of DBCP in the extracted gas stream is considered the primary variable to be monitored, for evaluating the performance of the VES. For this purpose, the system is equipped with an on-line GC that periodically analyses the gas extracted from the ground. For most of the operation to date, the system has been programmed to sample and analyze the extracted gas stream every eight hours. In addition, as part of each monitoring cycle, samples are collected and analyzed from the discharge of each carbon canister, to check for DBCP saturation in the first carbon canister, and to document that DBCP is not being released to the atmosphere in the gas discharged from the second canister. Also, in each analytical cycle, a sample of atmospheric air is analyzed to serve as a system blank. In Figure 2 is presented a copy of a typical strip chart produced by the GC during one complete analytical cycle. It may be seen in the figure that a peak for DBCP appeared only in the analysis of gas as extracted from the soil.

Backup checks to the data generated by the on-line GC are provided by passing calibrated flows of gas, from the same four sources, through sampling tubes containing granulated activated carbon (GAC), and submitting the samples to an independent, certified laboratory for extraction and analyses. These checks are routinely made each time the WCC project chemist visits the project site to check and adjust the overall system operation (i.e., once every two weeks). During these site visits, calibration checks are run on the on-line GC. If the calibration checks indicate that the results have drifted outside the range of acceptable accuracy the unit is recalibrated and the integrator reprogrammed with a revised response factor.

Secondary constituents of the extracted gas stream that are routinely monitored are carbon dioxide, oxygen and ammonia (CO_2, O_2, and NH_3). The concentrations of those three gases are checked by the project chemist during each site visit. The checks are made using compound specific, color reactive cartridges (Gastec™) and a hand-held, calibrated, piston-type pump (Sensidyne™) to draw measured quantities of gas through the cartridges, in accordance with the manufacturer's specifications. The concentration is indicated by the length of analyte in the cartridge that changes color, and is read directly from a scale printed on the cartridge.

TYPICAL ON-LINE G.C. PRINTOUT



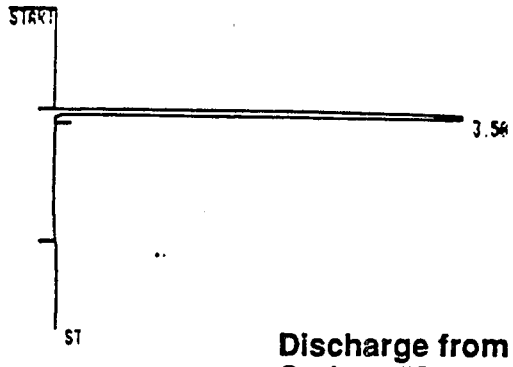
As extracted from soil

RUN # 2845 SEP/16/92 02:49:30
WORKFILE ID: A1
WORKFILE NAME:
ID: 1

ESTD

RT	AREA	TYPE	CAL #	AMOUNT
3.51	9775100	DSBB		0.000
3.74	748930	D BV		0.000
3.89	662340	D VB		0.000
4.26	44657	BV		0.000
4.87	375350	PP		0.000
5.28	128080	PB		0.000
6.41	2.2864E+07	SBB	1	1.258
9.40	404060	PB		0.000

TOTAL AREA= 3.4992E+07
MUL FACTOR= 1.0000E+00



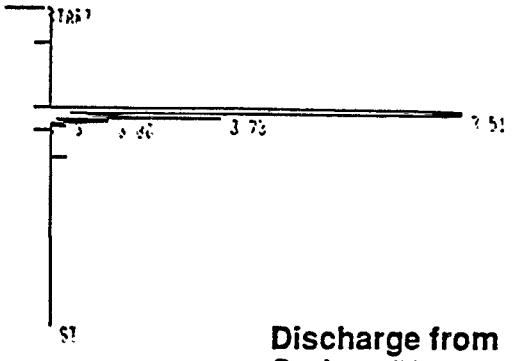
Discharge from Carbon #2

RUN # 2847 SEP/16/92 06:47:42
WORKFILE ID: A1
WORKFILE NAME:
ID: 1
NO CALIB PEAKS FOUND

AREA%

RT	AREA	TYPE	AR/HT	AREA%
3.50	9535400	DSBB	0.066	100.000

TOTAL AREA= 9535400
MUL FACTOR= 1.0000E+00



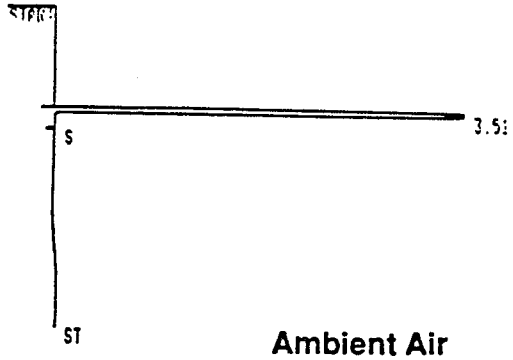
Discharge from Carbon #1

RUN # 2846 SEP/16/92 04:48:36
WORKFILE ID: A1
WORKFILE NAME
ID 1
NO CALIB PEAKS FOUND

AREA%

RT	AREA	TYPE	AR/HT	AREA%
3.51	9676100	DSBB	0.066	94.648
3.73	438440	DTBC	0.081	4.288
3.88	109580	D BB	0.064	1.072

TOTAL AREA= 1.0224E+07
MUL FACTOR= 1.0000E+00



Ambient Air – Blank –

RUN # 2848 SEP/16/92 08:46:48
WORKFILE ID: A1
WORKFILE NAME:
ID: 1
NO CALIB PEAKS FOUND

AREA%

RT	AREA	TYPE	AR/HT	AREA%
3.51	9433200	DSBB	0.066	100.000

TOTAL AREA= 9433200
MUL FACTOR= 1.0000E+00

Figure 2

DBCP REMOVAL

The concentration of DBCP in the extracted gas stream is measured by the on-line gas chromatograph. During the course of the operation, the concentration has varied from about 1 to 13 ppmV. A typical printout from the GC is presented in Figure 2. Figure 3 is a plot of the average daily DBCP concentration in the gas stream as extracted from the soil. The plot of Figure 3 is based, generally, on 3 analyses per day. Also shown in the figure is a schematic representation of extraction history by well. Much of the variation in concentrations may be explained by the well, or combination of wells, being pumped. Clearly, well VES-1 — screened at 20 to 40 feet below the ground surface — is the most productive of DBCP and well VES-2 — screened at 60 to 80 feet below ground surface — is the least productive of the three wells in the system. But none of the wells in the system has exhibited the type of concentration trend that might be expected for this type of operation (i.e., starting at a relatively high value, and a uniform progressive decrease in concentration). For example, well VES-1 started production in mid-January at about 3 ppmV, and this concentration was sustained for about the first month of operation. Then the concentration increased relatively quickly (i.e., over about two weeks) by a factor of about 3, to an average of about 10 ppmV, and this average was generally sustained for about the next two months. This was followed by a relatively rapid decrease in concentration over the next two weeks — from about 10 ppmV to about 7 ppmV. At that time (April 9) the system was shut down to make piping changes to allow reversing the order of flow through the two carbon canisters, as would be required following DBCP breakthrough in the first carbon canister and carbon changeout in that canister. The system was restarted with extraction simultaneously from Wells VES-1 and VES-3, and it was no longer possible to track the trend in DBCP concentration for well VES-1 by itself.

Based on the DBCP concentrations data, summarized in Figure 3, the quantity of DBCP extracted over time has been estimated (see Figure 4). For example, during the two months trial program operation the estimated extraction was about 60 pounds DBCP; the next three months of production operation resulted in an additional 180 pounds DBCP extracted, and during the next three months of production operation a further 50 pounds DBCP were removed from the ground. In summary, during the first nine months of operation a total of about 310 pounds DBCP were removed from the area soils. It appears that the VES operation to date has made substantial progress towards removing the approximately 800 pounds of DBCP that were estimated, in 1988, as being present in the area soils.

OTHER GASES IN EXTRACTED GAS STREAM

Approximate measurements (Gastec™ tube) of the concentrations of carbon dioxide, oxygen and ammonia present in the extracted soil gas have been made at about two-week intervals since the start of the VES operation. Values that are considered to be representative of the measurements for the three gases are as follows:

VES OPERATING DIAGRAM AND DBCP CONCENTRATION IN EXTRACTED GAS

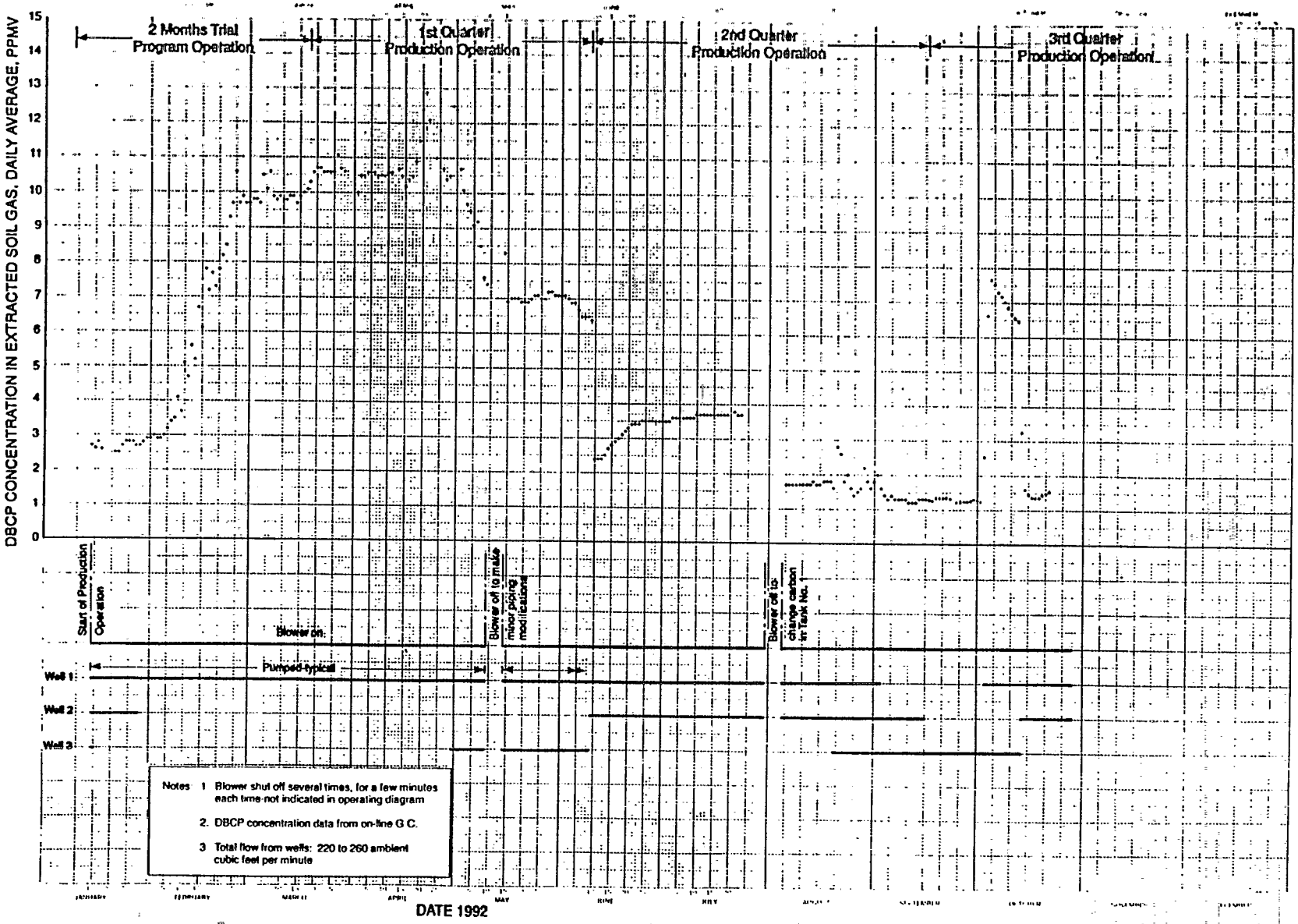


Figure 3

ESTIMATED QUANTITY OF DBCP EXTRACTED FROM SOIL, FROM START OF VES PRODUCTION OPERATION

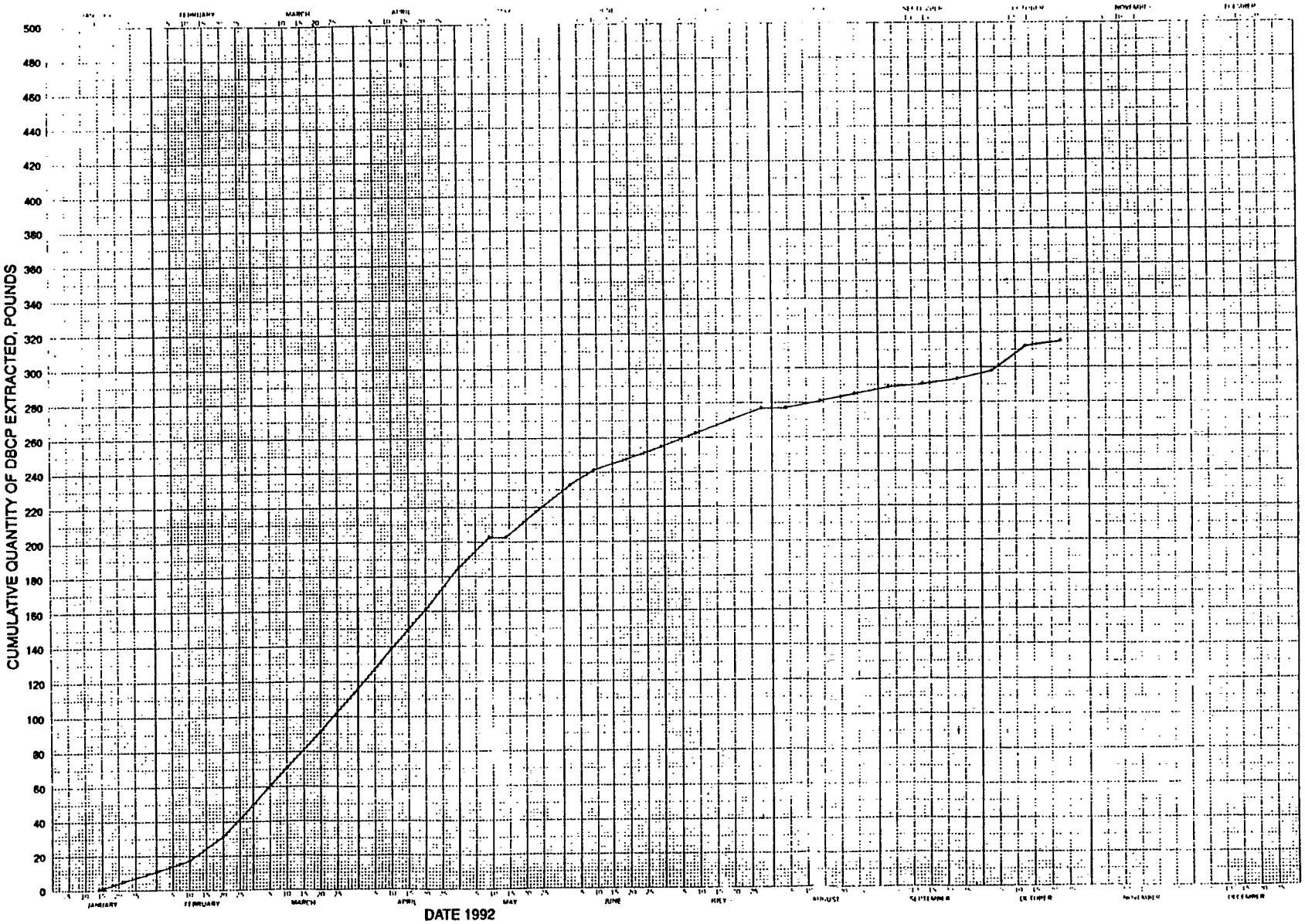


Figure 4

Constituent	Approximate Concentrations, ppmV		
	Low	Median	High
Carbon dioxide	10,000	20,000 to 30,000	70,000
Oxygen	8,000	17,000 to 18,000	20,000
Ammonia	100	1,000 to 3,000	20,000

In general, the carbon dioxide concentration increases as the depth from which gas is extracted increases, and the oxygen concentration decreases with depth. So far, no other trends have been detected in the data on these two gases. Ammonia has consistently been most concentrated in the gas extracted from well VES-3, which is screened from 40 to 60 feet below the ground surface. There has been a substantial, progressive decrease in the ammonia concentration in the gas extracted from all three wells in the system.

Throughout the VES operation, the CO_2 and O_2 measurements have indicated general agreement, on a mass balance basis, between the oxygen present in the extracted CO_2 and the oxygen deficiency in the gas stream, relative to ambient air. This indicates that the CO_2 is being produced, within the soil mass being vented, at about the same rate as it is being extracted. It is conjectured that the CO_2 is being produced mainly by on-going biological processes in the soil rather than by purely chemical reactions. The quantity of CO_2 extracted by the VES during the first nine months of operation is indicated by the following approximate calculation:

- Average soil gas extraction rate:
  about 230 cfm; or about 0.33×10^6 ft^3/day

- Assumed average CO_2 concentration in soil gas:
  about 25,000 ppmV, or 25,000 $ft^3/10^6$ ft^3

- Average CO_2 extraction rate:
  about 8,000 ft^3/day

- Assumed 400 ft^3/pound mole, at site average temperature and pressure (359 ft^3/mole at STP):
  about 20 lb mole CO_2/day

- One lb mole CO_2 = 44 lb, or 12 lb C/lb mole CO_2

- After 270 days of VES operation:
  20 lb mole/day x 44 lb CO_2/lb mole x 270 days
  = about 240,000 lb CO_2
  or about 65,000 lb carbon removed from soil

The source(s) of the extracted carbon is not known. Two candidate sources have been identified: organic carbon, naturally present in the soil, and the carbon component of the spilled DBCP. The estimated 3,100 gallons of spilled DBCP would have contained on the order of about 10,000 pounds of carbon, so clearly DBCP cannot account for all of the carbon that has already been extracted by the VES. But this does not exclude the possibility that some fraction of the extracted carbon in the CO_2 is the result of in situ biodegradation of DBCP and or intermediate degradation products of DBCP.

In another, unrelated, site investigation, conducted near the subject site, a total of 58 soil samples were collected and analyzed for total organic carbon. The samples were collected at depths ranging from 1 to 80 feet below the ground surface, and it is believed the results of the analyses are generally representative of conditions within the soil mass being affected by the VES operation. The average organic carbon content of the 58 soil samples was 0.12 percent.

To provide a qualitative appreciation of the quantity of carbon naturally present in the area soils, the following calculation is provided:

- Assume a cylinder of soil having a radius of 100 feet and a height of 80 feet (these dimensions may approximate the volume, but not the shape, of the soil mass being vented):

  - Volume of soil in cylinder:
    $100 \times 100 \times \pi \times 80$ = about 2.5×10^6 ft^3

  - Assumed average dry wt. of soil:
    100 lb/ft^3

  - Wt. of soil in cylinder:
    100 lb/ft^3 x 2.5×10^6 ft^3 = 250×10^6 lb

  - Wt. of carbon in the cylindrical mass of soil:
    0.0012 lb C/lb soil x 250 x 10^6 lb soil =
    about 300,000 lb carbon

The above calculation clearly indicates that organic carbon, naturally present in the area soils, can account for all of the carbon that has been extracted by the VES to this time, without having to make unreasonable assumptions concerning the outlines or dimensions of the soil mass being vented. It is noted that when only well VES-1 was being pumped, a vacuum of

about 3.8 inches H_2O was measured in the riser pipe of well VES-3. The distance between the two wells is about 53 feet. This would seem to indicate that in some strata and directions, the horizontal dimension of the soil mass being vented is significantly more than 50 feet from the extraction well. A semi-log plot of vacuum versus distance from the extraction well could be extrapolated to indicate a measurable effect probably occurs at 100 feet from the well.

The significance of the ammonia present in the extracted soil gas cannot be quantified with the presently available information. In general, on-going biological processes in soil, as seem to be occurring in this case, require more than simply the presence of free oxygen, which is being supplied by the VES operation. An adequate supply of water and nutrients also is required. These may be either naturally present in the soil or must be supplied. Because free water generally is being collected in the knockout tank, it is believed that the air being moved through the soil generally is at about 100 percent relative humidity and capable of supplying the water requirements of in situ biological processes. Also, it seems likely that the nitrogen available in the ammonia is serving as a supplied nutrient. On the assumption that the nitrogen is necessary for continued, stimulated biological activity in the soil, and that continuing the activity may be beneficial, with respect to remediating the DBCP contamination in the soil, we have limited our use of extraction from well VES-3 because it is the most productive of NH_3 in the system. It is expected that pumping of wells VES-1 and VES-2 causes ammonia present in the vicinity of well VES-3 to flow towards the two pumped wells. If the ammonia supply is depleted at some time during the operation it will be interesting to see if it has an effect on the CO_2 production rate.

COST INFORMATION

Costs incurred on this project to date, and estimated to the end of the Extension of the Variance From Permit Requirements — i.e. May 1, 1993 — are summarized as follows:

- Investigation to assess the extent of the contamination, including drilling, sampling, laboratory analyses, VES feasibility test, and reporting, but not including an on-going groundwater monitoring program

  about $150,000

- Cost to design, permit, purchase and install VES

  about $200,000

- Cost to operate VES for two months trial program, including maintenance, power, sampling and analyses, and reporting

  about $60,000

- Estimated costs to operate the VES for one year, (mid-march 1992 to mid-march 1993) including maintenance, power, carbon replacements and disposal, sampling and analyses, and reporting

  about $200,000

- Estimated costs to complete closure, assuming VES operation is terminated in March 1993, including: verification soil borings and soil sampling in Level C protective equipment, sample analyses, and a final report, but not including any post-closure monitoring

  about $30,000

Total about $640,000

SUMMARY AND CONCLUSIONS

A soil venting/vapor extraction system (VES) was installed to remediate vadose zone soils contaminated with DBCP. The system causes atmospheric air to flow through the contaminated soil mass, where it picks up vapor phase DBCP, and is then withdrawn from the soil through wells installed for the purpose. The system has been in essentially continuous operation since January 14, 1992. The estimated quantity of DBCP present in the soil, in 1988, was about 800 pounds. The DBCP spill occurred about 1971, and the estimated quantity spilled was about 3,100 gallons, or about 60,000 pounds. The maximum concentration of DBCP found in the soil, in the 1988 investigation, was 260 milligrams per kilogram. Ammonia is also present in the soil mass being vented, and has been found in the extracted soil gas at a concentration of up to 2 percent, volumetric.

The installed system includes three wells, each with a 20-foot-long screened section, and with screened intervals spanning 60 feet, or from 20 to 80 feet below the ground surface. The contaminated soils are of alluvial origin, moderately stratified, and vary from silty fine sands to coarse sands with gravel. The depth to groundwater is variable, but generally 90 to 110 feet below the ground surface.

The installed system uses a positive displacement blower, capable of pumping about 220 to 260 ambient cubic feet per minute, with the actual flow dependent on the well, or combination of wells, being pumped. In general, the blower operates at a vacuum of about 4 to 6 inches mercury column, and discharges to atmosphere.

The extracted soil gas has contained DBCP at varying concentrations, but within the range of about 1 to 13 parts per million, volumetric (ppmV). The DBCP is removed from the extracted gas stream by passing it through two canisters of granulated activated carbon, connected in series, and located on the vacuum side of the blower. The cumulative DBCP extraction, over the first nine months of system operation, was about 310 pounds. No estimate is provided of the remaining time the VES will be operated, nor of the concentration of DBCP in the extracted gas that will serve as a criterion for system shutdown. However,

for cost estimating purposes, we have assumed operation until about March 15, 1993, as presently covered by the Variance From Permit Requirements, granted by the Department of Toxic Substance Control, Alternative Technologies Division. It is planned that a soil sampling and analysis program will be implemented, following system shutdown, to allow comparison of before and after DBCP concentrations in the soil.

In addition to removing DBCP from the site soils, the VES has removed a large quantity of carbon dioxide. Through the first nine months of operation, at least 200,000 pounds have been removed. It appears that the carbon dioxide is being generated at the rate it is extracted because there is a balance between the oxygen present in the CO_2 and the oxygen deficiency in the gas stream relative to atmospheric air. The carbon in the CO_2 must be present in the soil, because only an insignificant fraction of it can be attributed to the CO_2 present in the air being circulated through the soil. Two possible sources of CO_2 have been identified. They are naturally occurring organic matter and the spilled DBCP. It is possible, but not documented, that the soil venting has caused stimulation of microorganisms present in the soil that are capable of biodegrading DBCP and or some of the intermediate degradation products of DBCP. The ammonia present in the extracted gas stream may be providing nitrogen to the soil bacteria.

The only waste stream generated by the project is the carbon in the air emissions control system. The extracted gas stream has, at times, contained water that has collected in an air/water separator tank located immediately downstream from the valved manifold that controls the flow from the wells. Initially, the collected water had a pH of about 11, but after about 9 months of operation it had declined to about pH 8 or 9. The decline may be attributed to the decrease in the ammonia present in the soil as a result of the VES operation. The collected water has been transferred to a holding tank, from where it has been reinjected into the extracted gas stream, at a controlled rate, immediately ahead of an air stream heater. The heater maintains the air stream entering the carbon canisters at a temperature of at least 90°F, in order to prevent the possible accumulation of water in the carbon canisters or the deposition of solids within the carbon, as occurred with the initial design of the system. The water reinjection process has resulted in all collected water being treated and disposed.

The existing system is being operated under a Variance From Permit Requirements, granted by the California Department of Toxic Substance Control, Alternative Technologies Division, and an Extension of the Variance, to May 1, 1993.

The total estimated costs associated with this DBCP remediation project are about $640,000; including $150,000 for site investigation; $200,000 for design and construction; $60,000 for a two month trial program operation; $200,000 for one year of production operation; and $30,000 for a post-operation, verification soils investigation. Post-closure monitoring costs may be additional.

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5 YEARS OPERATIONAL EXPERIENCE WITH THE HARBAUER SOIL WASHING PLANTS

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Harbauer GmbH & Co. KG

Dr. Hansgeorg Balthaus
Philipp Holzmann AG

1. Abstract

Soil washing has become a well established soil cleaning process that offers broad applicability, a high technological standard and consistent cleaning results. In addition, soil washing provides production reliability and general acceptance by the public.

The first large scale Harbauer soil washing plant began operation in early 1987 in Berlin. Since that time a wide range of soil contaminants have been successfully treated. More than 120,000 tons of soils have been brought from 70 sites to the plant for treatment. In 1990 a mobile HARBAUER soil washing plant started operation in Vienna.

The high efficiency of the Harbauer soil cleaning process is achieved by using a broad spectrum of processes partly similar to those commonly used in the mining and mineral processing industries. We can guarantee optimum cleaning results with relatively low energy consumption by selecting our mechanical agitation processes based on the grain size fraction.

This year a third generation of soil washing plants is under construction in Berlin with completion planned for March 1993. In mid 1993 a sophisticated soil washing plant for the removal of mercury from soil and rubble will begin operation in Bavaria. This plant will use a special vacuum distillation system to treat fines and other volatile and semi-volatile contaminants.

The main emphasis in the further developments of the HARBAUER soil washing system lies in the minimization of the residues from the washing process. While we have tested various techniques to date, vacuum distillation has proven to be the most promising additional step in the soil washing process. It has proven successfull for a large number of volatile or semi-volatile contaminants such as mercury, PAHs or other organics.

2. Introduction

The first large scale HARBAUER soil washing plant began operation in early 1987 in Berlin. This plant was designed for the treatment of contaminated soil from the former Pintsch used oil recycling site. This soil was heavily polluted by residues from the oil refining activities. During the operation of the soil washing plant from 1987 to 1991, the plant engineering was optimized, several treatment stages were added and the permitted uses of the plant were expanded. This made it possible to treat soil from other contaminated sites with different contaminants. Up to now more than 120,000 tons of contaminated soil from approximately 70 different sites have been cleaned successfully.

The gained operational experience has been used for the design of new soil treatment plants. In 1990 a mobile HARBAUER soil washing plant started operation in Vienna. This plant was designed for the treatment of cyanide contaminated soil and rubble.

This year a third generation of soil washing plants is under construction in Berlin with completion slated for March 1993. This plant will be a soil washing center for Berlin and its surrounding areas. It represents the latest developments in soil washing techniques with a broad application spectrum for different soils and pollutants.

Another soil treatment plant for removal of mercury is under construction in Marktredwitz, Bavaria. This plant consists of a soil washing unit and a newly developed vaccum distillation unit. It will start operation in mid 1993.

3. *Process Description*

To achieve a high cleaning efficiency for different types of soils and contaminants, the HARBAUER soil washing system uses a multi-step process. Some of the process units are similar to those used in the mining and mineral processing industry. Others have been developed especially for treatment of contaminated soils. The primary operational steps of the HARBAUER soil cleaning system that determine the cleaning efficiency are the following:

Process	Process Equipment
1. Dislodging of contaminants from soil particles using multi-step ***mechanical agitation***	- Bladewasher - Stirring Reactor - Vibration Reactor
2. Separation of highly contaminated grain-size fractions by means of ***classification***	- Hydrocyclones - Classification Screens
3. Separation of highly contaminated organic fractions by ***means of sorting***	- Mineral Jig - Fluidized Bed Sorter - Flotation
4. Exchange of contaminated interstitial water by means of ***rinsing*** and ***dewatering***	- High Pressure Water Sprays - Countercurrent Hydrocyclone Unit - Fluidized Bed Sorter - Dewatering Screens

A simplified flow chart of the HARBAUER soil cleaning system is shown in figure 1. At first, particles > 16 mm are separated using two classification screens. The oversize material has to be crushed and can then be added again to the material feed. Usually the amount of material > 16 mm is less than 1 %. Therefore crushing can be done in batch quantities using a mobile crusher.

The mechanical agitation takes place in three main stages (mechanical agitation I - III). Due to the fact that the required energy for the cleaning of coarse particles is much smaller than for the fines, the specific energy input increases in the direction of the material flow. In all agitation stages mainly shear forces between the particles or between the liquid and the particles are activated. This guarantees an optimum cleaning efficiency at a relatively low level of energy consumption.

After the dry classification the contaminated soil is conveyed to the first washing unit, a two-stage blade washer (mechanical agitation I). Before entering the blade washer metal scrap will be separated. The blade washers are followed by a classification screen (classification stage III) where the gravel and stone fraction is separated. Before this fraction is discharged as cleaned material, light materials like tar, wood, etc. are separated using a mineral jig (sorting stage I).

Following the classification of the coarse fraction a multi-stage hydrocyclone unit (classification stage IV - V) is used to separate the fines < 15 µm. These particles are concentrated through flocculation/sedimentation/thickening. Finally they are dewatered mechanically. The second stage for mechanical agitation is a stirring reactor followed by a fluidized bed sorter for the separation of light materials from the sand fraction (sorting/rinsing stage II).

The fine particle fraction between 15 µm and 150 µm is treated in sorting stage III. This is a two-stage pneumatic flotation step where very fine organic particles are separated. Finally the HARBAUER vibration screw is used to dislodge the remaining contaminants. In this machine the particles are subjected to intense vibrations using high amplitudes. The previous and following dewatering screen ensure that an intensive rinsing process of the cleaned material is achieved.

To avoid any emissions the soil treatment system is equipped with a process water and process air treatment unit. The total amount of process water which is needed for an operational capacity of 30 t/h of contaminated soil is 120 m³/h. The water runs in different circuits. The first treatment stage for the process water is a large flocculation/sedimentation unit consisting of 6 thickeners followed by a tilted plate separator. This unit needs to be so large because the soil treatment plant is able to treat soil with up to 30 % fines below 63 µm.

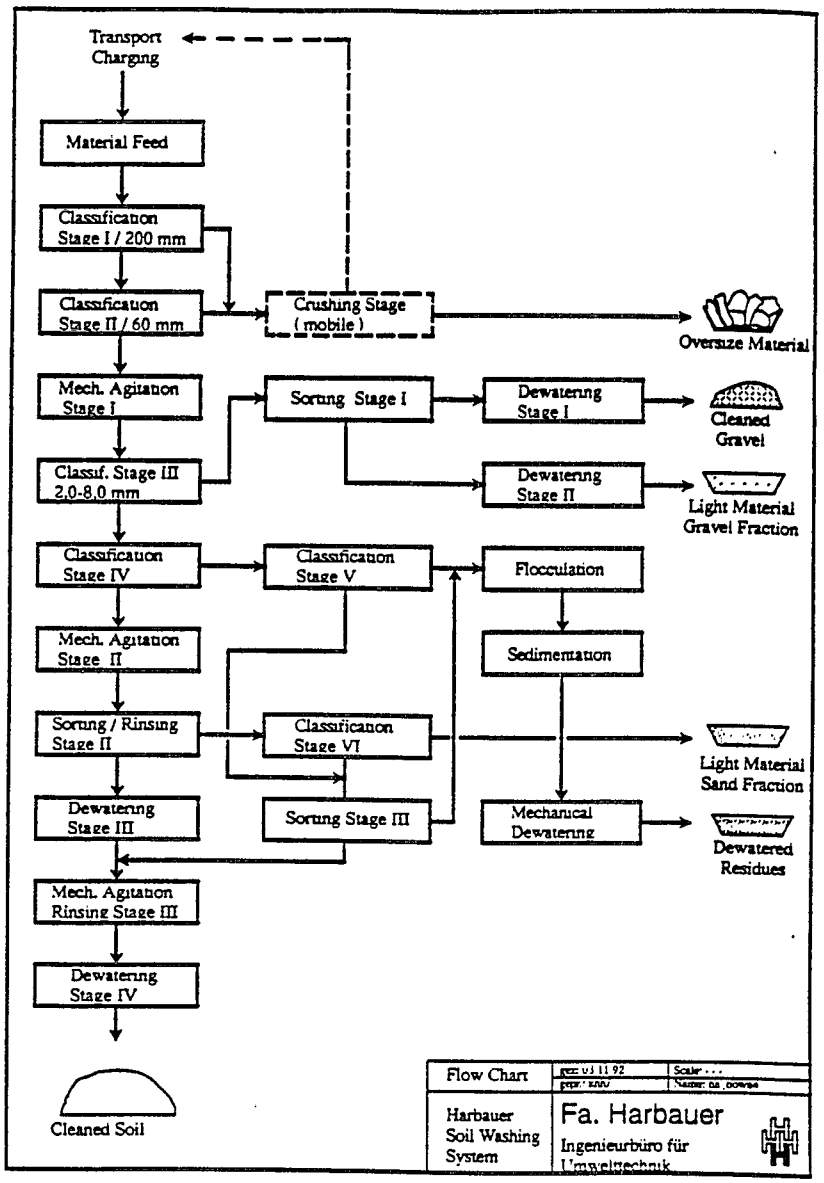


Fig. 1 Simplified Flow Chart

Light substances such as oil flow separately to a dissolved air flotation unit where they are separated. The cleaned overflow of the tilted plate separator is split into three streams. Stream I is directly reused in the first washing step of the soil treatment (circuit 1). Stream II is filtered using sand filters and then reused (circuit 2). The third stream of the process water is cleaned using the treatment stages of oxidation/precipitation and activated carbon adsorption. The operation of the oxidation and precipitation stages is optional and only used for heavy metals and cyanides. The cleaned water leaving the activated carbon adsorption stage is reused in the final rinsing processes of the soil treatment. Approximately 15 m³/h of this water is discharged and replaced by clean water. The sedimented solids are dewatered using chamber filter presses.

In the process air treatment unit 30,000 m³/h of air is cleaned. 15,000 m³/h are collected from the resource material feed/dry classification/intermediate storage areas. Dust is first removed from this stream and then together with the other collected air stream finally cleaned using activated carbon adsorption. The quality of the discharged air is controlled on-line using a TOC-monitor. Furthermore the cleaned air stream will be regularly tested in a laboratory.

4. *Design*

HARBAUER soil washing plants are subdivided in four main areas. Area I consists of a 1,000 m³ intermediate storage area for contaminated soil, the material feed and screens for dry classification at 200 and at 60 mm. If necessary a crusher can be integrated into the process here. To avoid emissions, this area is a closed hall provided with material locks and rolling bars. The soil is transported from here to area II using an enclosed belt-conveyor. Area II consists of all wet mechanical separation processes and the dewatering stages for the residues. Areas III and IV are the process water and process air treatment units. Figure 2 shows a top view of the Berlin soil washing plant with the required infra-structure. The minimum required space for a soil treatment plant of that size is 8,000 m². The whole site is subdivided into sections:

- intermediate storage and material feed: 700 m²
- soil washing plant: 1,600 m²
- intermediate storage for cleaned soil: 700 m²
- storage area for containers: 1,000 m²
- roads, offices, etc.: 4,000 m²

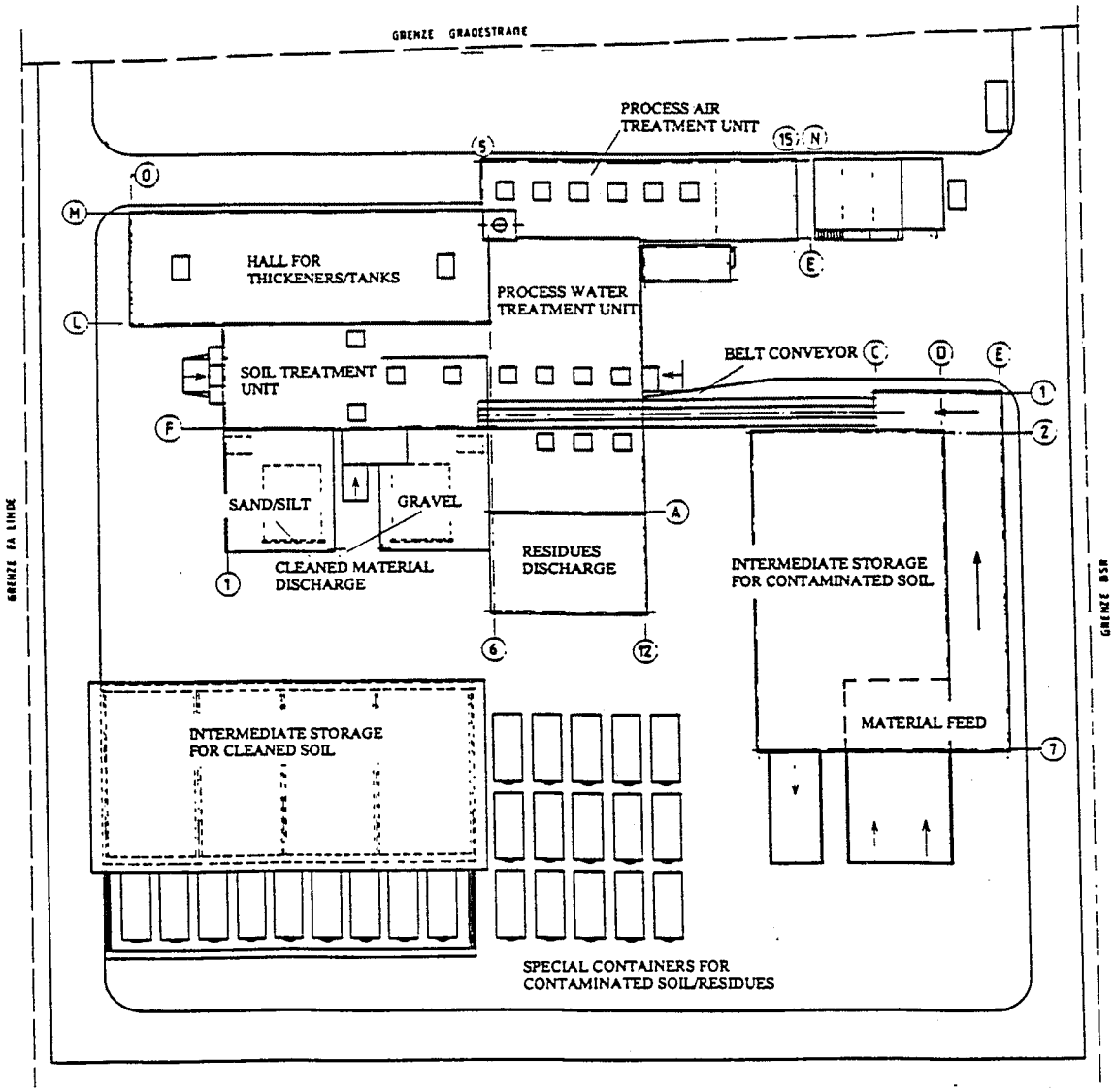


Fig. 2 Top View of the Soil Washing Plant Berlin

An example for the modular design of one of our plants is shown in figure 3. The whole plant consists of 50 containers that are 3 m wide, 3 m high and with a length of 10 or 14 m. The individual containers are prepiped and prewired with quick interconnections. This makes a rapid mobilization or demobilization possible which is very important for timely delivery and cost effective use during on-site treatment.

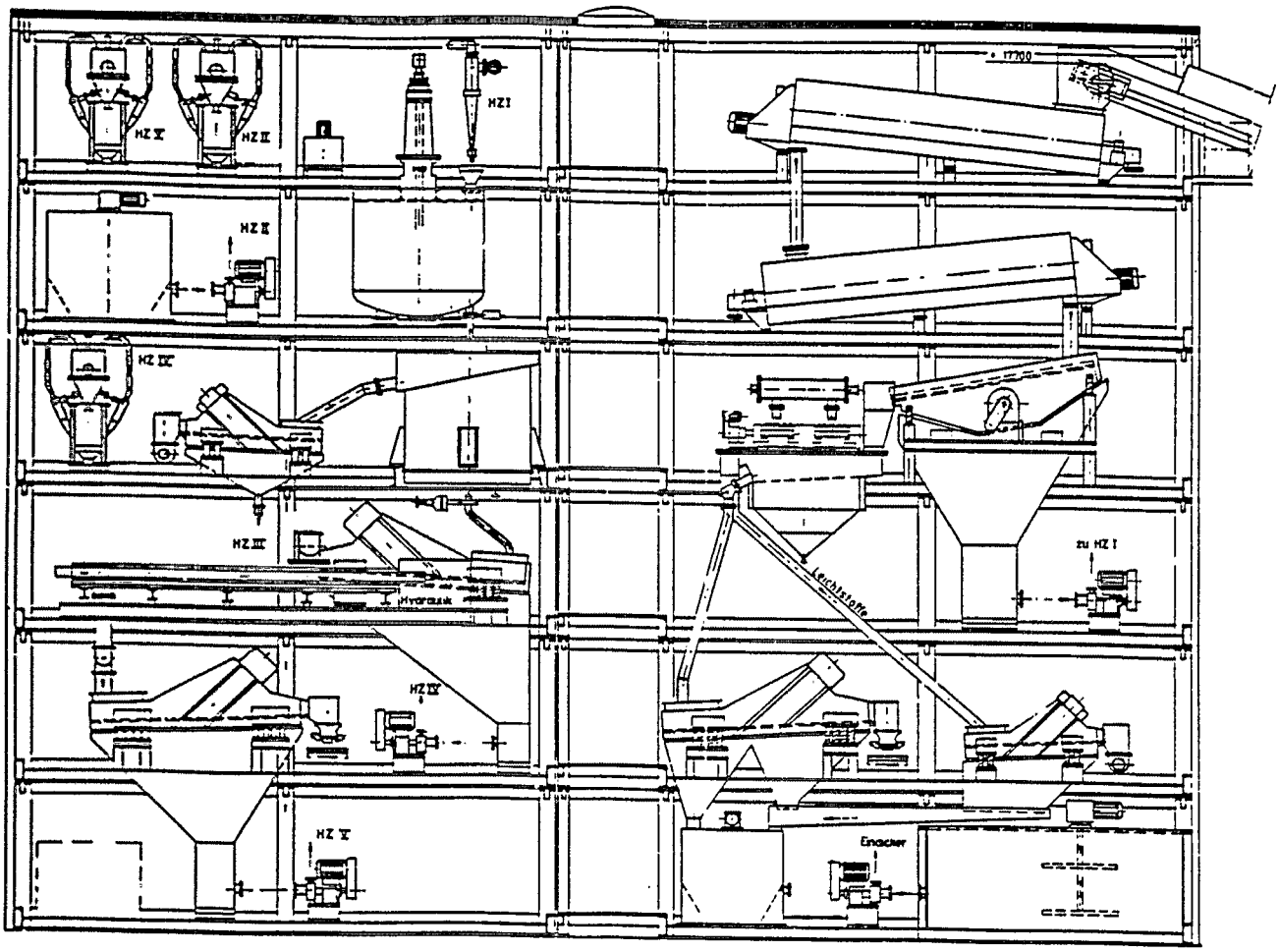
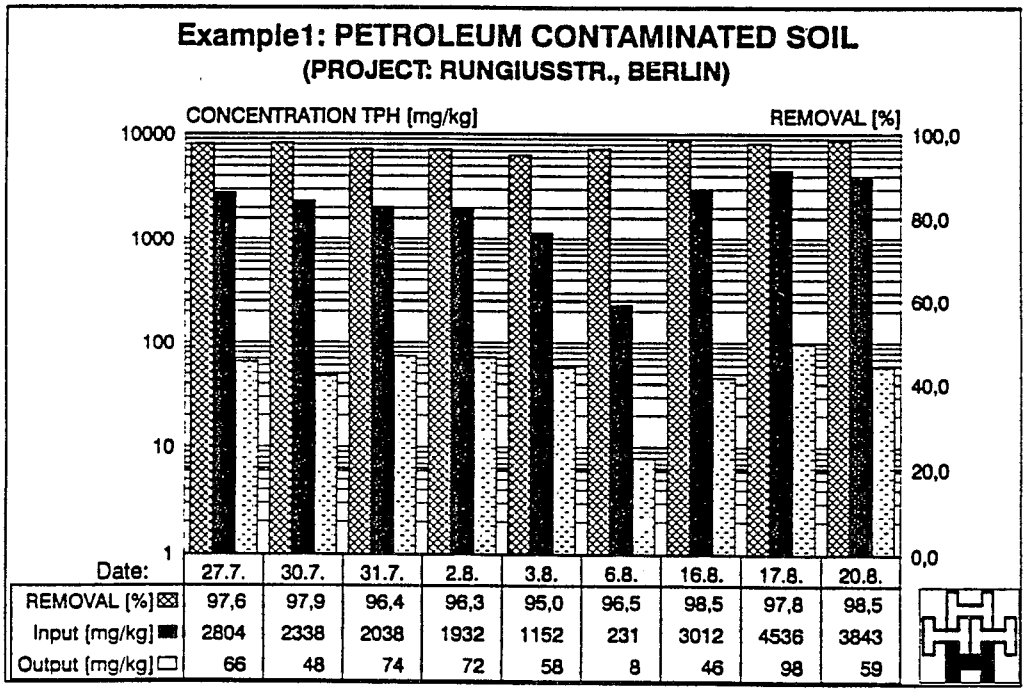


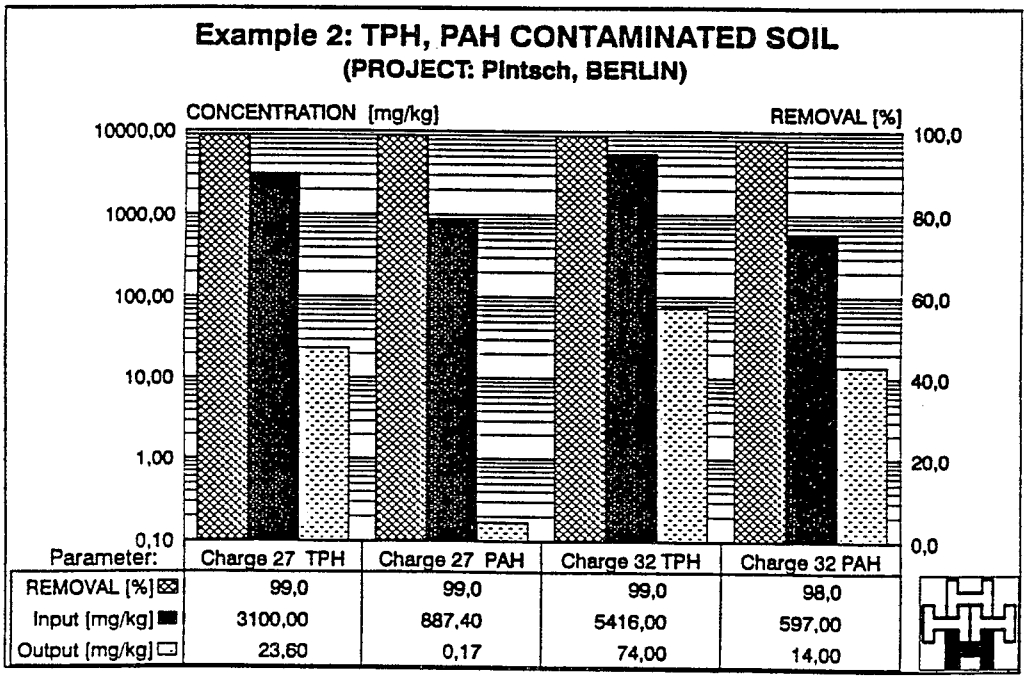
Fig. 3 Example for the Modular System Design

5. *Contaminant Specific Suitability*

The most operational experience gained thus far has been gained with organic contaminants specifically TPHs and PAHs. For TPHs the input concentrations varied between 500 and 20,000 mg/kg and for PAHs between 500 and 5,000 mg/kg. The residual concentration in the cleaned soil has typically been < 100 mg/kg for TPHs and < 5 to 10 mg/kg for PAHs. In some unusual cases of very high input concentrations, the maximum residual concentrations have been 300 mg/kg for TPHs and 20 mg/kg for PAHs. Figure 4 shows typical examples.



Date:	27.7.	30.7.	31.7.	2.8.	3.8.	6.8.	16.8.	17.8.	20.8.
REMOVAL [%]	97,6	97,9	96,4	96,3	95,0	96,5	98,5	97,8	98,5
Input [mg/kg]	2804	2338	2038	1932	1152	231	3012	4536	3843
Output [mg/kg]	66	48	74	72	58	8	46	98	59

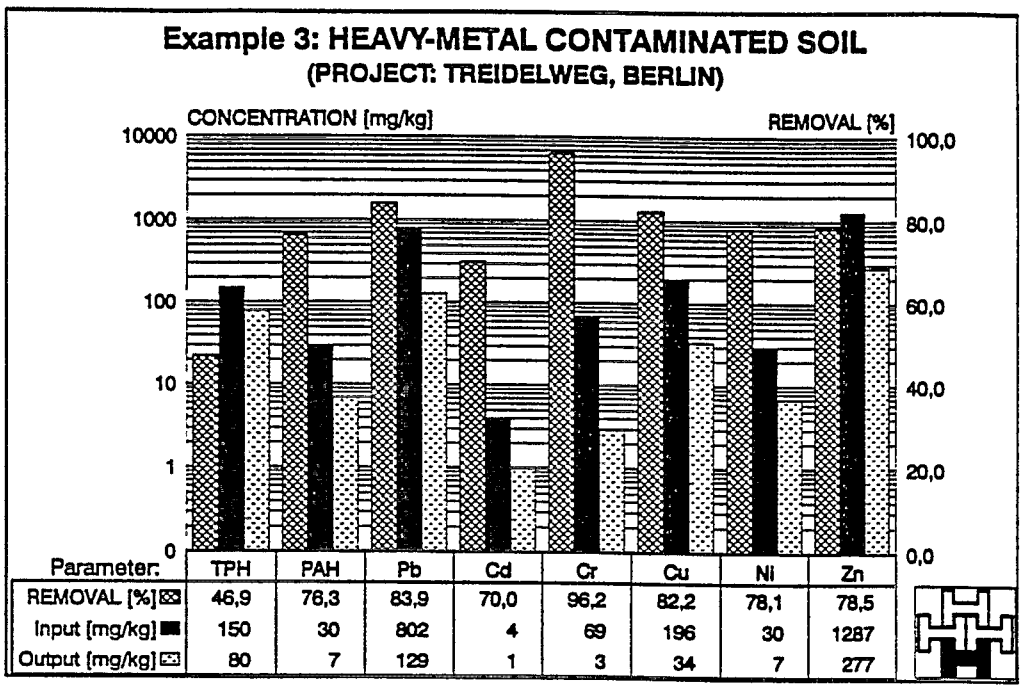


Parameter:	Charge 27 TPH	Charge 27 PAH	Charge 32 TPH	Charge 32 PAH
REMOVAL [%]	99,0	99,0	99,0	98,0
Input [mg/kg]	3100,00	887,40	5416,00	597,00
Output [mg/kg]	23,60	0,17	74,00	14,00

Fig. 4 Examples for Treatment Results of Soils Contaminated with Organics

The clean-up efficiency for volatile organic contaminants like chlorinated solvents or BTEX is very good. The residual concentrations always have been below the detection limits. For PCBs the input concentrations have been relatively low ranging from 5 to 25 mg/kg. The residual concentration has consistently been < 0.1 mg/kg or below the detection limit.

Soil washing is also an effective treatment method for heavy metal or cyanide contaminated soil. Examples are given in figure 5.



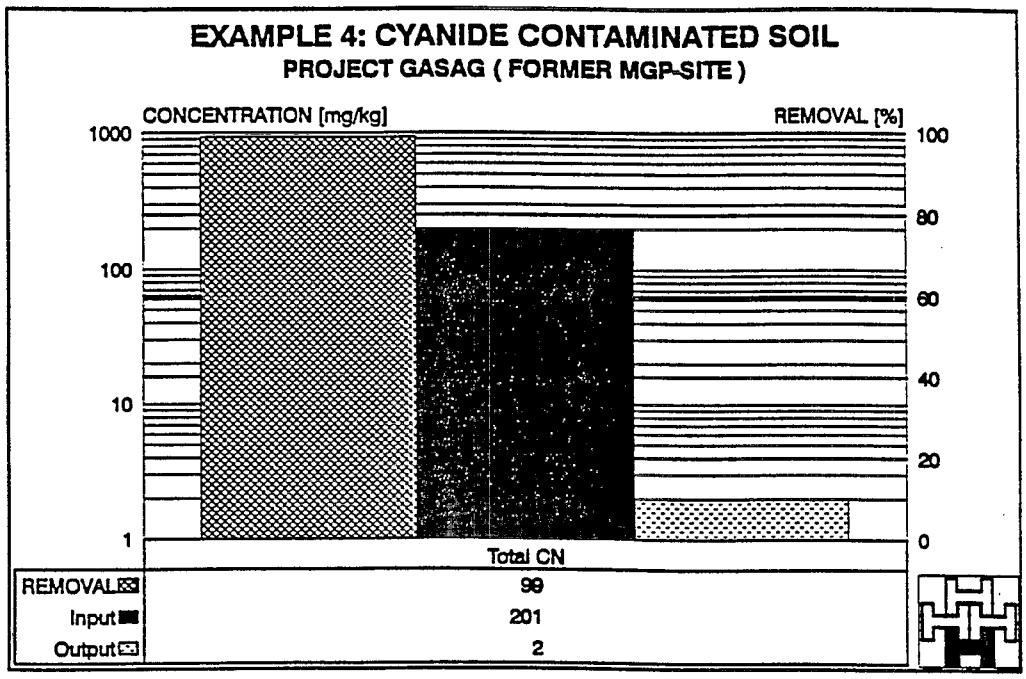


Fig. 5 Examples for Treatment Results of Soils Contaminated with Heavy Metals and Cyanides

6. *Technical/Operational Data*

The most relevant technical and operational data of the HARBAUER soil cleaning system is shown in figure 6.1. The operational capacity ranges between 25 and 40 t/h depending on the amount of fines in the soil. The annual capacity is 100,000 tons for two-shift-operation and 160,000 tons for three-shift-operation. We have proven that this capacity is sufficient for a stationary plant.

OPERATIONAL CAPACITY	25 - 40 t/h depending on the portion of fines < 63 µm
WASHING CAPACITY	The maximum washing capacity depends on the texture of the soil, the concentration and the kind of bindings of contaminants. Treatability tests are necessary to determine the minimum achievable residual concentration. The following concentrations for cleaned material are guide values refering to our operational experiences. TPH PETROL. HYDROCARB. : 10.0 - 200.0 ppm BTEX : 0.5 - 5.0 ppm PAH (EPA) : 1.0 - 20.0 ppm HALOGEN. VOL. ORGANICS : 0.5 - 5.0 ppm PCB : 0.5 - 10.0 ppm PHENOLE (EPA) : 0.5 - 5.0 ppm CN (total) : 1.0 - 20.0 ppm Hg : 1.0 - 50.0 ppm Pb, Cu, Ni : 50.0 - 300.0 ppm Cd : 1.0 - 20.0 ppm
TREATMENT RESIDUES	- FINES < 15 µm - SEPARATED ORGANICS - LOADED ACTIVATED CARBON
LIMIT FOR APPLICATION	PORTION OF CLAY/SILT: max. 30 - 40 %
SPEC. ENERGY CONSUMPTION	ca. 12 kWh/t
SPEC. WATER CONSUMPTION	ca. 200 - 1,000 l/t
OPERATIONAL MATERIAL	- FLOCCULANTS - HCl, NaOH (pH-adjustment if required) - SURFACTANTS (if required) - ACTIVATED CARBON
QUANTITY OF WASTE WATER/ OUTGOING AIR	INTEGRATED PROCESS WATER AND AIR TREATMENT UNIT: CLEANED PROCESS AIR: 15,000 - 30,000 m³/h CLEANED PROCESS WATER: 200 - 1,000 l/t
FLOOR SPACE REQUIRED	SOIL WASHING PLANT: 1,000 - 2,000 m² MAX. HEIGHT: 20 m ROADS, INTERMEDIATE DEPOSITS FOR CLEANED AND UNTREATED MATERIAL, ETC.: 8,000 - 10,000 m²

Fig. 6 Technical/Operational Data of the HARBAUER Soil Washing System

The energy and water consumption of the treatment process is relatively low. The specific energy consumption is 15 kWh/t or approx. 450 kWh/h. The specific water consumption ranges between 200 and 1,000 l/t and depends mainly on the type of soil and the input water content.

Additives used in the process are flocculants for the sedimentation, HCl and NaOH for pH-adjustment and activated carbon for the process water treatment. Surfactants are only used in special cases when otherwise the required treatment results cannot be reached.

Soil washing is a volume reduction process which concentrates the contaminants in the fine particle fraction of the soil. The economic limit for the application of soil washing is established generally by the portion of clay or silt in the soil. The clay/soil fraction should not exceed 30 to 40 % of the volume. This limitation exists because the amount of residues which remain following washing of soil with more than 40 % clays will increase to such a point that the additional landfill and post treatment costs plus the reduced operating capacity will push the soil washing per ton costs into the non-competitive range. To help minimize the amount of residues the cut-off point of the HARBAUER soil washing process is as low as 15 µm. In additional to the fines, solid organic matter such as roots, leaves, humus, etc. with a high affinity to contaminants must be separated. The soil washing process will generate a small quantity of loaded activated carbon as a waste by-product.

The quantity of filtered air ranges between 15,000 and 30,000 m^3/h and the cleaned process water discharge ranges between 200 and 1,000 l/t.

7. Costs

The investment cost for a large scale stationary soil washing plant is approximately 19 millions DM or 12 millions US$. The costs can be broken out as follows:

- Earthworks, foundations, subsurface sealings, etc. 2.5 millions US$
- Steel construction, buildings 3.0 millions US$
- Equipment 6.0 millions US$
- Infrastructure 0.5 millions US$

It should be noted that these are the investment costs for a stationary, multi-functional plant which is able to clean many soils with different textures and contaminant characteristics.

The specific operating costs are shown below:

- Power: 4.00 US$/t
- Water/waste water 2.80 US$/t
- Additives, activated carbon 5.30 US$/t
- Analytics 3.00 US$/t
- Labor 15.00 US$/t

These numbers are specific for German costs and conditions. Most important for the specific cost per ton is the rate of utilization. Figure 7 shows the specific cost depending on the rate of utilisation for a plant with an annual capacity of 100,000 tons. If the plant is running at full capacity, the total costs are 70.-- US$/t. If the rate of utilisation is only 50 %, the cost will be as high as 120.-- US$/t. These prices do not include any cost for the post treatment or deposition of residues. The most cost effective way to run a soil washing plant however is the treatment of big quantities of soil from just one remediation site with a specially designed plant.

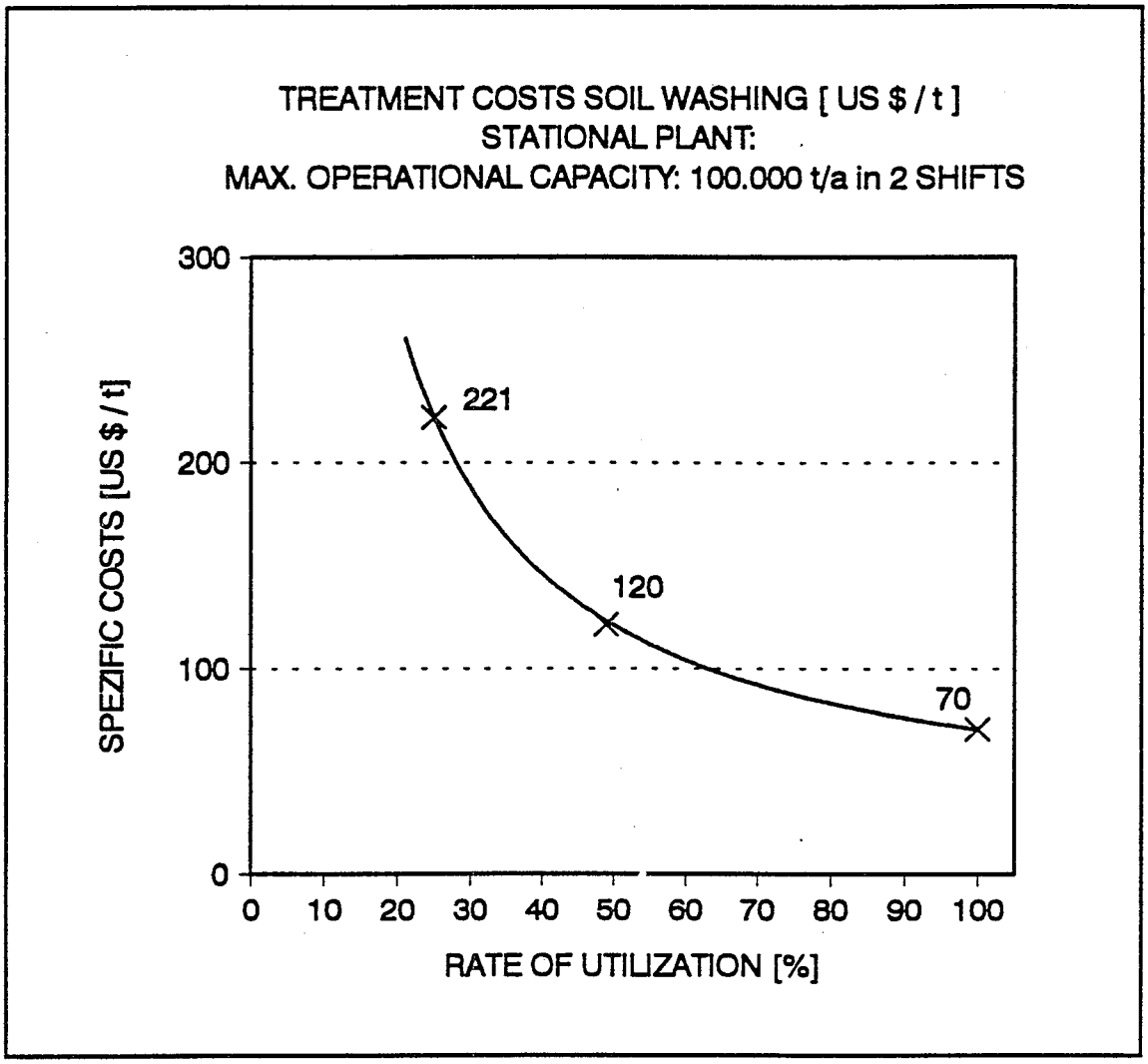


Fig. 7.1 Soil Washing Cost Relative to the Rate of Utilization

8. *New Developments*

The main thrusts in our soil washing research is to reduce the amount of residues which have to be post treated and to increase the application spectrum. One method is to use a flexible separation limit for the fines which goes down even below 15 µm in grain-size. By using this method, it is possible to adjust the optimum separation point for each type of soil which has to be cleaned. By doing this, the amount of fine particle residues is minimized.

In some cases of heavy metal contaminated soil it is possible to reduce the level of contamination significantly by soil washing but the required limits may not be reached. Then a chemical extraction using low concentrated acids is applicable. Results of tests which have been done with a lead contaminated soil are shown in figure 8.1. The input concentration in the range of 40,000 to 60,000 mg/kg was reduced under the required level of 150 mg/kg. After the treatment the fine particle fraction showed very high lead concentrations so that this material was suitable for metallurgical recycling. Chemical extraction without soil washing was also tested but was not successful.

The most promising new techology is the vacuum distillation system. This technology can be used as additional treatment step for the fines following the soil washing process or directly for soil which cannot be washed due to very high concentrations of silt/clay or contaminants. It has proven that soils contaminated with volatiles like BTEX, solvents or mercury as well as semi-volatile contaminants like TPHs and PAHs can be cleaned.

The process uses pressures in the range of 50 to 150 hPa and temperatures between 300 and 400 °C. To ensure that no dioxines are produced, the process works under inert conditions.

Figure 8.2 shows the boiling points of the EPA PAHs under normal pressure. It can be seen that the vacuum is necessary to reduce the boiling points of such semi-volatile substances. Figure 8.3 shows the results of laboratory scale tests for soil from a former coking plant. The removal of the input concentration has been > 99.9 % for PAHs, > 99 % for TPHs and even 99 % for cyanides.

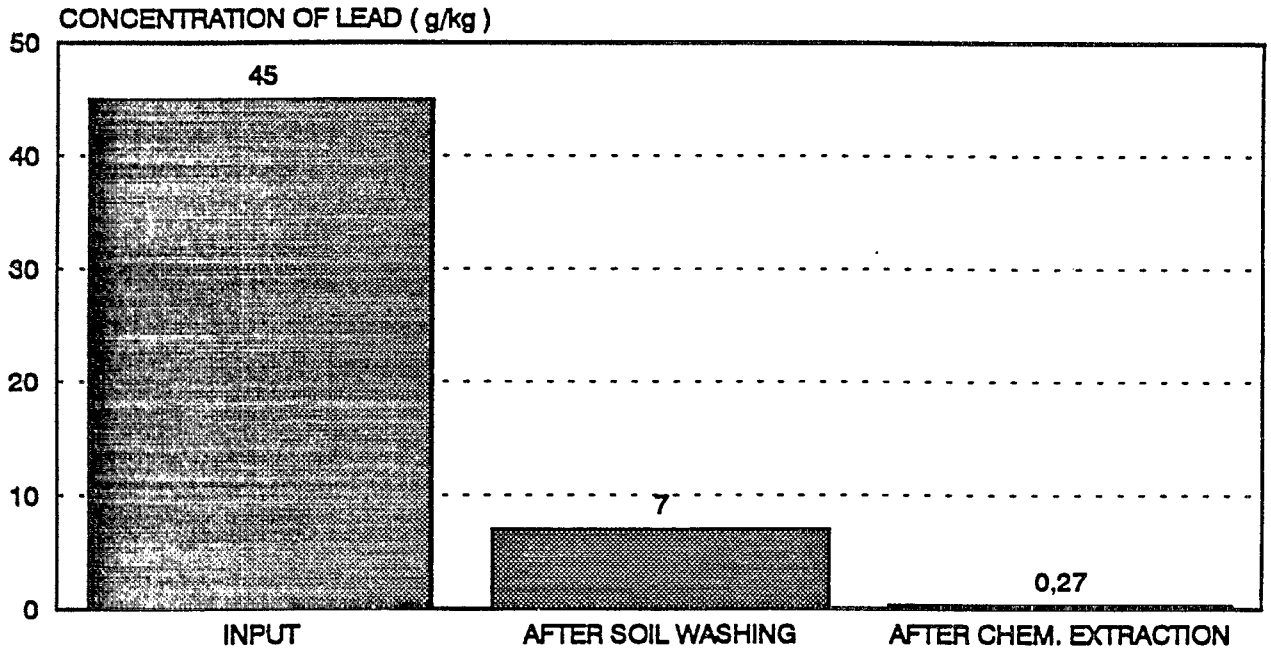


Fig. 8.1 Treatment Results - Combined Soil Washing and Acid Leaching Process

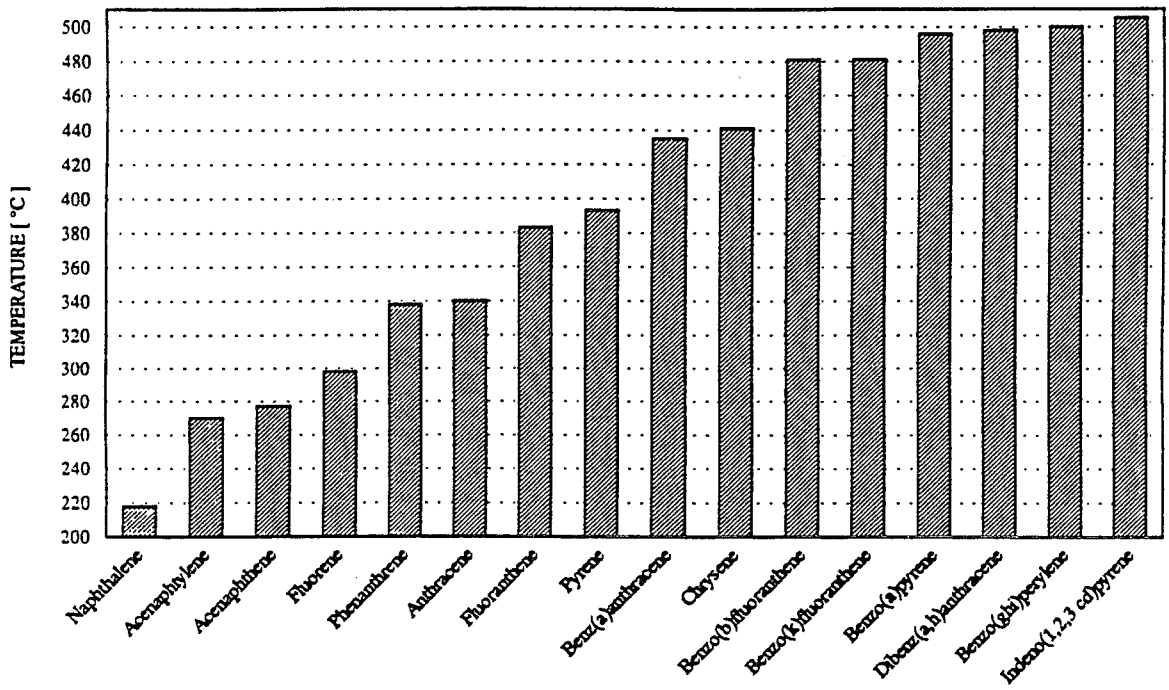


Fig. 8.2 Boiling Point of PAHs (EPA standard) at 1,013 hPa

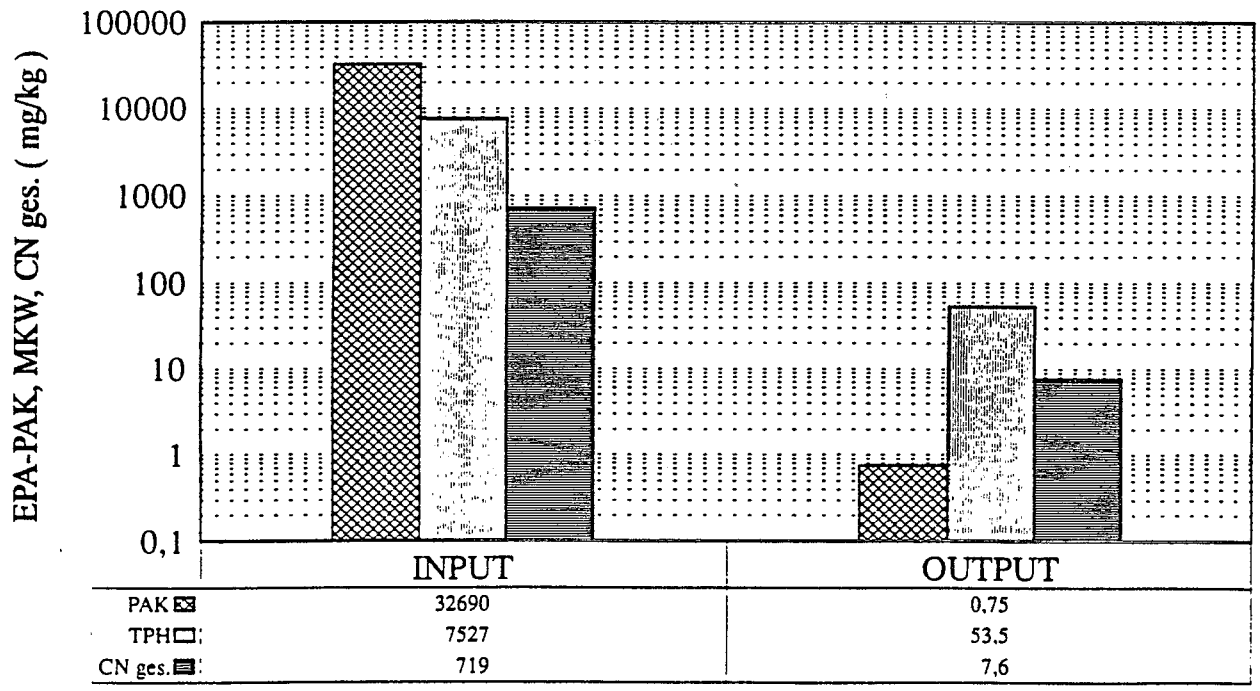


Fig. 8.3 Treatment Results Vacuum Distillation

9. Outlook

By using the HARBAUER soil washing system it is possible to clean soils with multiple complex pollutants and problematic particulate composition. The system allows the soil to be rapidly cleaned at site and immediately be used as backfill. As a result of the removal of clays and silt the cleaned backfill material has a greater loadbearing capacity than the original soil prior to the washing.

We have experience from over 70 sites producing more than 160,000 tons of soil. The sites include refineries, chemical plants, oil recovery facilities, process plants, landfills, and marine environments. The range of contaminants includes hydrocarbons, cyanide, heavy materials, mercury, lead, VOC, PAH, PCB, and others. In many of the soils more than one contaminant was present. Inspite of the field experience we have gained over the years we still believe that a treatability study must be done with each type of soil to be cleaned. Harbauer performs inhause the full range of services from treatability studies to equipment fabrication and from plant operation to the design of special treatment plants for unusual contaminated sites.

By 1993 there will be three large scale HARBAUER soil washing plants in operation plus other smaller scale operations. HARBAUER is also presently involved in the planning of four other soil treatment centers in Germany. Much of this growth and extensive research and development is possible as a result of the acquisition of HARBAUER by the Philipp Holzmann Company. Holzmann is Germany's largest civil engineering company and ranks in the top 10 in the world with over $ 10 billion in revenues. During the lat 12 years Holzmann has been aggressively entering the environmental remediation field through both acquisitions and internal development. Engineering News Record recently named Holzmann as one of the largest environmental contractors in the world.

If you have soil washing problems that you would like to discuss with us, we operate in the U.S. through J.A. Jones Construction Company of Charlotte, North Carolina. Jones is also a member of the Holzmann Family of companies.

We believe that soil washing will become a more acceptable method of remediation in the U.S. as landfill space decreases and the costs for incineration rise. Soil washing is not a panacea for every site but when applied to the proper set of circumstances is a quick and cost effective method for remediation of soil contamination.

FIELD DEMONSTRATION

of

SOIL WASHING

at the

KING OF PRUSSIA SUPERFUND SITE

MICHAEL J. MANN, P.E.
ALTERNATIVE REMEDIAL TECHNOLOGIES, INC.

and

HANS VAN DORD
HEIDEMIJ RESTSTOFFENDIENSTEN

FIELD DEMONSTRATION OF SOIL WASHING AT THE KING OF PRUSSIA SUPERFUND SITE

Overview

A soil washing demonstration run was conducted at Moerdijk, The Netherlands, on July 22, 1992. The demonstration run was conducted on soils from the King of Prussia Technical Corporation Site (KOP) in Winslow Township, New Jersey by Alternative Remedial Technologies, Inc. (ART) a Joint Venture Company of Geraghty & Miller, Inc. of the U.S.A. and Heidemij Reststoffendiensten of The Netherlands.

Site investigations had been accomplished through a Remedial Investigation (RI) and expanded by a Supplemental RI. The RI was further enhanced by the excavation of a number of test pits. The test pits provided an excellent means to physically examine the disposition of the target soils. Soil washing was selected as the remedy for the metals-contaminated soil at the site in the United States Environmental Protection Agency's (USEPA's) Record of Decision (ROD) dated September 28, 1990.

To define the soil washing system, a detailed treatability study was performed under the EPA's "Guidance Document for the Performance of Treatability Studies under CERCLA". The study was completed in March, 1992 and later approved by the USEPA. The treatability study confirmed the process and optimized the system configuration. The study did, however, leave some questions unanswered, and to further confirm the process, a "Demonstration Run" was proposed to be conducted at the full-scale Heidemij plant in The Netherlands.

First, approvals to ship the demonstration soils were obtained from the USEPA under the Resource Conservation and Recovery Act (RCRA) Export Rule and then from the Dutch VROM, the equivalent USEPA organization. For the demonstration run, representative soils were excavated, field-quantified using the Environmental Resources Management, Inc. (ERM) X-Ray Fluorescence (XRF) equipment, bagged in "super sacks", and placed in sea-going shipping containers. The containers were transported to the Port of Newark and then, by sea, to the Port of Rotterdam. In Rotterdam, the shipment cleared customs and was transported by land to the Moerdijk treatment facility.

At Moerdijk, the site soils were screened, blended, and processed in a state-of-the-art soil washing facility using an integrated system of screens, hydrocyclones, flotation cells, dewatering equipment, thickeners, and a belt filter press. The run lasted approximately seven hours during which time samples were collected from various intermediate stages, and, most importantly, from the process residuals, namely: sand product, sludge cake, and oversize materials.

The collected samples were first analyzed by Daniel C. Griffith (Holland) B.V. (D.C. Griffith), a multi-national environmental laboratory operating in The Netherlands. Split samples were analyzed by IEA Labs, a U.S. Contract Lab Program (CLP) Lab.

These data were consistent and confirmed achievement of the soil cleanup levels specified in KOP ROD.

The process residuals were returned to the U.S. on October 17, 1992. The oversize and the product sands were returned to the KOP site as clean, while the sludge cake was disposed at the GSX Pinewood Treatment, Storage and Disposal Facility (TSDF).

Preparation Activities

Excavation Plan

The excavation of target soils at the site was performed in accordance with a demonstration run plan. The original plan was to collect 200 short tons of target materials to be placed in 200 super sacks, but, due to lower than expected soil densities, the total amount of material collected was 164 short tons.

The material was shipped from the site to the Port of Newark, then to the Port of Rotterdam, and downloaded for the trip to the soil washing facility located at Moerdijk (near Dordrecht), The Netherlands.

At the Moerdijk site the soil was first rough screened in its received state at 4 centimeters (cm). A "gross oversize" fraction was defined as that material >4 cm, and consisted of less than one ton, comprised mostly of plants, tree roots, and some hard lumps of sludge. The gross oversize material was bagged for return to the site where debris-washing studies will be conducted. The underfall material, that is everything <4cm, was blended and staged as the process feed material.

Process Plant Configuration

The process plant was configured exactly as recommended in the KOP Treatability Study.

The plant consisted of the following primary subsystems:

- The Feed Hopper and Conveyor
- The Wet Screening System
- The Separation System, including Hydrocyclones
- The Flotation System, including the Contact Scrubber and Surfactant Addition
- Sand Dewatering and Conveying
- Lamella Clarifiers and Thickeners
- A Belt Filter Press and Conveyer

Systems available at the Moerdijk Plant that were not used for the demonstration run included the spiral concentrators, the 500 micron screen, and the sieve bend. These subsystems were intentionally bypassed in order to match the proposed configuration determined from the Treatability Study.

Chronology of Demonstration Run Activities

The key activities of the demonstration run were:

May 24, 1992	-	Soil excavation began.
May 30, 1992	-	Soil bagging and containerizing complete.
May 31, 1992	-	The SV Sextant sailed for Rotterdam.
June 14, 1992	-	Soil arrived in Rotterdam.
June 24, 1992	-	Soil downloaded and arrived in Moerdijk.
July 18, 1992	-	Soil screened and plant cleaned out.
July 22, 1992	-	Demonstration run performed.
July 24, 1992	-	Preliminary data presented to USEPA and discussed.
August 21, 1992	-	Demonstration Run report submitted to USEPA Region II.
October 17, 1992	-	Treated soils returned to the U.S.

Data Collected

Detailed data were collected to evaluate the process and the effectiveness of the treatment as measured by the ROD Soil Cleanup Standards. The data were verified by split sample analyses using a CLP-qualified laboratory. Based upon averages from data developed, successful compliance with the required standards was achieved.

Treatment Products, (mg/kg)

Source	Cr	Cu	Ni
Cleanup Goal	483	3571	1935
Process Feed	770	1500	460
Oversize	420	790	540
Sand	170	350	70
Sludge Cake	4750	8030	2630

Detailed data is included in Tables 1 through 12

Disposition of Process Residuals

The oversize material and the product sand meet the treatment standards and will be staged onsite and later incorporated into the restoration of the site. The gross oversize material will be returned to the site and staged for additional studies to determine whether a debris-washing system is appropriate for use in attaining additional volume reductions by removing fines from the material. The sludge cake has been disposed at an appropriate off-site facility.

Conclusions

Key conclusions drawn from the performance of the demonstration run were:

1. The system as recommended in the Treatability Study can treat the KOP soils to levels in compliance with the requirements of the ROD.

2. The distribution of the process residuals indicates that, on a dry solids basis, approximately 13% of the material introduced into the plant will require off-site disposal.

3. That several design modifications for the KOP plant will improve the operations of the facility on-site; specifically improvements in wet screening and in sludge cake production.

The Gross Oversize, the Oversize, and the clean sand will be returned to the site. The sludge cake consisting of approximately 55% dry solids or now approximately 20% of the total soil treated will be disposed at an off-site facility.

For more information about this project and soil washing, contact Michael J. Mann, P.E., Alternative Remedial Technologies, Inc., 14497 North Dale Mabry Highway, Suite 140, Tampa, Florida 33618. Telephone (813) 264-3506.

TABLE 1
MATERIAL TO BE TREATED

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

(All tons)

Source	Target	Actual	Gross Oversize	Process Feed
Sludge Band	145 (72.5%)	122 (74.4%)	0.5	121.5
Swale	5 (2.5%)	3 (1.8%)	<0.1	3
Lagoon 1	25 (12.5%)	21 (12.8%)	~0.25	20.5
Lagoon 6	25 (12.5%)	18 (11.0%)	~0.25	18
Total	200	164	~1.0	163

A nominal 200 U.S. tons of material were targeted for treatment in the soil washing process. Actual quantities received were 164 tons with a percentage relationship very similar to the targeted ratios. All source materials were dry-screened at 4 cm and yielded a gross oversize totaling nearly one ton. Lagoon 1 and 6 sludge, planned to be pre-screened dry as 1 cm, were found to be too wet and approval was given by the KOP Remedial Project Manager to conduct 1 cm screening on the 2 mm process oversize at the completion of the run. That data is contained in Table 3.

TABLE 2
PROCESS FEED MATERIAL

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

Influent Concentrations

(All mg/kg)

Sample	Cr		Cu		Ni		Dry Solids (%)
	DCG	IEA	DCG	IEA	DCG	IEA	
1	790	872	1600	1470	433	409	83.5
2	745		1600		415		83
3	705	759	1300	1080	408	357	85.5
4	705		1400		420		85
5	910	982	1850	2170	660	639	82
6	815		1900		473		85
7	855	1080	1500	1310	460	368	83.5
8	710		1250		393		86
9	735	675	1250	1110	435	378	86
Average	770	870	1500	1430	460	430	84.4

Per the agreed plan, all discrete process materials were mixed into a feed blend pile. Results of this activity were captured on video tape.

Efficiency of the blending operation and feed to the plant was measured via a series of nine (9) radial hollow stem auger borings, analyzed for contaminant metals chromium, copper and nickel. In addition, five (5) samples were split for CLP analysis by IEA Laboratories in the United States.

Analysis of the nine samples by D.C. Griffith showed good consistency with averages and ranges for each metal. CLP analysis by IEA on five split samples showed similar consistency and close agreement to the results generated by the Dutch laboratory. From these data, it was concluded that the feed pile was sufficiently blended to introduce a consistent feed to the process.

TABLE 3
PROCESS OVERSIZE

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

(All mg/kg)

Material	Concentrations						% Dry Solids
	Cr		Cu		Ni		
	DCG	IEA	DCG	IEA	DCG	IEA	
<4 cm >2 mm Initial Feed (10% misplacement)	890	696	1400	1220	1200	932	87
<4 cm >2 mm Reprocess O/S	420	305	790	617	540	345	80
<4 cm >1 cm Screened	270	185	335	300	970	730	94
<1 cm >2 mm Screened	540	408	800	700	730	498	86

The process oversize is the result of the overflow solids from the wet screening operation. Initial feed runs resulted in some misplacement. The actual screening will produce an oversize in the range of <4 cm >2 mm which meets the treatment requirements.

TABLE 4
PRE-FLOTATION PRODUCT

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

	mg/kg
Cr	375
Cu	680
Ni	170
% Dry Solids	76%

*No splits on this sample.

This sample was a composite of samples taken every 30 minutes during processing. This sample was taken from the underflow of Cyclone #1.

TABLE 5
FLOTATION IMPACT

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

Sand Product

Process Step	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	% Dry Solids
Pre-Flotation Composite	375	680	170	76
Final Sand Product (Avg. composite of 15 Data Points)	170	350	70	84
Contamination Reduction Percent of Flotation Input	45%	51%	41%	

This table demonstrates that the use of the flotation step provides a significant reduction in contamination residing on the sand. Flotation provides an important protection to make sure that the sand returning to the site meets the clean-up standards.

TABLE 6
PRODUCT SAND

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

(All mg/kg)

Sample	Cr		Cu		Ni		% Dry Solids
	DCG	IEA	DCG	IEA	DCG	IEA	
1 - 0900	No sample taken, sand not discharging						
2 - 0930	98		195		41		90
3 - 1000	250	266	465	668	105	119	81
4 - 1030	185		370		73		83
5 - 1100	130	97	270	187	53	43	84
6 - 1130	115		240		46		84
7 - 1200	155	161	315	353	67	77	83
8 - 1230	76		145		33		84
9 - 1300	150	129	305	258	63	66	84
10 - 1330	140		280		54		84
11 - 1400	140	183	310	428	65	98	84
12 - 1430	235		520		120		81
13 - 1500	185		455		87		83
14 - 1530	205		465		97		86
15 - 1600	220	195	445	429	91	99	83
16 - 1630	205		430		89		83
Average	170	170	350	390	70	80	84
Treatment Requirement	483		3571		1935		

ERM Split Sample #13 was broken during shipment. This product sand is the material to be placed back on the site. It clearly meets the treatment requirements.

TABLE 7
SLUDGE CAKE RESULTS

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

(All mg/kg)

Sample	Cr		Cu		Ni		% Dry Solids
	DCG	IEA	DCG	IEA	DCG	IEA	
1	4400		7300		2300		44
2	4400	4470	7400	7330	2300	2360	46
3	4700	4760	8100	7950	2700	2670	46
4	5500		9300		3200		44
Average	4750	4615	8030	7640	2630	2515	45

This table tabulates the results of the produced sludge cake. The sludge cake contains the treated contaminants and will be disposed at an appropriate off-site facility. Work will be focused on improving (increasing) the produced sludge dry solids concentration. A reasonable goal is 55% dry solids.

TABLE 8
SLUDGE CAKE RESULTS - TCLP METALS

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

IEA Analyses Only

TCLP Metal	Regulatory Standard (mg/l)	Results			
		Sample Number (mg/l)			
		1	2	3	4
Arsenic	5.0	<0.61	<0.61	<0.62	<0.63
Barium	100	<14	<17	<48	<37
Cadmium	1.0	<0.12	<0.12	<0.12	<0.12
Chromium	5.0	2.1	1.8	<0.65	<0.67
Mercury	0.2	<0.02	<0.03	<0.02	<0.02
Lead	5.0	<0.65	<0.71	<1.0	<0.96
Selenium	1.0	<0.11	<0.11	<0.11	<0.11
Silver	5.0	<0.60	<0.60	<0.60	<0.63

The TCLP Metal Analyses confirm that the produced sludge cake does not exceed TCLP regulatory standards. The sludge cake is not the product of the treatment of any listed RCRA hazardous waste and does not demonstrate any hazardous characteristics. Therefore, the sludge cake is not a RCRA hazardous waste.

TABLE 9
PROCESS WEIGHT COMPARISON

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

	In/Out as Weighed (tons)	% Dry Solids	Dry Solids in Tons
Feed	163	0.844	137.5
Products			
> 1 cm O/S	9.92	0.96*	9.5
<1 cm O/S	12.56	0.90*	11.3
Sand Product	104.20	0.953**	99.3
Sludge	36.56	0.479**	17.5
Total	163.0	---	137.5
Recovery	---	---	100%

* - Measured by DCG and adjusted for overnight drying
** - Measured by HRD

This table documents a mass balance for the demonstration run. The recovery is excellent, and the mass distribution of produced sludge is reasonable.

TABLE 10
CHROMIUM MASS BALANCE

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

	Dry Solids in Tons	Cr mg/kg		Cr lbs	
		DCG	IEA	DCG	IEA
Feed	137.5	770	870	212	239
Products					
> 1 cm O/S	9.5	270	185	5	4
<1 cm O/S	11.3	540	408	12	9
Sand Product	99.3	170	172	34	34
Sludge	17.5	4750	4615	166	162
Total	137.5	---	---	217	209
Recovery	---	---	---	102%	87%

This table demonstrates the mass balance and recovery for chromium. The concentrations for DCG use all data, while the IEA uses the split sample results. In both cases, the recovery was excellent.

TABLE 11
COPPER MASS BALANCE

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

	Dry Solids in Tons	Cu mg/kg		Cu lbs	
		DCG	IEA	DCG	IEA
Feed	137.5	1500	1430	413	393
Products					
> 1 cm O/S	9.5	335	300	6	6
<1 cm O/S	11.3	800	700	18	16
Sand Product	99.3	350	387	70	77
Sludge	17.5	8030	7640	281	267
Total	---	---	---	375	366
Recovery	---	---	---	91%	93%

This table demonstrates the mass balance and recovery for copper. The concentrations for DCG use all data, while the IEA uses the split sample results. In both cases, the recovery was excellent.

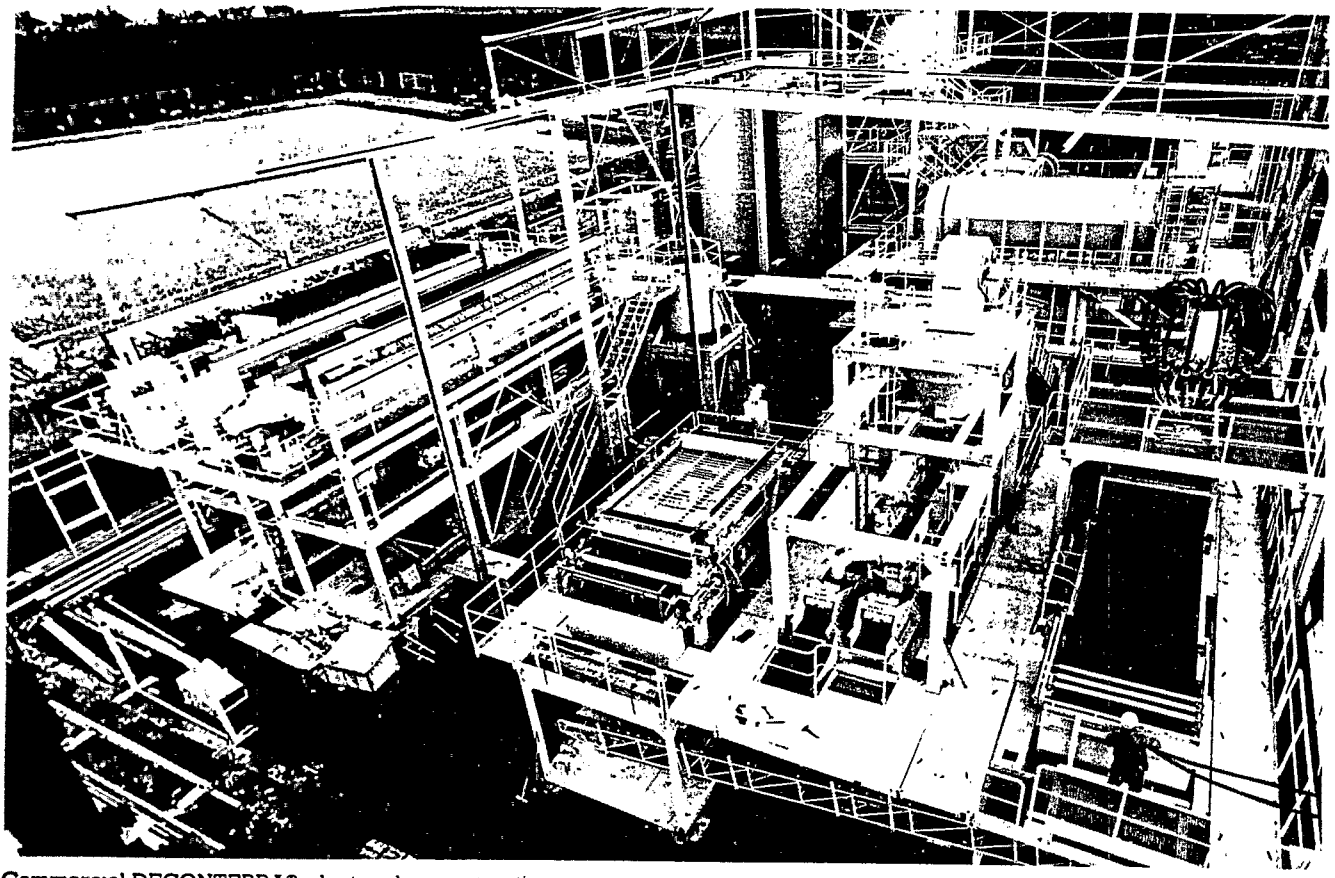
TABLE 12
NICKEL MASS BALANCE

King of Prussia Technical Site
Demonstration Run
Moerdijk, The Netherlands
July 22, 1992

	Dry Solids in Tons	Ni mg/kg		Ni lbs	
		DCG	IEA	DCG	IEA
Feed	137.5	460	430	127	118
Products					
> 1 cm O/S	9.5	970	730	18	14
<1 cm O/S	11.3	730	498	16	11
Sand Product	99.3	70	84	14	17
Sludge	17.5	2630	2515	92	88
Total	---	---	---	140	130
Recovery	---	---	---	110%	110%

This table demonstrates the mass balance and recovery for nickel. The concentrations for DCG use all data, while the IEA uses the split sample results. In both cases, the recovery was excellent.

The Lurgi-DECONTERRA® Process Soil Washing



Commercial DECONTERRA® plant under construction

Dr. Eckart Hilmer

Ted J. Pollaert

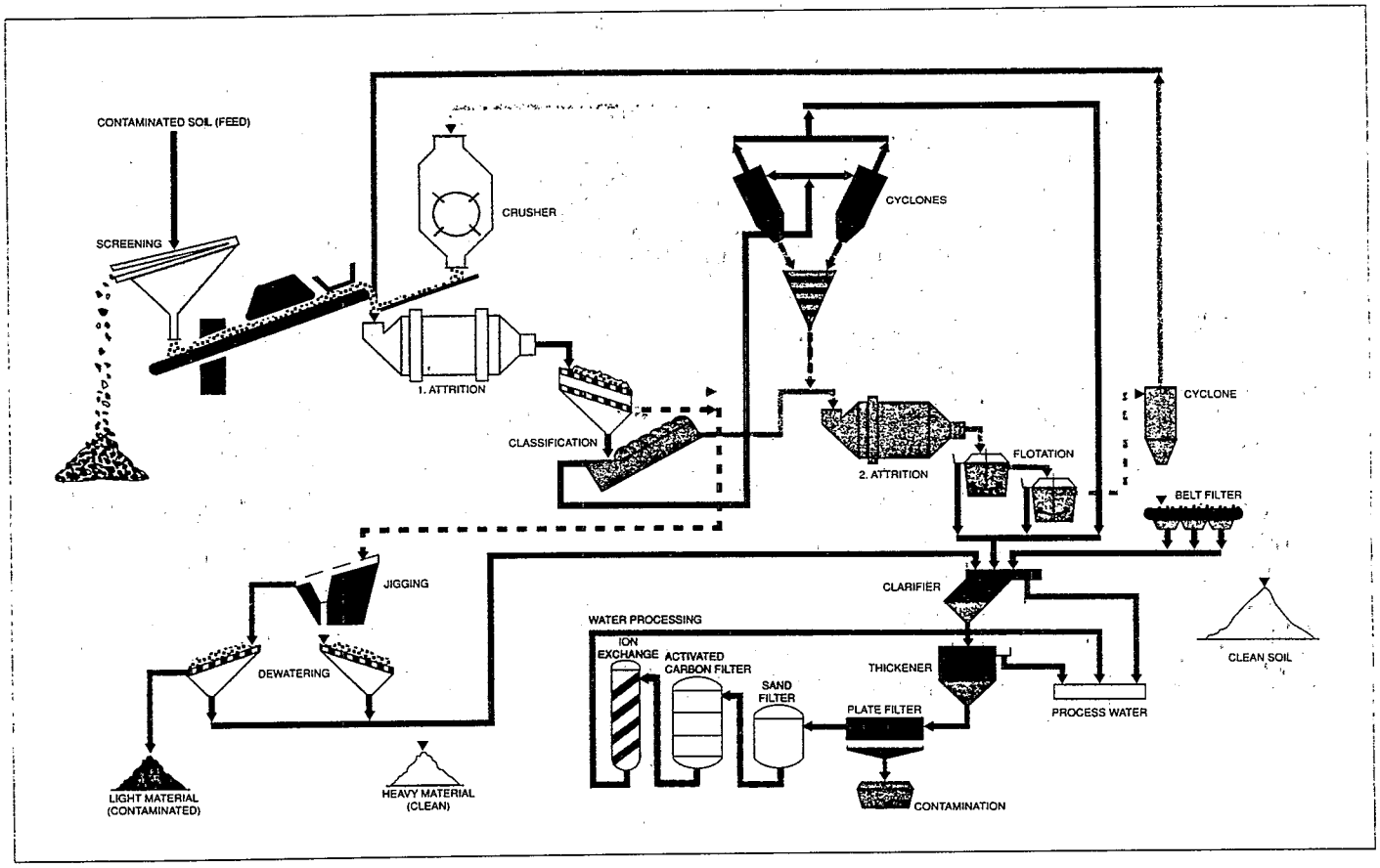
The DECONTERRA® process is a multi-stage wet mechanical separation process for the remediation of contaminated soil (organics and inorganic compounds), building rubble and railway ballast.

As extraction agent, water is used commonly without any addition of detergents, solvents, emulsifiers or acids.

In addition to the size separation procedure, it uses sorting techniques for separating contaminated particles from the clean bulk. This is why soil types with extremely high silt or clay contents can still be treated economically.

The development of this process is based on Lurgi's know-how in the field of wet mechanical processing of minerals, especially of ores and salts, as well as of sludges from stagnant and running waters, and on the equipment experience, which Lurgi has gained building such plants.

DECONTERRA® Process



Process Description

The contaminated soil is reclaimed, fed to a grizzly, followed by a vibratory screen.

The coarse fraction is crushed and, together with the fine fraction, is transferred to a wet attritioner drum.

In the attritioner drum, the bulk of the adhering pollutants is rubbed off with a controlled input of energy and first of all suspended in the liquid and then bound adsorptively to the fine particles of the soil.

The energy required for the attrition is matched to the type of soil and the character of the contamination, up to 10 kWh/ton being transferred to the material. The material discharged from the drum is screened in several stages. The fraction over 20mm is returned via the crushing cycle back to the attrition stage. The 1–20mm fraction is either discharged from the process as purified end product or subjected to a gravimetric sizing, the heavy material being discharged clean, whereas the light material, such as contaminated coarser coal, tar and wood particles, being obtained as a pollutant concentrate.

Of the fraction under 1mm, the finest fraction is cleared from mud and transferred to a hydrocyclone, the overflow of which is concentrated.

The cyclone underflow, together with the deslimed coarse fraction of the classifier, is introduced into the 2nd attrition step and subjected to a further purification.

The material discharged from the 2nd attrition step reaches a flotation system, the special reagents of which are matched to particular requirements of the pollutants involved.

The flotation underflow contains the purified material, which is subsequently dewatered to a residual moisture content of about 15–20% and can be disposed or piled as cleaned product.

The pollutants are concentrated in the froth discharged during flotation. This froth reaches the thickener for pre-dewatering. The thickener underflow is brought to a moisture content of about 20% in a dewatering step and being discharged as filter cake.

The pollutant concentrate is composed out of the following process streams:

1. Light fraction from the gravimetric sorting (such as wood, tar fragments, coal, coke, etc.).
2. Overflow from the hydrocyclone, essentially the fines portion of the soil with the adsorbed pollutants.
3. Flotation froth.

Fractions 2 and 3 are obtained together as filter cake.

It has turned out that the process can also effectively clean the fine grain fraction. The process, therefore, is also able to decontaminate soils with a high proportion of fine grain (less than 63 microns in diameter). Depending on the composition of the soil and the nature of the contamination, the yield of decontaminated soil is between 70% and 90% of the untreated soil. The residual pollutant content in the purified soil is clearly below the B values of the "Dutch list."

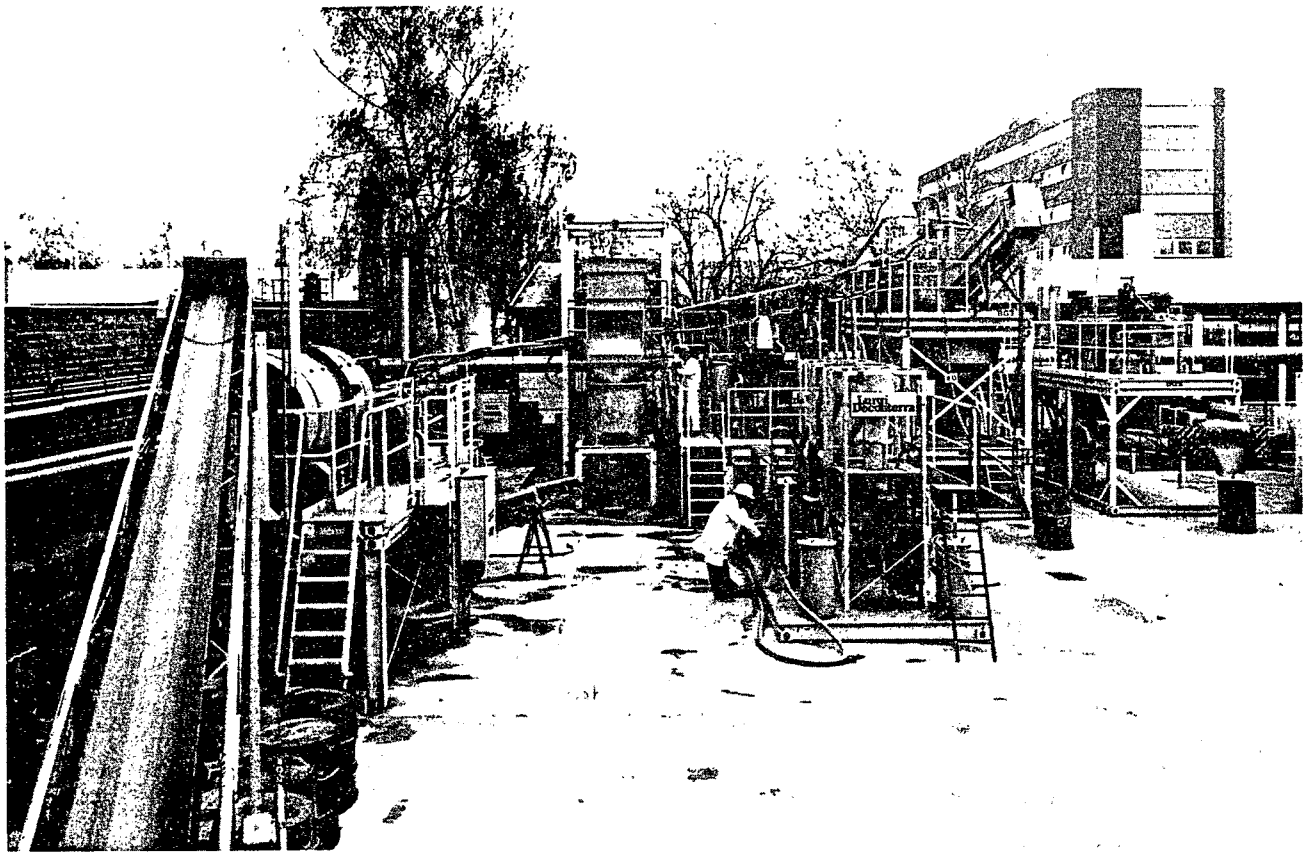
The process water used in the Lurgi-DECONTERRA® plant is recycled. The input of fresh water, therefore, is limited to about 25 gallons/ton, depending on feed moisture. In order to prevent an accumulation of contaminants, the process water passes a water treatment unit, where fines as well as dissolved compounds are precipitated and removed from the circuit.

Batch Scale Tests and Pilot Plant

Lurgi has investigated and cleaned laboratory scale samples of 50 kg of many different contaminated soils from coking plants, gas works and other locations of contaminated waste.

The knowledge gained led to the development of the DECONTERRA® -process and to the construction of a pilot plant with a throughput of about 1 ton/hour.

The soils tested on a laboratory scale were also treated in the pilot plant, in which the decontamination results were confirmed.



Transportable Pilot Plant

Some of the materials tested so far:

PROJECT: Town Gas Plant Site

Material Characteristics:
Silt content: 30%

All values given in ppm

Contaminants	Raw Soil	Clean Soil	Limit	Reduction (%)
PAH, sum (EPA)	1,150	16	20	98.6
Naphthalene	16	1.6		90
Anthracene	23	<1		99
Pheno anthrene	180	1.7		99
Fluoro Anthrene	150	2		98.6
Pyrene	88	<1		99
3, 4 Benzo pyrene	18	<1		99
Hyrdocarbons	1,900	50	200	97.3

Clean soil recovered: 85%

PROJECT: Non-Ferrous Smelter Site

Material Characteristics:
Silt content: 28–47%

All values are in mg/kg

Contaminants	Raw Soil	Clean Soil	Limit	Reduction (%)
Pb	840	42	150	95
Cu	2,615	28	100	98.9
Zn	1,970	87	500	95.5
Hg	265	36	50	86

Clean soil recovered: 75–86%

PROJECT: Ammunition Plant Site / Stadtallendorf

Material Characteristics:
Silt content: 20%

Type of soil: Residue of weathered sandstone

All values are in ppm

Contaminants	Raw Soil	Clean Soil	Limit	Reduction (%)
PAH	—			
Hydrocarbon	—			
2, 4, 6 TNT	6,400 (max) 1,500 (middle)	0.7	1	99.9

Clean soil recovered: 79%

PROJECT: Coking Plant Site

Material Characteristics:
Silt content: 62%

Type of soil: Sandy-clayey, with some coal and coke rests

All values are in ppm, except as noted

Contaminants	Raw Soil	Clean Soil	Limit	Reduction (%)
PAH	1,030	13	20	98.8
Phenol (ges.)	1.5	0.4	0.5	73
Cyanide	8.9	0.4	1.0	95.5
Total Carbon (%)	5.9	1.8	—	70
Cu	16	7.2	10	55
Hg	2	<0.5	1.0	75

Clean soil recovered: 76%

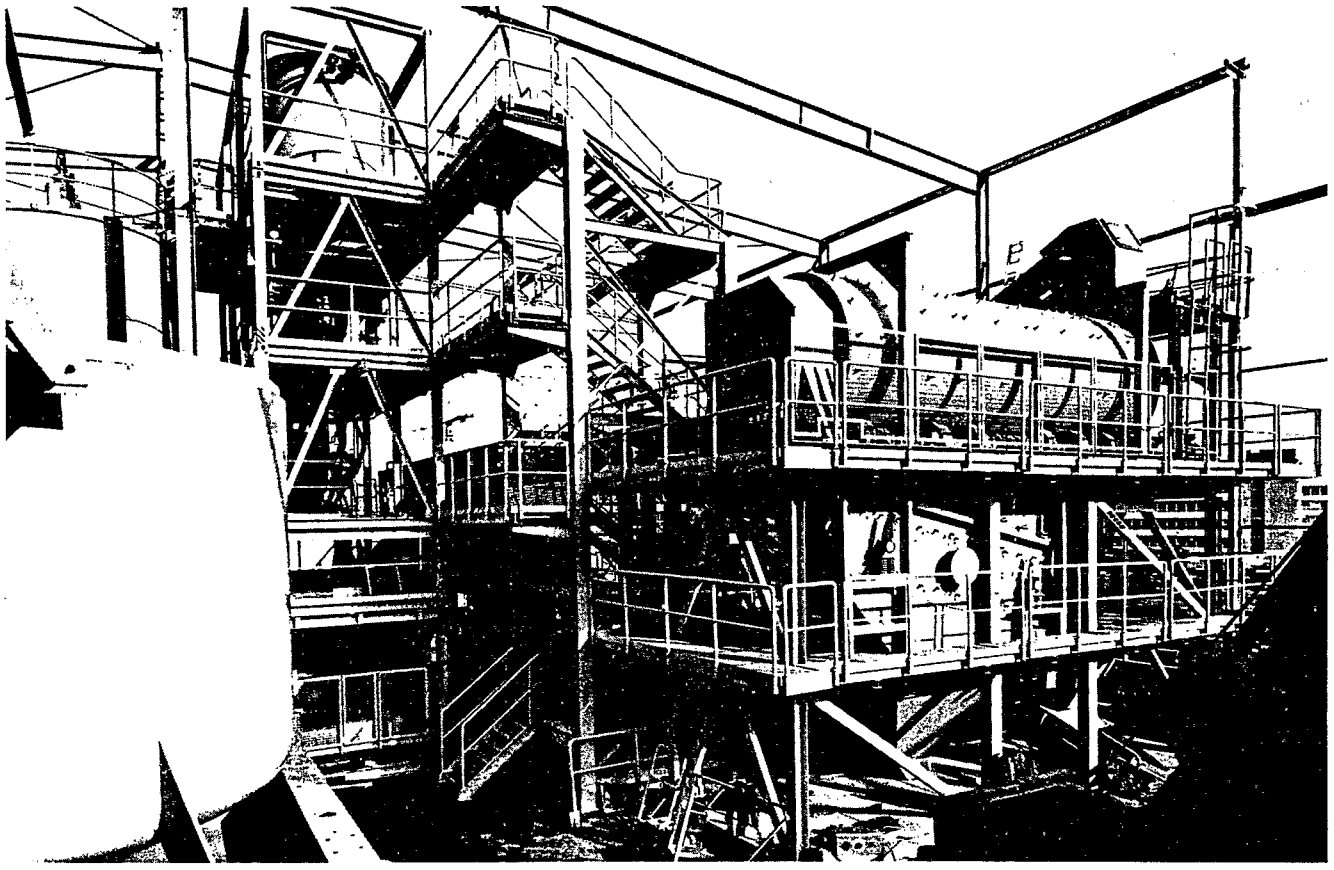
Many other materials have been tested. So far we have not run pesticide and / or arsenic contaminated material, but we are set up to do so.

Commercial Experience

The commercial plants have a capacity of 25 MTPH. The first one started up in June of this year. It is cleaning up a former smelter site which is being converted into an office park. Its performance confirms the pilot plant results.

Another commercial plant with a capacity of 40 MTPH has been in operation since June 1990. It removes and recovers mercury from soil removed from a former wood treating factory; now a shopping mall.

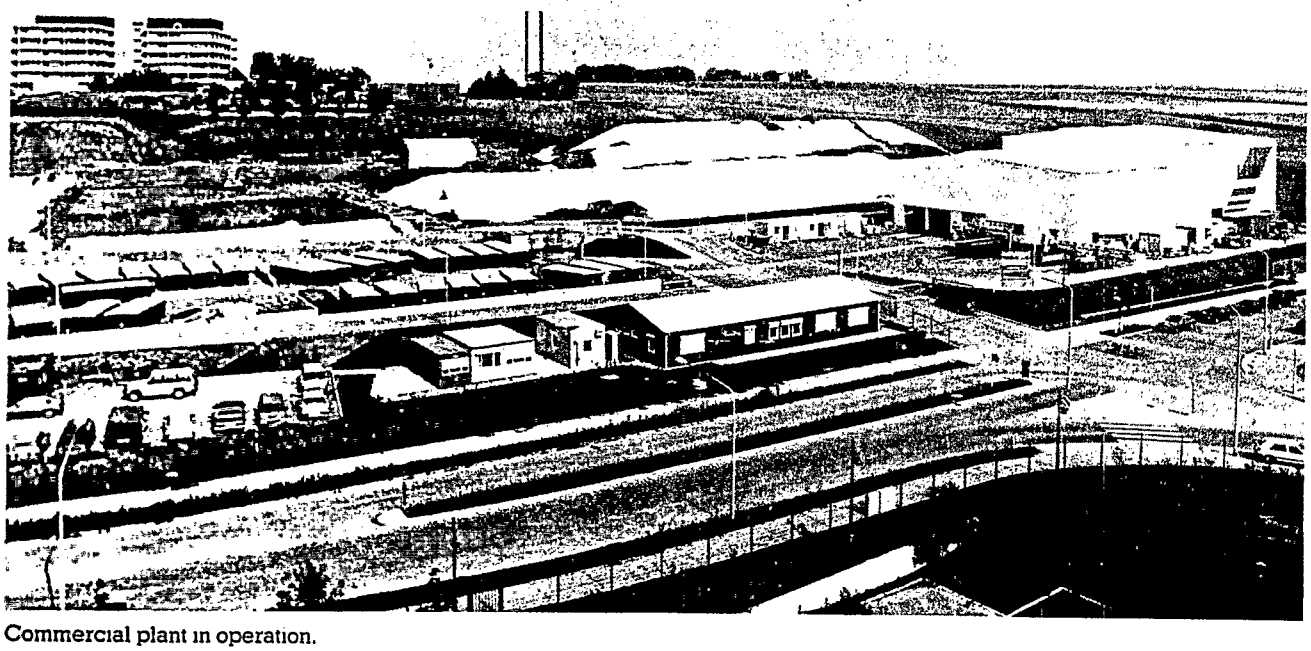
A third commercial plant is cleaning soil at a former coke oven site. It is in operation since October 1992.



Commercial plant under construction. Attritioner drum and clarifier at the right side of the picture.

A fourth one, to clean up the Stadtallendorf TNT, is in fabrication.

In general these plants are built up of transportable modules.



Commercial plant in operation.

Dutch List

Since the question is asked so often, a copy of the Dutch list is reprinted, with permission. In this list

— A, B, C are indicative values.

— A — Reference category, natural background

— B — Threshold value, postulate further investigation.

— C — Anomalous value, which indicates remediation activities.

Holländische Liste

Vorkommen in:	Boden (mg/kg TS)			Grundwasser (µ/l)		
Stoff / Konzentration	A	B	C	A	B	C
I. Metalle						
Cr	100	250	800	20	50	200
Co	20	50	300	20	50	200
Ni	50	100	500	20	50	200
Cu	50	100	500	20	50	200
Zn	200	500	3000	50	200	800
As	20	30	50	10	30	100
Mo	10	40	200	5	20	100
Cd	1	5	20	1	2,5	10
Sn	20	50	300	10	30	150
Ba	200	400	2000	50	100	500
Hg	0,5	2	10	0,2	0,5	2
Pb	50	150	600	20	50	200
II. Anorganische Verbindungen						
NH^4 (als N)			-	200	1000	3000
F (gesamt)	200	400	2000	300	1200	4000
CN (gesamt-frei)	1	10	100	5	30	100
CN (gesamt-kompl.)	5	50	500	10	50	200
S (gesamt)	2	20	200	10	100	300
Br (gesamt)	20	50	300	100	500	2000
PO^4 (als P)	-	-	-	50	200	700
III. Aromatische Verbindungen						
Benzol	0,05	0,5	5	0,2	1	5
Athylbenzol	0,05	5	50	0,2	20	60
Toluol	0,05	3	30	0,2	15	50
Xylole	0,05	5	50	0,2	20	60
Phenole	0,05	1	10	0,2	15	50
Aromaten (gesamt)	0,1	7	70	1	30	10
IV. Polycyclische aromatische Kohlenwasserstoffe (PAK)						
Naphthalin	0,1	5	50	0,2	7	30
Anthracen	0,1	10	100	0,1	2	10
Phenanthren	0,1	10	100	0,12	2	10
Fluoranthen	0,1	10	100	0,02	1	5

Holländische Liste

Vorkommen in:	Boden (mg/kg TS)			Grundwasser (µ/l)		
Stoff / Konzentration	A	B	C	A	B	C
Crysen	0,1	5	50	0,005	0,5	2
Benzo (a) anthrazen	0,1	5	50	0,005	0,5	2
Benzo (a) pyren	0,05	1	10	0,005	0,2	1
Benzo (k) fluoranthen	0,1	5	50	0,005	0,5	2
Benzo (ghi) perylen	0,1	10	100	0,005	1	5
PAK (gesamt)	1	20	200	0,2	10	40
V. Chlorierte Kohlenwasserstoffe (CKW)						
aliphatische CKW (einzeln)	0,1	5	50	0,01	10	50
aliphatische CKW (gesamt)	-	7	70	-	15	70
Chlorbenzole (einzeln)	0,05	1	10	0,01	0,5	2
Chlorbenzole (gesamt)	-	2	20	-	1	5
Chlorphenole (einzeln)	0,01	0,5	5	0,01	0,3	1,5
Chlorphenole (gesamt)	-	1	10	-	0,5	2
chlorierte PCX (gesamt)	0,05	1	10	-	0,2	1
polychlorierte Biphenyle (PCB) (gesamt)	0,05	1	10	0,01	0,2	1
EOCl (extrahierbares organisches Chlor) (gesamt)	0,1	8	80	1	15	70
VI. Pestizide						
org. Chlorpestizide (einzeln)	0,1	0,5	5	1/0,01	0,2	1
org. Chlorpestizide (gesamt)	-	1	10	-	0,5	2
Nicht-Chlorpestizide (einzeln)	0,1	1	10	1/0,01	0,5	2
Nicht-Chlorpestizide (gesamt)	-	2	20	-	1	5
VIII. Sonstige Verunreinigungen						
Tetrahydrofuran	0,1	4	40	0,5	20	60
Pyridin	0,1	2	20	0,5	10	30
Tetrahydrothiophen	0,1	5	50	0,5	20	60
Cyclohexanon	0,1	6	60	0,5	15	50
Styrol	0,1	5	50	0,5	20	60
Phthalate (gesamt)	0,1	50	500	0,5	10	50
Oxydierte PAK (gesamt)	1	200	2000	0,2	100	400
Mineralöl	100	1000	5000	50	200	600

Efficient and Cost-Effective Programs for Soils and Groundwater Restoration

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ABSTRACT

As the nations of the world struggle with the complexities of cleanup of the hazardous waste which already exists and attempt to control and manage the discharge of more wastes, they are caught in a dilemma between a plethora of regulatory guidelines and the limitations of technology development. It is difficult to enforce regulations on industry if there is no technology available to remediate the waste.

Usually, the most serious form of hazardous waste is that which cannot be seen; waste that is in the soils and groundwater.

The wastes, commonly in the form of petroleum hydrocarbons, volatile organic compounds, and inorganic compounds, slowly leach through the soils and into the groundwater where conventional methods of remediation may take decades, and the costs may become outrageous. More effective means of subsurface remediation may be accomplished by treatment of the contamination at the source and managing the migration of the contaminants away from the source.

Complex subsurface contamination problems require innovative solutions, and fortunately, for the most part, the advances of technology have kept pace with the regulatory environment.

This paper presents three common, yet complex, cases of subsurface contamination where both soils and groundwater were restored by the application of innovative and cost effective remedial measures.

INTRODUCTION

To citizens worldwide, environmental topics pose major concerns. Industrialized nations battle the severe, polluting effects of hazardous waste discharges while the developing nations torment with ideas on how not follow in the footsteps of their brethren while building their own economies.

How then to manage such a task; to clean up the hazardous waste which already exists and manage the discharge of all future hazardous waste?

During the recent Earth Summit in Rio de Janeiro, nations all over the world took it upon themselves to make a cooperative effort toward a cleaner environment. Some of the time, such "cooperative efforts" mean individual efforts and voluntary constraints, but most of the time "cooperative efforts" result in regulations.

Regulations may be the key, but one factor is how we keep pace between regulations and technology. After all, how can nations enforce regulations if there are no suitable and cost effective technologies available to solve to the problem? Hazardous waste problems are complex and they require innovative solutions.

Notwithstanding these complexities, most cases of hazardous waste can be grouped into three general categories; petroleum hydrocarbons, volatile organic compounds, and inorganic compounds.

One way to mitigate the problems associated with hazardous waste in surface water is to treat the waste at the source by controlling and treating discharges. This is an obvious, healthy, and aesthetic move toward making the environment pristine.

However, the silent killers rest beneath the ground surface, in contaminated soils and groundwater. Contamination which enters the soil eventually leaches into the groundwater; groundwater which eventually finds its way to fresh water supply wells and also some surface waters. Subsurface contamination is a major problem, and to treat it, you do the same thing as you do for surface water. That is, treat the problem at the source and control its migration.

This paper presents three cases where cost effective and innovative solutions were applied to solve a problem in each of the three categories of subsurface contamination.

These cases represent only a sampling of the many technologies which are available, nevertheless they depict three situations where cost effective, innovative techniques of source treatment and migration control were utilized to solve the problems of subsurface contamination.

SUBSURFACE CONTAMINATION

Typically, the source of subsurface contamination begins in the soils. Surface spills, leaking underground storage tanks, heap leaching fields, and worn or ruptured pipelines are just a few ways in which soils can become contaminated.

The contamination may exist in several different phases in the subsurface soils as pictured in Figure 1 (next page). The aqueous phase is that which is dissolved in the soil's water saturation. If the contaminant is volatile, the vapor phase fills the soil's air porosity fraction. Lesser amounts are adsorbed to the soil matrix. In addition, there also may be free phase liquid product. With all

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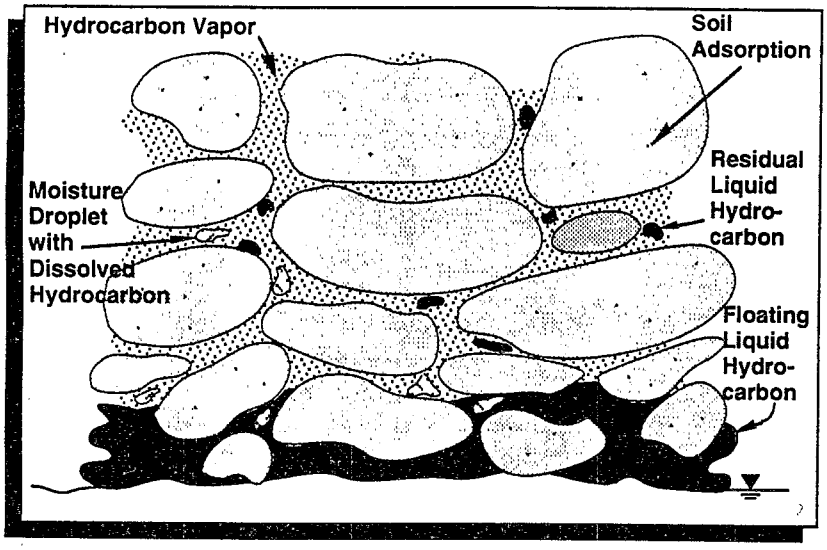

FIGURE 1: HYDROCARBONS IN THE SUBSURFACE

these fractions describing the source of soil and groundwater contamination, it is essential that remedial techniques address all phases of the contamination.

PETROLEUM HYDROCARBONS

Some of the more common contaminants in the subsurface are petroleum hydrocarbons. Petroleum production, refining, transfer, and marketing operations all contribute to the oil, gas, diesel, and jet fuel, amongst some contaminants, which are known to be in the soils, floating on the groundwater, or migrating off somewhere in a groundwater plume. Nearly everyone knows of a case like this, however what many do not realize is that it takes just one liter of gasoline to render one billion liters of water non potable.

One particular case reported by Trowbridge and Malot, 1991, involves a residential subdivision in the northwestern U.S.A where in 1987, petroleum hydrocarbons were found in an underlying aquifer. The subdivision is located down gradient from several petroleum refining, pipeline, pumping, and storage facilities. The discovery of liquid phase hydrocarbons directly beneath a residential area was of immediate concern.

Figure 2 is a site map that shows the location of the hydrocarbon plume and the apparent hydrocarbon thickness contours. The measured liquid phase hydrocarbon thickness varies from 0.06 to 0.2 meters. The unsaturated soils above the water table were tested, but their low hydrocarbon content confirmed that the liquid hydrocarbons had indeed migrated to the residential area along the surface of the water table. Groundwater levels in the area fluctuate about one meter per year.

The geology of the site is unconsolidated alluvial deposits overlying a sandstone and shale bedrock. The alluvium is characterized by discontinuous clayey silts and silty clays to a depth of approximately 1.5 meters. The next 20 meters are a fairly homogeneous medium to course grained sand with gravels and cobbles. The groundwater table begins at about 10 meters, and the aquifer is believed to have a thickness of about 10 meters.

Initial efforts to recover free floating product included a product pumping system; however, after several weeks of operation and obviously much more product in the ground, the product pumps were collectively delivering a mere four liters per day of product. The radius of influence of the product pumps was insignificant, and the system was incapable of drawing the long plume of floating hydrocarbons into the recovery wells.

In the fall of 1988, a pilot test of the innovative vacuum extraction system was installed to evaluate the effectiveness of the technology for removing liquid phase hydrocarbons from the water table. Four vacuum extraction wells were installed for the pilot test. Design specifications for the test were $14m^3$/min vapor flow, and the process system included a vapor/water separator, extraction blower and a catalytic oxidizer for vapor treatment. Figure 3 (next page) is a process diagram of the pilot system.

The recovery rate of the four-well pilot test was approximately 50 gallons per day, with a radius of influence of over 30 meters per well. Over a period of four weeks 4,500 Kg of hydrocarbons, or the equivalent of about 5,300 liters of gasoline, were removed.

The success of the pilot system led to expansion into full scale operations. Several more wells were installed and the process equipment was upgraded. Interestingly enough, many wells showed no evidence of free floating product until vacuum was applied to the wells, indicating the effectiveness of the vacuum extraction system in capturing and vaporizing free product much faster than other pumping schemes.

Figure 4 (next page) is a crossplot of typical wellhead vapor

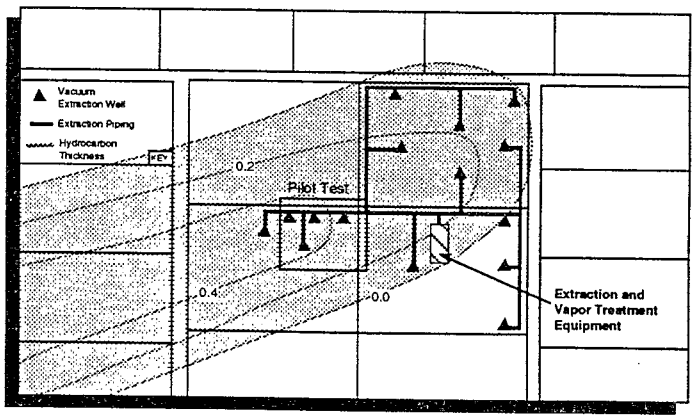

FIGURE 2: SITE MAP WITH HYDROCARBON PLUME

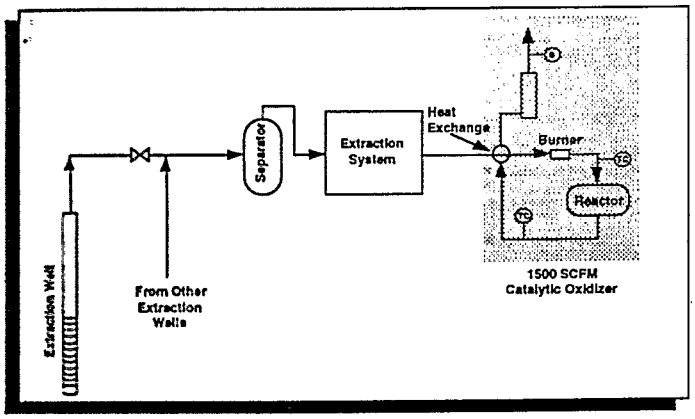

FIGURE 3: PILOT SYSTEM PROCESS DIAGRAM

concentrations for one well during the pilot test. The plot is indicative of the rapid vaporization and recovery of petroleum hydrocarbons by the vacuum extraction process.

In all, the expanded vacuum extraction system recovered approximately 87,400 liters (23,000 gallons) of hydrocarbons over a 350-day period. Figure 5 shows the removal trend and cumulative amount of hydrocarbons extracted. These high extraction rates and cumulative removal trends support the effectiveness of vacuum extraction to vaporize liquid phase hydrocarbons which were otherwise not removable with traditional pumping techniques. After 350 days, the vacuum extraction system was

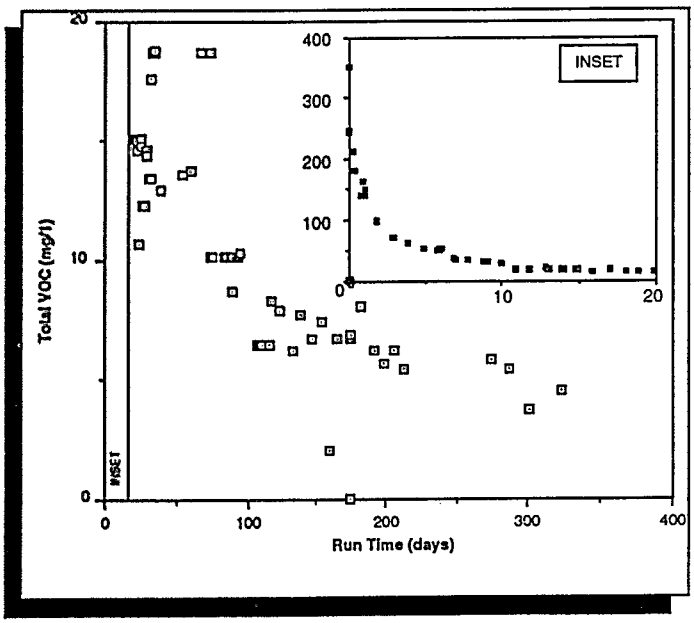

FIGURE 4: WELLHEAD VAPOR CONCENTRATION TREND

still recovering hydrocarbons at a rate of 190 to 230 liters per day.

CHLORINATED HYDROCARBONS

Another common form of subsurface contamination are volatile organic compounds (VOCs). Virtually every manufacturing process of raw materials, from high tech industries to machine shops and dry cleaning establishments, have used some sort of chlorinated solvents for de-greasing or cleaning purposes. In fact, of the 1,700 sites on the United States National Priority List (i.e. Superfund Sites), more than 60% have VOCs as the primary pollutant.

At one Superfund Site in Michigan, U.S.A., (Malmanis et al, 1989, Malmanis et. al. 1990, Trowbridge and Malot, 1991) the

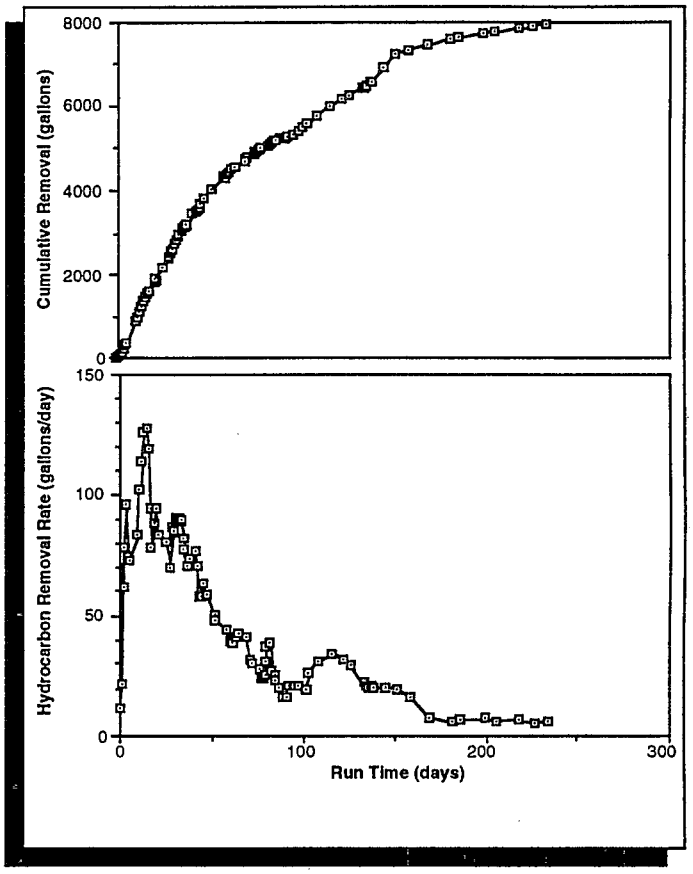

FIGURE 5: HYDROCARBON REMOVAL TREND

facility was used as a transfer and storage plant for handling industrial solvents. The site had 21 buried underground storage tanks (USTs), and a variety of VOCs were found in the subsurface soils and groundwater, including trichloroethylene (TCE), tetrachloroethylene (PCE), trichloroethane (TCA), methylene chloride, xylenes, acetone, toluene, ethyl benzene, and 1,1,-

dichloroethylene. Soil concentrations were as high as 1,800 mg/kg (ppm), and the area of contamination covered approximately 3,250 m^2. The groundwater table is situated at a depth of about 7 m. The site plan is shown in Figure 6.

The U.S. EPA designated vacuum extraction as the remedial technology to clean the soils. The cleanup criteria were for soil samples to be less than 10 mg/kg, with no more than 15% of the samples above 1 mg/kg total VOCs.

A vacuum extraction system similar to the schematic in Figure 7 was installed at the site. The system included 23 vacuum extraction wells strategically placed throughout the area of the buried tanks. The system began operations with activated carbon for vapor treatment; however, with extraction rates as high as 2,000 kg/day, preparations were made to switch to a catalytic oxidizer. Since catalytic oxidation of chlorinated compounds had previously never been permitted at a Superfund Site with VOCs,

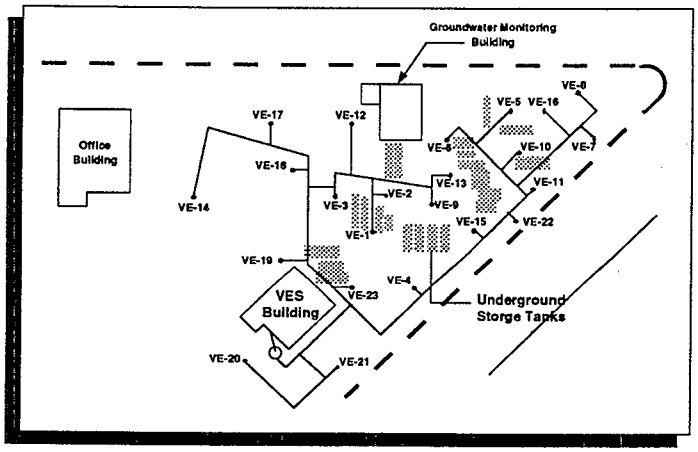

FIGURE 6: SITE PLAN

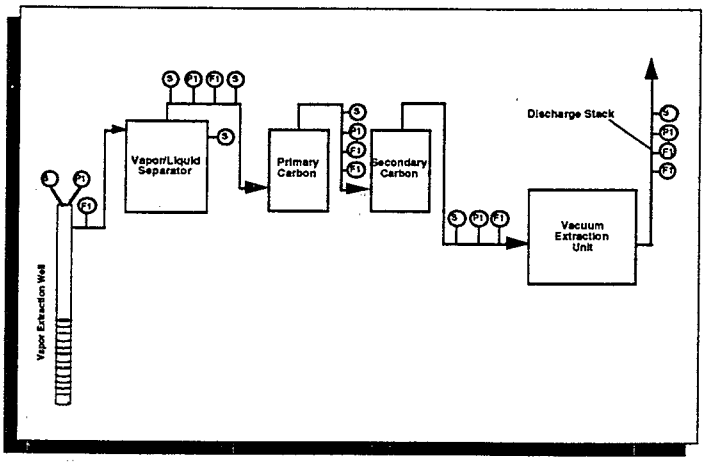

FIGURE 7: VACUUM EXTRACTION SYSTEM SCHEMATIC

a source test was completed which demonstrated the effectiveness of the catalytic oxidizer to destroy the chlorinated hydrocarbons and other compounds. Figure 8 shows the results of the source test which achieved an overall destruction rate of 99.8%.

Free floating non aqueous phase liquids (NAPLs) were also identified at the site, but as in case 1, many wells did not contain any free product until vacuum was applied. Nearly 0.6 meter of free product was identified in selected locations. Once gain, the innovative vacuum extraction remedy showed unparalleled performance for removing free floating contaminants from the groundwater table, and Figure 9 (next page) illustrates that the vacuum extraction system completely vaporized the free floating product within a period of 40 days.

In all, over 20,000 kg of VOCs were removed form the soils within two years. The soils have been declared clean by EPA to 0.1 mg/kg, yet groundwater treatment continues. A separate groundwater treatment system has been modified to allow Dual

CATOX EFFICIENCY FOR CHLORINATED HYDROCARBONS

COMPONENT	INLET (ug/l)	OUTLET (ug/l)	PERCENT REMOVAL
Acetone	7.7	ND	—
Methylene Chloride	0.8	ND	—
TCA	8.3	ND	—
Benzene	0.1	ND	—
TCE	21	ND	—
Toluene	18	ND	—
PCE	54	0.6	—
Xylene	25	ND	—
Other	184	ND	—
Total	**319**	**0.6**	**99.8**

FIGURE 8: SOURCE TEST RESULTS

Extraction™, or the simultaneous recovery of vapors and groundwater from the same wells. The Dual Extraction™ system significantly increased VOC recovery rates from the saturated zone, and impact of applied vacuum in the wells concurrent with groundwater pumping greatly accelerated vapor phase partitioning of VOCs. Figure 10 (next page) is a schematic of the Dual Extraction™ system.

To further accelerate in the groundwater cleanup, an innovative nitrogen sparging system was installed in October 1991. Known as SpargeVAC™, this in-situ water treatment functions just like an in-ground air stripper. As fresh air or nitrogen is injected into the saturated zone, the air rises through the groundwater. The dissolved, adsorbed, and liquid phase VOCs are partitioned into the vapor phase, rise to the unsaturated zone (i.e. vadose zone), and are recovered by the vacuum extraction

process. Figure 11 represents the SpargeVAC™ process. The sparge gas used at this Superfund Site was nitrogen, as the high iron concentrations in the groundwater raised concerns regarding the formation of ferric oxide in the pore space of the aquifer if regular compressed air was used.

The sparging system resulted in a 21-fold increase in extracted

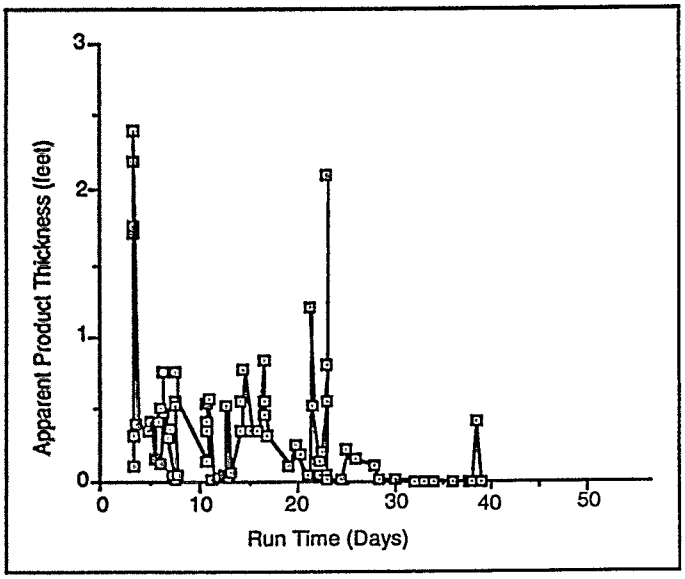

FIGURE 9: NAPL THICKNESS VS. VES RUN TIME

toluene concentrations, and 300% increase in the PCE and TCE concentrations being extracted in the vapor phase by the vacuum system. The EPA's groundwater extraction system had operated for 5 years at 200 m^3 per day and it was only effective in reducing the groundwater concentrations from an initial level of about 19 ppm to about 3 ppm.

Using the SpargeVAC™ technology, the groundwater concentrations were reduced 93% to less than 150 ppb within four months. There was no comparison between the effectiveness nor the costs of conventional groundwater pumping and the superior

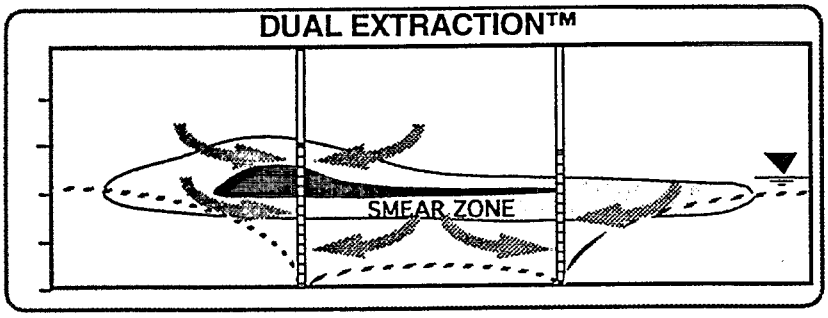

FIGURE 10: DUAL EXTRACTION™ REMEDIATION

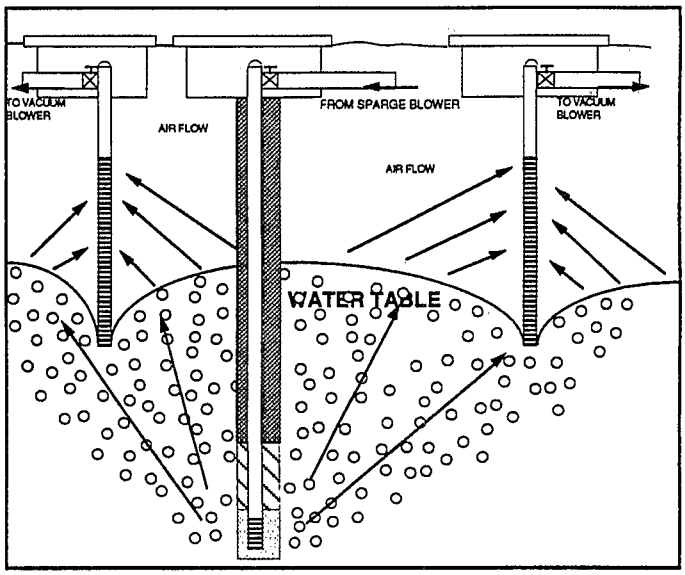

FIGURE 11: VACUUM EXTRACTION/AIR SPARGING

performance and lower costs noted with the innovative vacuum extraction, Dual Extraction™ and SpargVAC™ technologies. The EPA had spent more money studying the site than the innovative remedial technologies cost to clean it.

INORGANIC COMPOUNDS

The generation and release of inorganic compounds into the soils and groundwater are yet more cases of hazardous waste contamination which have fallen under intense scrutiny by regulatory agencies worldwide. Industries such as mineral exploration and metal working industries are vital contributors to an economy, yet they are also major causes of contaminated waterways and estuaries by heavy metals and other compounds.

However, inorganic compounds undergo several different geochemical and biological interactions in the subsurface, and many situations which might appear disastrous at first can be controlled and mitigated by innovative techniques involving chemical oxidation, natural attenuation, and enhanced biodegradation.

One inorganic compound, cyanide, is widely used in the mining industry to leach gold silver and other ores from processed rock. It is well documented that cyanide undergoes numerous reactions in the subsurface by a variety of geochemical and biological mechanisms. Rouse and Pyrih, 1991 describe several different physio-biochemical mechanisms in the subsurface in which cyanide may participate.

In 1991, routine ground and surface water monitoring activities at a heap leaching mine facility discovered cyanide contamination in the ground

and surface water (Rouse and Gochnour, 1992). A schematic diagram of the site is depicted in Figure 12.

Although the leach pad was constructed with triple liners, apparently a silicone seal in one of the drain pipes failed and allowed the cyanide-bearing leachate solution to migrate out of the pad and into the underlying pad fill material and soils beneath. The cyanide solution subsequently moved along a shallow buried alluvial channel and was detected in seep springs near a monitoring well. The cyanide seepage was found to contain approximately 80 mg/l CN WAD (weak acid dissociable). There were also elevated quantities of copper, gold, silver, and zinc.

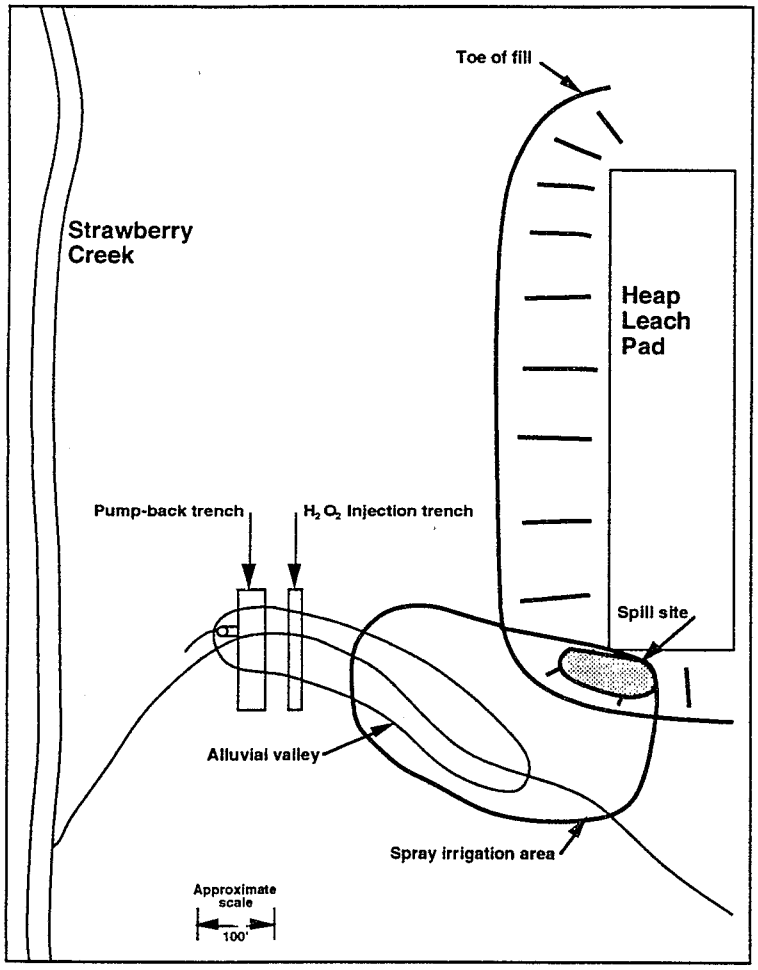

FIGURE 12: SITE MAP

The mine owner responded immediately, and a series of trenches and ponds were constructed to capture and control some of the migration of the cyanide and to treat the contaminated media. Treatment of the seepage was accomplished by adding hydrogen peroxide to oxidize cyanide, and a recirculating sprinkler system which enhanced the ultraviolet decomposition of cyanide in the water.

Upon the addition of hydrogen peroxide, the water in the trenches turned green as the copper cyanide complexes degraded and a copper precipitate was formed. In addition, biological studies on the soils revealed that they contained indigenous microorganisms which were capable of biologically degrading the residual cyanide. The addition of phosphate fertilizer enhanced the process, and bacteriological counts confirmed that the biodegradation of residual cyanide was successful.

The result was a rapid decline in cyanide concentrations in the seepwater and soils in response to the containment, chemical oxidation, and biodegradation processes. Total cyanide concentrations were reduced to < 0.1 mg/l within one month.

CONCLUSION

The case studies presented herein are representative of only some of the many technologies which are available to remediate hazardous waste in the subsurface and restore the environment. Environmental problems involving subsurface contamination are complex; however, innovative technologies do exist to control, mitigate and cleanup subsurface contamination.

Moreover, an aggressive approach toward cleanup of the sources of contamination is nearly always the most cost effective.

ACKNOWLEDGMENTS

The authors would like to thank Steve Thompson for his efforts in preparing the graphics for this paper.

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RADIOLYTIC REMEDIATION OF A TCE GROUND SPILL USING AN ELECTRON ACCELERATOR*

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ABSTRACT

Radiolytic decomposition of chlorinated hydrocarbons and other toxic compounds has been experimentally measured using ionizing radiation produced by electron accelerator and nuclear isotope sources. Decomposition products have been identified. A portable, commercially available electron accelerator was set up at a Superfund site where vapor extraction wells were removing trichloroethylene (TCE) from a spill into the unsaturated soil. The extraction vapor was passed through the accelerator beam to decompose the TCE. On site radiolytic decomposition of TCE vapor using an accelerator is shown to be significantly less expensive than filtration of TCE vapor using activated charcoal.

KEY WORDS

Ionizing radiation, bremsstrahlung, electron beam, chlorinated hydrocarbons, Superfund site, radiolytic decomposition, VOC, TCE.

INTRODUCTION

Toxic compounds and hazardous materials can be radiolytically decomposed when exposed to ionizing radiation. We have experimentally demonstrated this effect on samples of volatile organic compounds (VOCs) and high explosives dissolved in groundwater and on polychlorinated biphenyls (PCBs) dissolved in transformer oil. These results have been reported elsewhere. This report describes results of a trial demonstration at a Superfund site where an electron accelerator was used to radiolytically decompose trichloroethylene (TCE) vapor.

FIELD DEMONSTRATION

Site-300 is on the National Priority List (NPL) due to a TCE ground spill that permeated the unsaturated subsurface soil. This Superfund site was in remediation process using vacuum extraction wells that removed subsurface air enriched with TCE vapor. The air was passed through an activated charcoal filter to remove TCE before release to the atmosphere. An industrially available, portable, 2 MeV electron accelerator with a beam power of 1 kW was brought to the site and connected into the remediation system upstream of the activated charcoal filter so that all vapor extracted from the soil was passed through the electron beam before

*Work performed under the auspices of the U.S. Department of Energy, DOE Contract Nos. W-7405-ENG-48.1

reaching the filter. Electric power to the accelerator was provided by a 10 kW input. Retrofitting the accelerator and related equipment into the Site-300 system required one week. Vapor samples upstream and downstream of the electron accelerator were analyzed and compared with the beam power set at six different levels. The TCE concentration in the vapor was monitored using a field portable gas chromatograph (GC). Vapor samples were also collected in steel spheres and sent to four independent chemical laboratories for analysis of TCE content and reaction products. Two of these labs were EPA approved to perform a T0-14 chemical analysis scan for forty different VOCs.

The hardware that was installed at the site to radiolytically decompose the TCE vapor is schematically shown in Fig. 1.

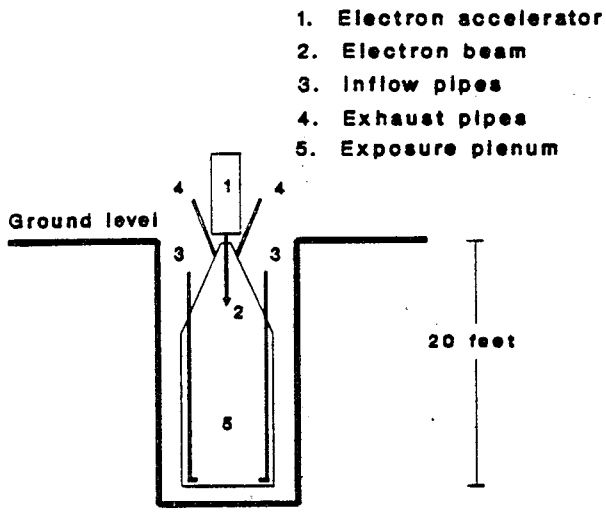

Fig. 1. Schematic of field hardware setup to radiolytically decompose TCE vapor from vacuum extraction wells.

The exposure plenum (5) was fabricated from sheet steel as a cylindrical chamber with a 45° conical section at one end. The plenum diameter was 213 cm with an overall length of 610 cm. This length was chosen because it is approximately the range of a 2 MeV electron through atmospheric air. The plenum structure was placed within a 610 cm deep hole with an oversized diameter to allow clearance between the sides of the plenum and hole. The apex of the plenum conical section pointed vertically upwards giving an appearance similar to a missile in an underground silo. The electron accelerator was placed on the ground surface with the beam pointed vertically downward, entering the plenum through a foil window placed at the conical apex. A small shielded structure made from cement blocks was constructed about the accelerator. This arrangement minimized background radiation exposure to personnel while the accelerator was operating. Background exposure outside the shielded structure was 5 micrograys/hr with beam power at 40 watts. The accelerator was operated by two workers located at a control module placed inside a truck approximately 18 meters away. The control

module was connected to the accelerator by a cable.

The TCE enriched vapor was pumped from the wells by a vacuum extraction pump that exhausted the vapor at atmospheric pressure. Plastic PVC pipe was connected to the vacuum pump exhaust and brought the vapor to the two inflow pipes (3) where it entered the plenum. The entering vapor was deposited at the chamber floor at atmospheric pressure and moved vertically upward toward the two exhaust pipes (4) at the top of the plenum where the vapor exited. The vapor was exposed to the electron beam (2) during its passage through the plenum. The vapor exited the plenum and was routed through PVC pipes to the activated charcoal filter. Vapor circulation through the system was provided by the vacuum extraction pump.

Maximum electron beam power was restricted to 400 watts because the accelerator was originally designed as an industrial x-ray unit and had to be modified for this demonstration. The vacuum extraction pump provided vapor circulation through the system at a fixed rate of 270 CFM (127 l/s). Vapor travel time through the plenum was approximately 2 min. Monte carlo calculations of the electron beam transport through the plenum indicated, that at this circulation rate, the vapor received a dose of 0.9 kGy with the beam power set at 400 watts. The electron beam power was increased from zero to 400 watts in 80 watt increments to provide data at six power levels. The accelerator ran for one hour at each power level while vapor circulated through the system so that equilibrium could be established before gas samples were collected.

The TCE concentration in the unirradiated vapor was measured to be 60 ppmv. The TCE concentration in the irradiated vapor is plotted as a function of accelerator beam power in Fig. 2.

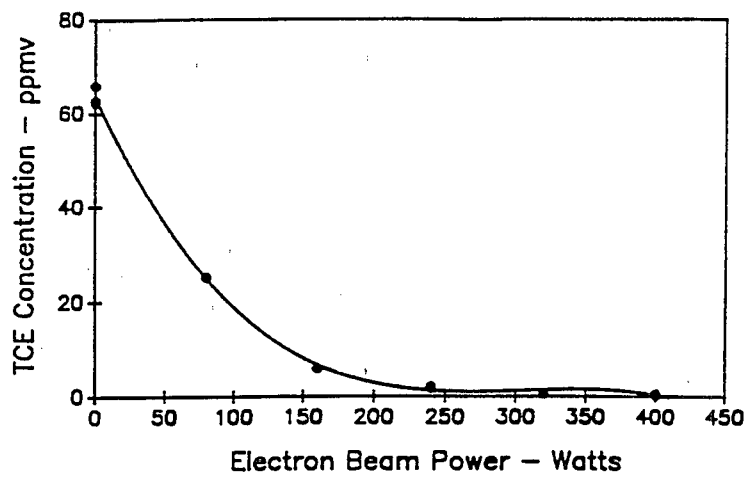

Fig. 2. TCE concentration in irradiated soil extraction vapor as a function of electron beam power.

These TCE concentration data were gathered using the on-site portable GC and are in good agreement with the measurements made on the collected vapor samples by the off-site analytical laboratories. These data show that the TCE concentration in the vapor extracted from the soil is reduced from 50 ppmv to less than 1 ppmv when the electron beam is operating at the 400 watt power level. Data obtained from off-site analysis of the collected vapor samples are shown in Fig. 3. where the concentrations of organic reaction products are plotted logarithmically as a function of exposure dose.

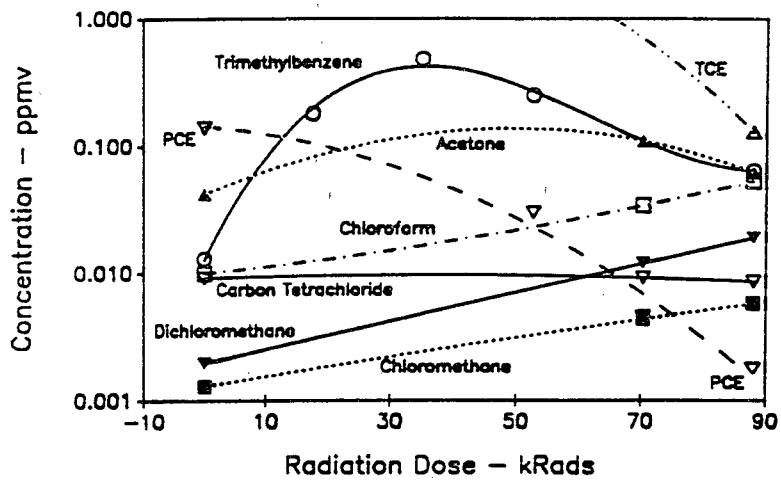

Fig. 3. Concentration of organic reaction products in irradiated soil vapor as a function of exposure dose.

The 90 kRad (0.9 kGy) dose shown in Fig. 3 corrosponds to 400 watt beam power. The figure shows that the TCE concentration is reduced to approximately 0.2 ppmv. A small concentration of perchloroethylene (PCB), initially present in the vapor at 0.1 ppmv, was reduced to 0.002 ppmv while carbon tetrachloride, initially at a concentration of 0.01 ppmv was reduced by only 10%. Three VOCs were produced in low concentration from the TCE reaction products. These were chloromethane and dichloromethane which were increased to a maximum concentration of 0.008 ppmv and 0.020 ppmv respectively and chloroform which was initially present in the vapor at a concentration of 0.01 ppmv and increased to 0.1 ppmv by exposure to the electron beam. Trimethylbenzene was produced in the vapor at a maximum concentration of 0.4 ppmv when irradiated to a dose of 0.35 kGy but decreased in concentration with increased dose. It is suspected that the trimethylbenzene was formed from trace amounts of diesel fuel that accompanied the TCE spill. Small concentrations of acetone at less than 0.1 ppmv were also produced and then partially destroyed with increasing dose. It is not understood how the acetone was formed.

The net concentration of organic reaction products shown in Fig. 3 amount to much less that the initial 50 ppmv TCE concentration present in the unirradiated vapor. Most of the TCE

decomposition products are suspected to be inorganic chloride and carbon dioxide. Indications of hydrochloric acid corrosion in the plenum were present. Unfortunately, the collected gas samples could not be analyzed for hydrochloric acid because of chemical reaction of the acid with the walls of the stainless steel collection spheres. The increase in carbon dioxide was calculated to be only a small fraction of the normal concentration of CO_2 in air and therefore was not measured. An analysis of other inorganic compounds in the irradiated vapor found no oxides of nitrogen or ozone. Only oxygen, nitrogen, argon, carbon dioxide and water vapor were found at nominal concentrations.

This demonstration was terminated after six weeks at the site because the electron accelerator, which was borrowed from another program, had to be returned.

ECONOMICS

The experience gained with the Site-300 demonstration provided information on hardware requirements, fabrication costs, retrofit installation problems, performance parameters, and operating expenses. We were able to estimate the economic performance of an electron beam remediation system and compare costs with remediation using activated charcoal filtration. Our estimates were based upon a system sized to the TCE spill at the Savannah River Site (SRS) where vacuum extraction wells withdraw subsoil vapor at a TCE concentration of 500 ppmv and extraction rate of 500 CFM (236 l/s). If the extraction wells operate with an average up-time of 80%, then 17.5 metric tons of TCE would be removed annually.

A portable, 2 MeV electron accelerator with a 3 kW beam power can be coupled with an exposure plenum similar to that used at the Site-300 demonstration. This system could operate with an annual up-time of 80% and provide a radiation dose of 3.6 kGy to a TCE vapor stream flowing at a rate of 500 CFM. This dose is sufficient to reduce TCE concentration from 500 ppmv to below 0.2 ppmv. Trace organic reaction products formed in the vapor are also expected at concentrations below this level. The hardware required to construct this type of system consists of the accelerator, exposure plenum, and shielded structure. Operating expenses consist of salaries for two employees working 24 hours per day, annual equipment maintenance at 10% of capitalization, electricity costs, and miscellaneous. The estimated capital costs and annual operating expenses are summarized in Table 1.

These data indicate that the capital expenditure for an electron beam remediation system is approximately $975,000 with an annual operating expense of approximately $465,000.

Table 1. Costs for electron beam remediation system.
TCE vapor concentration - 500 ppmv.
Vapor flow rate - 500 CFM (236 l/s)

Capital Equipment	**Capital Costs**
3 kW electron accelerator	$750 K
Exposure plenum	75
Shielded facility	25
Retrofit installation	50
Miscellaneous	75
TOTAL CAPITAL COST	**$975 K**
Annual Operation	**Annual Operating Expense**
Labor - two workers 24 hours per day	$300 K
Maintenance at 10% capitalization	98
Electricity at $0.09 per kWH	19
Miscellaneous	50
TOTAL OPERATING EXPENSE	**$467 K**

The TCE could be removed from the vapor using activated charcoal filters. Approximately 623 metric tons of activated charcoal would be needed annually to remove 17.5 metric tons of TCE from the vapor. This estimate assumes that the charcoal is recycled twice before disposal. The TCE concentration in the filtered vapor would be 1 ppmv which is higher than with the accelerator system. The cost for activated charcoal and disposal when loaded with TCE is estimated at $12.50 per kg. The annual charcoal cost for the system is $7.78 million or more than an order of magnitude higher than the annual operating cost of the accelerator remediation system.

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Rethinking the hydraulic cage concept for hazardous waste disposal facilities and mitigation of contaminated sites[1]

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Abstract

In comparison with conventional hazardous waste disposal facilities, a hydraulic cage facility relies on a zone of increased hydraulic conductivity around the control region to redirect groundwater flow around the disposed waste. Waste containment is achieved by decreasing the hydraulic gradient through the disposal facility. This approach is potentially more reliable than conventional engineered barriers, such as a clay layer, because the consequence of a breach in a low conductivity barrier is much greater than a hydraulic cage.

This paper discusses a series of analyses that were performed to investigate the performance of a hydraulic cage in a number of rock types. Three different methods for constructing a hydraulic cage are considered. The percentage of the groundwater a cage can divert around a disposal facility is very sensitive to the contrast between the hydraulic conductivity of the cage and the conductivity of the surrounding rock mass. The greater the contrast, the better the performance. The analyses demonstrate that cages constructed using surface-based methods can successfully improve the performance of a waste disposal site but are inferior to underground construction techniques in most rock types. Surface-based methods are most appropriate in rocks having a low hydraulic conductivity.

1 Introduction

A "hydraulic cage" is an engineered structure that short-circuits groundwater flow within a site by providing a flow path with much lower resistance to flow than the natural system. The groundwater is redirected around a central region, isolating the enclosed zone from the regional groundwater flow system.

The hydraulic cage concept has potential application as part of waste disposal and

[1] This work was supported by the U.S. Department of Energy under contract number 87-3497.

contaminated site remediation. In both instances, movement of hazardous substances through a saturated zone takes place by advection processes. Advection, or groundwater flow, is governed by the hydraulic conductivity of the medium (rock or soil) and the pressure gradient over the site. The relationship is defined by the simple equation

$$Q=KiA$$

where Q is the volumetric flow rate, K is the hydraulic conductivity of the medium, i is the gradient, and A is the cross-sectional area of flow. In order to reduce the movement of materials either from a disposal site or a contaminated area either the conductivity or the gradient must be reduced.

Conventional engineering methods typically rely on low conductivity barriers such as grout or bentonite slurry walls. The difficulty with this approach is ensuring low hydraulic conductivity for all possible pathways through the area over long-time periods. A hydraulic cage produces a low gradient within the cage boundaries creating a stagnant groundwater flow zone. The head (pressure) in the cage will be approximately equal to the mean value of the heads at the upstream and downstream portions of the cage. As a result, the water in the cage adjacent to the upstream portion will be lower than the site and water will drain into the cage. The opposite is true at the downstream part of the cage where the water will be discharged back into the surrounding medium. Without the pressure gradient, contaminant transport within the cage will be dominated by diffusion, a very slow process.

The original concept of the hydraulic cage originated in the early 1980's in the Swedish High-Level Nuclear Waste Program (SKB, Svensk Kärnbränslehantering AB) (Figure 1). The nuclear waste is stored in an array of inclined boreholes within a central storage chamber. The chamber is surrounded by an excavated slot containing compacted bentonite and sand to seal any fractures and provide a low conductivity barrier to flow and transport. Outside the bentonite-sand barrier is the hydraulic cage consisting of a series of tunnel and boreholes that reduce the gradient within the storage chamber by short-circuiting the groundwater flow around the repository. The WP-Cave design employs a redundant barrier approach for reducing the potential for groundwater flow and transport by providing a conventional engineered barrier to reduce the hydraulic conductivity and a hydraulic cage to reduce the pressure gradient.

The approach was eventually abandoned for high-level radioactive waste disposal applications because the heat produced by the decaying waste would create thermal gradients inside the hydraulic cage. The resulting groundwater flux would potentially negate the isolating capability of the hydraulic cage. The concept is still attractive for other types of waste disposal facilities that do not generate heat. A hydraulic cage could also be used to enhance the performance of some in situ remediation technologies such as microbial

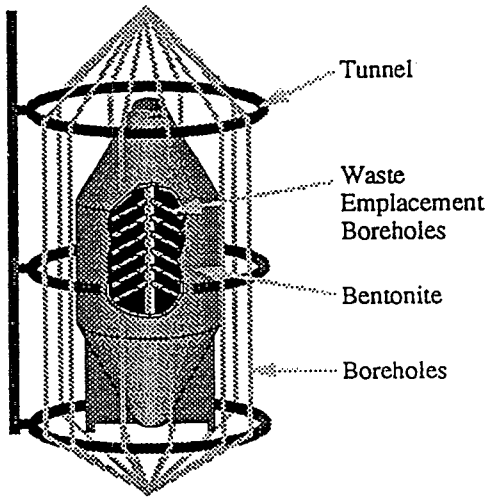

Figure 1. Original WP-Core Concept

degradation by increasing the resident time of the contaminant plume.

Some of the additional advantages provided by the hydraulic cage include:

- The reliability of a hydraulic cage should be greater than a low permeability barrier. The consequence of a breach in a traditional, low permeability barrier is potentially more significant than a partial plugging of the hydraulic cage.
- A more favorable environment for engineered barriers such as waste canisters and buffer materials.
- The cage could be used for dewatering of the waste containment facility during construction, waste emplacement, and backfilling of the facility.
- The behavior of a hydraulic cage can be measured directly and with more

confidence than low hydraulic conductivity barriers.

This paper discusses a series of analyses that were performed to investigate the performance of a hydraulic cage in a number of rock types. Three different methods for constructing a hydraulic cage are considered. Section 2 reviews earlier analyses that were performed to evaluate the performance of the WP-Cave design. Section 3 presents two alternative approaches for constructing a hydraulic cage using surface-based methods. The performance of the alternative cage designs is evaluated in Section 4. Section 5 discusses additional applications of the hydraulic cage concept in waste disposal facilities.

2 WP-Cave Performance

Earlier analyses of the WP-Cave design for nuclear waste disposal were performed by Strack (1985), and Axelsson and Olsson (1985). Two- and three-dimensional groundwater flow models were developed to assess the relative contribution of the two barriers (bentonite-sand and hydraulic cage) and the sensitivity of system performance to various design assumptions such as the number of boreholes in the cage and the thickness of the bentonite-sand barrier.

The hydrologic conditions at the site were assumed to be homogeneous and isotropic. A relatively low hydraulic conductivity was assigned to the site based on measurements in crystalline rock (the candidate repository sites in Sweden are located in crystalline rocks). The hydraulic cage was assumed to have a diameter of 150 m and, in the three-dimensional model, a height of 300 m.

Several borehole spacing designs were considered. The minimum spacing considered was less than 2 m with a maximum of 23.5 m. The hydraulic head in the tunnels connecting the borehole drains was assumed to be constant (i.e., there is no resistance to flow inside the cage).

The contributions of the hydraulic cage and the bentonite barriers to controlling groundwater flow were assessed separately. The results of the hydraulic cage model were as follows:

- The percentage of the groundwater flow that passes through the zone within the hydraulic cage is reduced by 70 to 99% depending on the borehole spacing. The closer the spacing the better the performance.

- Cage performance decreases as the resistance to flow within the cage (hydraulic conductivity) increases. Plugging of boreholes or backfilled tunnels would reduce the amount of water diverted by the cage.

- The effectiveness of a hydraulic cage will vary depending on the site conditions. A hydraulic cage will provide a more effective barrier in low

conductivity sites.

The numerical model of the bentonite-sand barrier assumed a barrier radius of 50 m. Variables in the analyses included the thickness and hydraulic conductivity of the barrier. Barrier thicknesses of 1 m and 5 m were modelled with hydraulic conductivities varying by one order of magnitude. The results are summarized in Table 1.

Table 1. Results of the Bentonite-Sand Barrier Analysis

Thickness (m)	$K_{barrier}/K_{rock}$	% Passing Barrier
5	0.1	63
5	0.01	12
1	0.01	52

The analyses demonstrate that the percentage of groundwater flow that passes through the interior of the bentonite-sand barrier is sensitive to the hydraulic conductivity contrast between the barrier and the host medium. An order of magnitude decrease in the $K_{barrier}/K_{site}$ ratio improves the performance by a factor of 5. The thicker barriers would be required in low conductivity rock (e.g. crystalline rock containing few fractures) because of the low conductivity contrast that can be achieved. The barriers would be more effective for sites with relatively high hydraulic conductivities where the contrast would be greater.

The relative contributions of the hydraulic cage and bentonite-sand barriers depends on their conductivity contrast with the site and the efficiency of the hydraulic cage. The contribution of the bentonite-sand barrier would be minimal in a crystalline site with a relatively low hydraulic conductivity (10^{-9} to 10^{-12} m/s) and a cage with 3 m borehole spacing. As the borehole spacing increases, less water is diverted by the cage and the contribution of the barrier increases significantly. The performance of the two barriers will vary significantly depending on site conditions. For sites with higher conductivities, such as sandstones or fractured systems, the isolation capability of the bentonite-sand barrier would be similar or better than the hydraulic cage.

Alternative Methods for Constructing a Hydraulic Cage

The earlier analyses summarized above demonstrated that the WP-Cave design is capable of isolating disposal facilities from the groundwater flow field. The analyses were limited to crystalline sites and assumed the connectivity of the cage to be ideal (i.e., there was no resistance to flow). This section discusses two alternative methods for constructing a hydraulic cage: hydraulic fracturing and blast fragmentation. The designs employ vertical boreholes, similar to the WP-Cave concept, but rely on surface-based methods for

hydraulically connecting the boreholes. The alternative approaches are intended as possible means for enhancing clean-up activities at contaminated sites or as part of waste disposal facilities where the original design may be prohibitively expensive.

Blast Fragmentation

The effectiveness of the hydraulic cage relies on developing a highly conductive and continuous region within the rock mass. The WP-Cave design employs a series of tunnels to connect the drainage holes within the cage and provide a low resistance pathway for diverting the groundwater flow. An alternative method for connecting the boreholes would be to fragment the rock between the boreholes by detonating explosives in the boreholes.

The feasibility of successfully constructing a network of interconnected boreholes using explosives depends on several factors:

- The ability to fragment the rock over considerable distances.
- The magnitude and direction of the in situ stresses at the site.

The ability to create and propagate fractures with explosives decreases as the distance to a free face or relief surface increases. For the case under consideration, the lithostatic and tectonic stresses will tend to increase with depth with a corresponding increase in the rock mass strength. In general, blast fragmentation zones having high hydraulic conductivities will be difficult to construct at depths below 100 m.

The size and shape of fragmentation zones will also be influenced by the rock quality. Fractures propagated during a blast will tend to terminate when they intersect existing discontinuities such as joints or bedding planes. The impact of such features will depend on their orientation and frequency. Vertical discontinuities oriented perpendicular to the direction between adjacent boreholes would limit the extent of the blast induced fractures. The impact of discontinuities will be less important in sites where the mean spacing of discontinuities is greater than the distance between boreholes.

The in situ stress state will also influence the shape of the fragmentation field. In highly anisotropic stress fields, fractures tend to propagate preferentially in the direction parallel to the maximum principal stress. Notched boreholes or shaped charges could be used to focus the energy between boreholes or the spacing between boreholes parallel to the minimum principal stress could be decreased.

In addition to a well connected set of fractures, the hydraulic conductivity of the network must be significantly greater than the surrounding rock mass in order to be an effective cage. The conductivity of a blast fracture will depend on the shear dilation that occurs and the intact strength of the rock. Dilation resulting from the dislocation of the fracture surface

causes the conductivity of the fracture to increase. This effect is less pronounced in weaker rocks where crushing of asperities would reduce the dilation of the fracture.

Hydraulic Fracturing

Hydraulic fracturing has been used extensively in the petroleum industry for improving production in oil and gas reservoirs. A segment of the borehole containing the formation is isolated with inflatable packers and the zone is pressured until the stresses exceed the strength of the surrounding rock. The resulting fracture is propagated by pumping additional fluid into the region. The fracture can be propped open to increase its aperture (and, therefore, the conductivity) by including sand, bauxite, or ceramic particles in the pressurizing fluid.

The use of hydraulic fracturing for constructing a hydraulic cage is limited by many of the same constraints as blasting. Existing discontinuities will tend to limit the distance a hydraulic fracture can be propagated and the significance of these features will depend on fracture orientation and frequency.

The in situ stress field has a large influence on the orientation of the induced fracture plane. Technology is available for controlling the initial geometry of hydraulic fractures although the fracture will tend to realign parallel to the maximum principal stress as it propagates. Nevertheless, hydraulic fracturing experts from the petroleum industry estimate that existing hydraulic fracturing techniques could reliable connect boreholes 5 m apart even in sites with high deviatoric stresses.

Performance of Alternative Designs

In order to consider the performance of hydraulic fracture and blast fragmentation cages, additional analyses were performed. Four different rock types were considered based on conditions at a number of DOE sites. A probabilistic approach was used in order to account for the uncertainty in the site conditions and the hydraulic properties of the cages. The assessment consisted of the following:

1. Two-dimensional finite element analyses to develop a response surface describing the relationship between the cage performance and the hydraulic conductivity of the cage and rock mass.

2. A literature review to develop probability distribution functions for the hydraulic properties at different sites.

3. A probabilistic analysis of cage performance using the Monte Carlo method and the results from steps 1 and 2.

This approach reduced the number of numerical models required and provided an estimate of the range in performance that can be expected.

Numerical Analysis

A two-dimensional finite element flow model was used to evaluate the relationship between cage performance and the hydraulic conductivity contrast between the cage and the rock mass. A two-dimensional model was chosen based on the results of Strack (1985) who demonstrated that two-dimensional and three-dimensional models give very similar results especially when the groundwater flow is assumed to be horizontal (perpendicular to the cage).

The conceptual model assumed a cage diameter of 125 m with a uniform hydraulic conductivity. The model did not include other types of barriers. The hydraulic conductivity of the site was assumed to be 10^{-12} m/s with a horizontal hydraulic gradient equal to 0.002.

The response surface was constructed by substituting a range of hydraulic conductivity values for the cage and monitoring the amount of water diverted by the cage. The greater the amount of water diverted by the cage, the better its performance. Cage performance P_{cage} is given by

$$P_{cage} = \frac{Q_{cage}}{Q_{base}}$$

where Q_{cage} is the flow through the interior of the cage and Q_{base} is the flow through the same region if the cage is not present. The range of hydraulic conductivity values for the cage was 10_{-12} to 10_{-1} m/s. The results of the analyses are summarized in Figure 2.

The results illustrate that the amount of groundwater passing through the cage is markedly reduced as the conductivity contrast between the cage and rock mass is increased. An order of magnitude difference reduces the flow through the cage by only 15% while the corresponding reduction for a cage with a two order of magnitude difference is more than 50%. The rate of change in performance slows considerably with additional increases in the conductivity contrast. The analyses by Strack (1985), and Axelsson and Olsson (1983), assumed the head was equal at all points within the cage (i.e., the cage offered no resistance to flow). Their results correspond to K_{cage} values > 10^{-4} m/s.

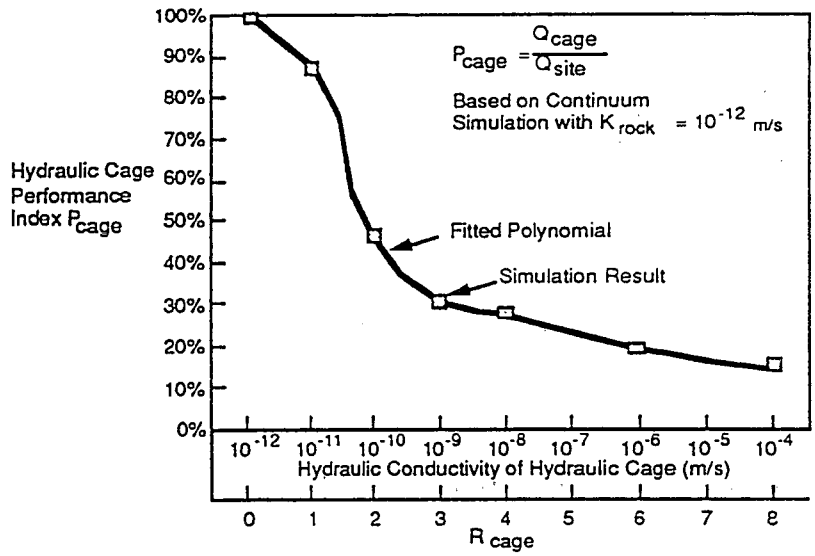

Figure 2. Results from 2-D Model of Hydraulic Cage

A simple relationship between cage performance and the ratio of conductivities (K_{cage}/K_{rock}) was developed from a regression analysis of the results. The expression is given by:

$$P_{cage}=c_1R+c_2R^2+c_3R^3+c_4\log_{10}R+c_5R^{-1}+c^6$$

Values for constants c_1 through c_6 are provided in Table 2. The parameter R is the ratio of conductivities and is defined as:

$$R=\log_{10}\left(\frac{K_{cage}}{K_{site}}\right)$$

Table 2. Constants for Pcage Relationship.

Constant	Fitted Value from Regression Analysis
c1	6.94
c2	-0.514
c3	0.0176
c4	-42.52
c5	-14.32
c6	8.873

The equation for P_{cage} was used to evaluate the performance of hydraulic cages in a range of rock types. Four rock types, limestone, sandstone, basalt, and weathered limestone, were chosen based on literature reviews of documents describing the site conditions at several Department of Energy (DOE) defense sites. The dependent variable K_{site} was estimated from DOE site documents and conversations with hydrogeologists familiar with the areas. Because of the uncertainty related to these estimates, the parameter was represented by a probability distribution function that reflects the uncertainty about the expected value. Triangular distribution functions were assumed. The minimum, maximum and expected values for K_{site} are listed in Table 3.

The hydraulic conductivity of a cage was assumed to be a multiple of the site conductivity. The increase varies according to the rock type and construction method. In general, fracture dilation in hard rocks, e.g., basalt, is greater than in sandstones or other soft rock. Therefore, the conductivity of a hydraulic cage in the basalt site was assigned a higher range of values than the limestone and sandstone rock types. The expected increase in conductivity for blast fragmentation cages was assumed to be greater than hydraulic fracture cages because of the greater number of fractures involved. The probability distributions for K_{cage} are also triangular. Table 4 contains the minimum, expected, and maximum values for calculating the cage conductivity.

Table 3. K_{site} Values for Monte Carlo Analysis

Rock Type	K_{site} (m/s)		
	minimum	expected	maximum
Limestone	5×10^{-10}	3.2×10^{-8}	5×10^{-7}
Sandstone	10^{-6}	10^{-5}	10^{-4}
Basalt	10^{-10}	10^{-9}	10^{-7}
Weathered Limestone	10^{-7}	10^{-5}	10^{-4}

Table 4. Distributions for K_{cage} multiplication factor.

Rock Type	Blast Fragmentation (x's K_{site})			Hydraulic Fracture (x's K_{site})		
	min	exp	max	min	exp	max
Limestone	75	750	1000	10	100	1000
Sandstone	10	100	1000	10	50	500
Basalt	75	1000	10^5	10	250	5000
Weathered Limestone	75	500	5000	10	100	750

Monte Carlo Analysis

The relative performance of hydraulic fracture and blast fragmentation cages in the four rock types was assessed using the polynomial relationship for P_{cage}. Values for R were calculated by sampling from the distributions for K_{site} and K_{cage}. The Monte Carlo method was used to sample from the distributions and the process was repeated 1000 times to obtain a probability distribution of cage performance for each of the rock types.

The results of the analysis are summarized in Figure 3. Each of the box plots represents the results for a different combination of cage type and rock type. The box represents the .25 to .75 percentile values for P_{cage} and the horizontal line the .50 percentile value. The vertical lines

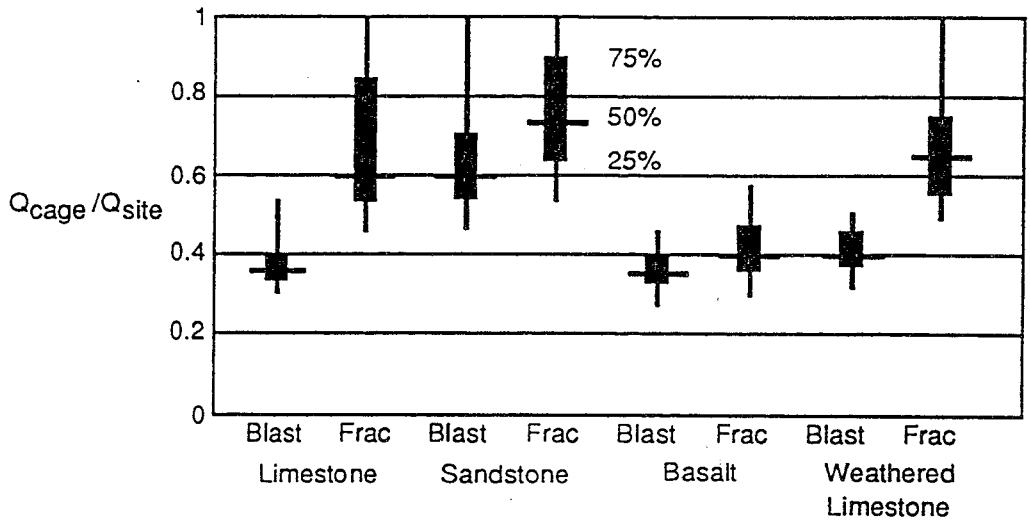

Figure 3. Results of Monte Carlo Analysis of Hydraulic Cage Performance

extending above and below the box represent the range of values between the .05 and .95 percentile values.

The magnitude and range of the hydraulic cage performance results varies considerably depending on the rock type and construction method. The blast fragmentation cage performed significantly better than the hydraulic fracture cage due to the higher conductivity that could be developed. The difference in performance is less noticeable in the basalt rock because of the greater contrast in conductivities. The results show that there is a significant probability that a hydraulic fracture cage would divert a relatively small percentage of the groundwater flow in most of the rock types. The performance of the blast fragmentation cages is much better and fairly consistent within the different rock types with the exception of the sandstone which has the lowest conductivity of the rock types considered.

5 Discussion

The expected performance of the alternative hydraulic cage designs is considerably poorer than the original design. This reflects the difficulty in developing highly conductive fracture networks in situ and the optimum conditions that can be engineered in an underground facility. Nevertheless, the results indicate that the surface based methods could divert a significant portion of the groundwater flow around an area and contribute to the isolation capability of a disposal site retarding the movement of contaminants. Therefore, the hydraulic cage represents an additional engineered barrier concept that should be considered as part of an underground disposal facility.

Underground disposal facilities could be constructed using old underground mines. The hydraulic cage could be developed using existing openings that are adjacent to a disposal room or by developing new tunnels. An alternative would be to construct high conductivity panels that could be placed inside the waste disposal rooms. The high conductivity panels would be attached to the walls of the disposal rooms and low conductivity materials, such as bentonite clays, would be added to separate the panels from the waste. The combination of low and high conductivity barriers would improve the reliability of the inner clay barrier by decreasing the gradient inside the storage area and reducing the significance of a breach. A similar approach could be used for surface disposal facilities (Figure 4).

6 References

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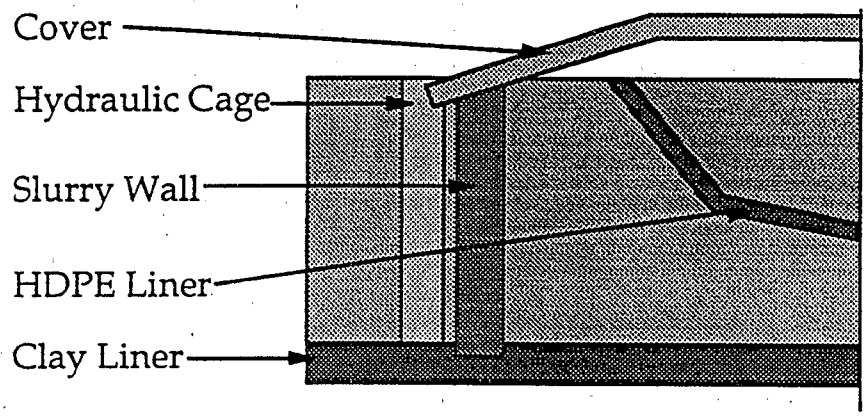

Figure 4. Conceptual Design of Surface Waste Disposal Facility Incorporating Hydraulic Cage Barrier

Innovative Contracting Strategies for Equipment Procurement
Bofors Nobel Superfund Site
Muskegon, MI

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I. Site History: The Bofors Nobel Superfund Site is located six miles east of downtown Muskegon, Michigan along Evanston Road in Edelston Township. The site is located in a chemical manufacturing area and is currently owned and operated by Lomac, Incorporated. The superfund site has been divided by Region V of the Environmental Protection Agency (EPA) into two operable units, designated as Lagoon Area Operable Unit (LOU), and the Groundwater/Plant Area Operable Unit (GOU). The LOU is irregularly shaped and includes ten abandoned sludge lagoons and associated soils south of the Lomac facility. The POU area consists of the contaminated groundwater located beneath the entire 85 acre site. The southern boundary of the site is bordered by Big Black Creek, which has been chosen as the selected point of discharge.

Lakeway Chemicals, Incorporated began producing industrial chemicals in 1960. During this period, the manufacturing facility produced such chemicals as 3,3-dichlorobenzidine (DCB), benzidine, and azobenzene for use in alcohol based detergents and as die intermediates. Raw materials used in the production of these components included fatty alcohols, fatty ether alcohol, sulfur dioxide, aqua ammonia, muriatic acid, sulfuric acid, nitrobenzene, o-nitrobenzene, methanol, benzene, sodium chloride and zinc.

During the late 1960's and 1970's, DCB, zinc oxide and other process wastes were discharged through open trenches to the lagoons located south of the plant area. The lagoons functioned as either direct discharge basins or overflow settling ponds. The basins do not

themseleves contain a homogeneous waste material. During the 1970's, lagoon berm failures resulted in the discharge of lagoon sludge into Big Black Creek. The use of lagoons for waste disposal was discontinued in 1976 when the facility was connected to the Muskegon County Wastewater Treatment System.

In 1977, Lakeway merged with Bofors Industries, Incorporated and the company name was changed to Bofors Lakeway, Incorporated. In 1978, the State of Michigan filed a Consent Judgement against the company. The consent judgement required Bofors Lakeway to remediate the contamination which had occurred both on and off site. In 1981, a Consent Judgement was entered into between the State of Michigan and Bofors Lakeway, Inc. calling for full restoration of the air, land, and waters of the State contaminated through previous operations at the Bofors site.

In 1981, Bofors Lakeway, Inc. merged with Nobel Industries of Sweden and the company name was changed to Bofors Nobel, Incorporated. In order to conform with the requirements stipulated within the consent judgement, Bofors and other investors established the Environmental Systems Corporation of Michigan (ESCM) to own and operate the PACT™ (Powdered Activated Carbon Treatment) system and a clay lined waste disposal landfill required by the judgement. The disposal landfill was constructed on site to accept ash from a sludge pyrolysis process. Before the sludge pyrolysis system was implemented, however, Bofors Nobel and ESCM filed for bankruptcy.

The Bankruptcy Court granted permission to Bofors Nobel and ESCM to procure a broker and pursue a potential buyer. Sale of the Bofors assets to Lomac was completed in 1987. As a part of the sales agreement, an "Agreement and Covenant Not to Sue" was also entered

into between the State and Bofors Nobel for the previous contamination of air, ground, and water caused by facility operators. These agreements and covenants allowed Lomac to operate the facility independently of previous site activities.

Because of the nature and extent of the contamination on the Bofors Nobel site, the State of Michigan contacted the U.S. EPA to evaluate the site for possible placement on the National Priorities List (NPL), pursuant to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA). The EPA conducted their site evaluation, with the results calling for nomination to the NPL in July of 1988, with listing occurring in March 1989. A Remedial Investigation/Feasibility Study (RI/FS) was initiated in August 1987 and the Record of Decision (ROD) for the Bofors Nobel site was signed in September 1990. The ROD addressed remediation of the lagoons, as well as restoration of the groundwater aquifer.

II. Problem Background: One of the primary concerns associated with the contracting effort on the Bofors Nobel Superfund Site was the procurement of equipment required to treat the contaminated groundwater. The previously referenced Feasibility Study and the project ROD called for Ultraviolet Oxidation (UV Oxidation) as the selected technology for destruction of organic contaminants contained in the groundwater. The option for effluent discharge spelled out in the ROD mandated a restrictive discharge requirement which had not been considered in the Feasibility Study. The Feasibility Study had considered the groundwater treatment system as necessary only for "pretreatment" prior to discharge to the sanitary sewer. The final ROD, however, directed final effluent discharge to a cold water trout stream located on site. Rapid

and complete evaluation of the chosen technology was performed to determine whether the low discharge levels for the organic contaminants contained within the groundwater could be achieved. The results of this study indicated that the technology was suitable for application on a waste of this type.

The relatively recent development of the UV Oxidation technology has limited the corporate competition within this field. To date, only three vendors have exhibited the capabilities necessary to effectively treat a groundwater contaminated with both volatile and semivolatile constituents on a full scale basis. An important factor to consider when reviewing this treatment technology is the high operational and maintenance costs (O&M) associated with its use. In the case of the Bofors Nobel groundwater treatment system, the O&M costs for the UV Oxidation system were projected to comprise the majority of the annual operational expense. Because of this fact, consideration was given to life cycle cost rather than simply capital cost during the design and predesign phase of the project. By promoting a predesign effort that emphasized treatment capability as well as life cycle cost, the most effective system could ultimately be procured for the contract. Based upon the outcome of the predesign testing, a sole source justification would be initiated to procure that UV Oxidation system deemed to be most appropriate for this specific groundwater application. Justification would be contingent upon the capability of the system to treat the contaminated groundwater to acceptable levels, and life cycle cost to the end user.

III. Nature of the Corporate Technologies: At the time contractors were being solicited for the treatability and predesign work associated with this superfund site, there were essentially

three vendors who had demonstrated proven technologies at non-related sites. The three corporations have expended a great deal of energy in the promotion of their specific technology as the "best" for implementation under conditions similar to those present at the Bofors site.

The traditional method for determining full scale operational parameters for UV Oxidation has been to provide a specific vendor with samples of the contaminated water. The vendor is responsible for sampling and testing the water sample for various water quality parameters, and to then use laboratory scale equipment to determine the optimum operational parameters for full scale equipment. An alternative that each of the vendors has available is use of a pilot scale treatment system which is mobilized to an individual site. An on site pilot scale system yields more accurate results regarding upsizing criteria for full scale implementation than does bench scale treatability testing.

Following the gathering of this predesign data, the project design is normally developed in a generic fashion, whereby any one of the three vendors would have an equal opportunity to bid on a project and potentially be awarded the contract for supply, based upon the lowest bid. The plans and specifications are normally prepared with a performance requirement, so that the successful bidder is contractually obligated to perform to predetermined levels. The train of thought on the Bofors project was to provide an opportunity to all vendors to travel to the site, treat the contaminated groundwater, and propose a full scale system suitable for the treatment of the contaminants. Based upon the validated laboratory data and the vendor reports, a decision regarding the most appropriate vendor would be made, and the project design would proceed around a specific vendor, rather than around a generic performance requirement. Life cycle cost would figure highly in the decision making process. It was felt that the costs associated with

the predesign effort would be more than offset by the savings associated with annual O&M over the life of the project.

IV. Lessons Learned Guidance: At the same time that the Bofors Nobel project was planning its predesign requirements, a nearby superfund site was performing treatability testing on a waste stream of similar quality and clarity. The choice of a UV Oxidation vendor for the other superfund site's treatability testing was based upon which vendor provided the lowest quote for performing the work. The results of the bench scale treatability testing by that specific vendor indicated that the O&M requirements for a UV Oxidation system would exceed the initial capital cost of a complete system within approximately two years. Because of the excessive cost associated with the UV Oxidation technology at this site, this treatment alternative was removed from consideration. Other UV Oxidation vendors claimed they could treat the waste stream at a significantly lower cost but were not considered because of time constraints.

Based on the results of the bench scale testing at the other superfund site, it was felt that the alternate contracting techniques previously discussed should be investigated for application at Bofors Nobel. Because each individual UV Oxidation vendor holds patents on their equipment and all market their equipment as "significantly different" from the other competitors, it was determined that the most appropriate course of action would be to compare each of the three available UV Oxidation vendor's products under identical conditions. This decision led to a "treat-off" between the vendors at the Bofors Nobel site. All vendors were contracted to be on site during a specific time frame, and all vendors were provided the contaminated groundwater from a common header. The results of the testing period are discussed in

subsequent paragraphs.

V. Buy American Act Applicability: One of the proven UV Oxidation companies selected for the on site treatability testing is wholly owned and manufactured outside the United States. This was a concern because of potential conflicts with the Buy American Act restrictions contained within the federal procurement regulations. If the non-American produced equipment was found to be most competitive, on the basis of treatment capability and cost effectiveness, the ability and legality of a government contract to purchase the process equipment was questionable. This issue was quickly resolved upon further investigation within the Corps. Reference to Part 25, subpart 25.1, section 25.101 of the Federal Acquisition Regulations indicated that "Components, as used in this subpart, means those articles, materials, and supplies incorporated directly into the end products." The section continues "End Products, as used in this subpart, means those articles, materials, and supplies to be acquired for public use under the contract." Further review of the section indicated that "On acquisitions above $25,000 in value, components of Canadian origin are treated as domestic." These issues specifically applied to the concern regarding the use of a Canadian manufactured and supplied UV Oxidation system. With these passages in mind and according to the FAR, the UV system marketed by the Canadian supplier would qualify as a Buy American product if procured through a supply contract, or provided as Government Furnished Equipment.

The equipment could be legally provided under a construction contract, but the approval process would be lengthy and the product would have to qualify for a waiver under the FAR. Waiver to the FAR involves one of three potential scenarios:

a) If the cost of the Canadian product is less than the American product by ten percent after all tariffs, taxes, and fees, the product would qualify;

b) If the usage of any other product is "impracticable", the foreign product would qualify; and,

c) If there are no American products which meet the job requirements, the foreign product would be acceptable.

The DoD further determined that application of the Buy American Act to the end products of Canada and other specific countries (under subpart 225.103) would be inconsistent with the public interest.

VI. Presentation of Concept to Applicable Entities: The concept of providing an avenue for all competent and capable vendors to treat the Bofors groundwater from a common header had previously not been used within the Omaha District Corps of Engineers. The task remained to coordinate with the other parties involved in the preparation or approval of the completed set of plans and specifications. Concurrence from the Contracting Division of the Corps, the state of Michigan and the U.S. EPA, Region V were all necessary prior to proceeding with the development of a workplan suitable for the on site treatability testing. By emphasizing the expected recurrent annual O&M costs associated with a UV Oxidation system, it was shown that the overall cost associated with the up-front (predesign) testing could be recouped, with both the state and the government potentially saving a significant amount of money. All appropriate agencies concurred with the concept of treatability testing with all three vendors brought on site during the same time period.

The capital costs associated with the unit process were also a primary consideration, but overall life cycle costs would be the ultimate vehicle used in the selection of the successful equipment supplier. The first and foremost criterion within the predesign treatability testing was the capability of the individual vendor to successfully treat the combined purge well flow to acceptable discharge levels, as defined by the state of Michigan. Upon successfully meeting this criterion, the vendor was subsequently reviewed on the basis of expected life cycle cost. Following completion of the treatability testing and receipt of the individual vendors final reports, the Corps made the decision as to the most appropriate vendor to be incorporated within the final design of the groundwater treatment plant.

VII. Performance of On-site Treatability Testing: The UV Oxidation vendors were brought on site to determine the efficacy of their individual treatment processes. The specific testing objectives, based upon the workplan prepared by the Corps, were as follows:

a) Evaluate the effectiveness of the individual vendor treatment systems at treating the combined purge well flow. See Table 1 for the analytical results of the raw groundwater.

b) Determine specific design parameters such as required oxidation time and pretreatment requirements necessitated by the site specific groundwater.

c) Monitor and define the individual vendor's electrical consumption and chemical usage (if applicable) during the system optimization and performance periods. This information was subsequently used to estimate and establish the requirements for the full scale systems.

d) Determine any interferences caused by the native raw water quality, and define any pretreatment requirements necessary for adequate treatment of the contaminated groundwater in

the proposed full scale system.

TABLE 1
DETECTED ORGANIC COMPOUNDS - UV OXIDATION PILOT TESTING
COMBINED PURGE WELL MANIFOLD
Bofors Nobel Superfund Site, Muskegon, MI

Concentration: ug/l	Sampling Date				
Volatile Organic Compounds	2/89 - 5/91[A]	14 Aug 1991	27 Sep 1991	1 Oct 1991	2 Oct 1991
Benzene	ND-1800	1400	1400	1900	1700
Chlorobenzene	ND-120	140	160	220	190
1,2- Dichloroethane	ND-6	ND	ND	ND	ND
trans 1,2-Dichloroethene	ND-200[B]	170[B]	170[B]	200[B]	180[B]
Ethylbenzene	ND-70	34	51	61	67
Methylene Chloride	ND-90[C]	15	47	53	200
Tetrachloroethylene	66 - 340	320	320	470	360
Toluene	ND-1500	750	1500	2000	1700
1,1,2- Trichloroethane	ND-40	ND	ND	ND	ND
Trichloroethylene	ND-50	77	91	120	110
Vinyl Chloride	ND-80	120	110	120	150
Xylene	ND-40	43	73	88	91
Concentration: ug/l	Sampling Date				
Semi-Volatile Organic Compounds	2/89 - 5/91[A]	14 Aug 1991	27 Sep 1991	1 Oct 1991	2 Oct 1991
Benzidine	ND-970	360	930	390	590
1,2-Dichlorobenzene	ND-12	30	28	18	23
1,4-Dichlorobenzene	ND	ND	2	ND	1
DCB	ND-210	120	180	100	110
Isophorone	ND-19	7	ND	ND	14
1,2,4-Trichlorobenzene	ND	ND	4	ND	3
2-Chloroaniline	71-1500	1400[D]	760[D]	1100[D]	740[D]
Aniline	83-250	140	230	110	160
Dichlorobenzidine Isomer	320-680	NR	NR	NR	NR
Benzidine Isomer	ND-1300	NR	NR	NR	NR

[A] Data from Michigan Department of Natural Resources
[B] Reported as total 1,2-DCE
[C] Methylene Chloride data from Groundwater FS (GZA/Donohue, 1989)
[D] Concentrations reported as total o-chloroaniline and chloroaniline from Tentatively Identified Compounds (TICs) analysis.
ND Not Detected
NR Not Reported

As previously indicated, sampling and analysis of the raw combined purge well flow produced the results contained within Table 1. The concentrations of the volatile and

semivolatile constituents compare favorably with results from previous sampling activities.

The existing groundwater manifold transporting contaminated groundwater to the Lomac PACT™ facility was tapped to provide water to the treatment area established for the purpose of the predesign testing. The four inch manifold line was then split into three feeds to service each individual vendor's equipment. The data from the 14 August 1991 sampling round was sent to each of the individual vendors prior to their coming to the Bofors site for equipment setup purposes. This information allowed the vendors to tentatively establish and initial starting point, based upon institutional knowledge gained from previous operating experience. Specific mention was made to the vendors that well cleaning activities in early September had generated a groundwater that was noticeably colored, and which carried a higher suspended solids concentration than had previously been experienced. Each vendor was instructed that the responsibility for any pretreatment activity was strictly their own. Non-potable water for use in equipment cooling and decontamination was brought to the treatment area through the construction of a temporary pipeline from an existing well located on site. Each vendor was supplied electricity for their individual process through the use of a 150 kW portable generator. The electrical usage was monitored through a microprocessor based meter on each connection.

Each vendor was instructed that the intent of the on site testing was to treat the contaminated groundwater to a level suitable for discharge to Big Black Creek. The preliminary discharge standards were established by the state of Michigan, and are contained in Table 2.

TABLE 2 UV/OXIDATION ON SITE PILOT SCALE TESTING PRELIMINARY DISCHARGE STANDARDS			
Bofors Nobel Superfund Site Muskegon, Michigan			
Compound	Conc. (ug/l)	Compound	Conc. (ug/l)
Aniline	4.0	1,2-Dichloroethane	5.0
Azobenzene	TBD	1,2-Dichloroethylene	5.0
Benzene	5.0	Trans-1,2-Dichloroethylene	5.0
Benzidine	0.04	Ethylbenzene	5.0
3,3'-Dichlorobenzidine	0.06	Isophorone	5.0
Methylene Chloride	5.0	Phenols	5.0
Acetone	500.0	Tetrachloroethylene	5.0
Butyl Benzyl Phthalate	5.0	Toluene	5.0
Chlorobenzene	5.0	Trichloroethylene	5.0
Dichloroazobenzene	5.0	1,2,4-Trichlorobenzene	5.0
3,3-Dichlorobenzidine Isomer	0.06	Vinyl Chloride	5.0
Dichlorobiphenyl	5.0	Xylene	5.0
TBD = To Be Determined			

Each vendor erected their equipment on the 110'x 30' asphalt pad constructed for the pilot test. A three inch lip was constructed around the periphery of the pad to contain any potential leakage. Any water captured on the pad was drained to the effluent tank to be subsequently discharged to the PACT™ treatment system.

The initial three days of the on site treatability testing period were devoted to equipment unloading and setup. Approximately two days were expended making the necessary plumbing and electrical connections.

Two separate sampling and analysis activities were performed during the on site treatability testing. The initial round of samples was taken by the vendors during the system adjustment period. Each individual vendor was responsible for the sampling, shipping, and receipt of the sample analysis in the required turnaround time. A one to three day turnaround time was contracted during the system adjustment period. This was necessary due to the nature

of the on site testing. This stringent turnaround time was not required for the optimization monitoring period. The results obtained from the initial system adjustment period were used to determine the appropriate unit dosages for the optimization period. The specific analytes were chosen by the vendor based upon the most critical compound which dictated the chemical usage and flow rates from their equipment.

The second sampling event occurred during the optimization monitoring period. A specified number of samples were taken by the vendors at common sampling times. The optimization monitoring period was a two day cycle during which time the vendors operated their equipment ten to twelve hours a day. Each of the three systems was allowed to equilibrate prior to being sampled.

VIII. Results and Conclusions:

A. Metals and Water Quality Data: Tables 3, 4, and 5 show the results for specific metals and water quality parameters which were monitored during the performance period. The data were taken to verify raw water quality and to monitor the pretreatment of the individual vendors. All three vendors utilized a pretreatment filter on the influent line supplying the process equipment, although the filters were of different mesh sizes. Vendor #1 utilized a pretreatment tank prior to the pressure filters to remove iron and manganese in the raw water. Sodium hydroxide and hydrogen peroxide were added to the holding tank to form floc particles prior to filtration. Vendors #2 and #3 utilized conventional cartridge filters to remove suspended solids. Table 3 indicates that the measures taken by Vendor #1 were relatively ineffective in terms of overall removal of the iron and manganese. The pretreatment system used by Vendors

#2 and #3 had no appreciable affect on the water quality parameters. Acid addition to improve the performance of their individual processes was performed by both Vendors #1 and #2. The use of acid in the process train significantly lowered the alkalinity of the groundwater, and elevated the Total Dissolved Solids of the flow. Other water quality changes worthy of mention include the oxidation of nitrite to nitrate and the reduction of the total COD by Vendors #2 and #3. Vendor #1 did not experience either of these changes. The inability of Vendor #1 to affect these changes may be attributed to a non-optimized system. All vendors experienced only a slight reduction in the Total Organic Carbon (TOC) as the groundwater was treated. This may be attributed to the formation of daughter products during the oxidation process.

B. Volatile Organic Compound Analysis: Tables 6, 7, and 8 provide information relating to the performance of the vendor equipment on treating volatile organics (VOCs) contained within the contaminated groundwater. Based upon the final reports submitted by the vendors, tetrachloroethylene (PCE) was indicated as the most recalcitrant of the VOCs in this water matrix. The influent concentrations of toluene and benzene are typically more than four times higher than the PCE concentration, however, these compounds are rapidly reduced in all of the vendor's systems. In general, the chlorinated compounds such as 1,2-Dichloroethane (1,2-DCA), PCE and Trichloroethylene (TCE) are the most difficult to degrade due to the higher energy associated with the molecular bonds in these saturated organic compounds. Other compounds such as acetone and methylene chloride were present in the effluent, but these VOCs are common laboratory contaminants, and the results may not be reflective of actual conditions. In general, vendor's #2 and #3 were able to effectively treat the contaminated groundwater to

the required discharge levels. The removal of PCE was typically down to the discharge limit of 5 ppb. The final effluent for Vendor #3 did contain PCE and benzene above the discharge standards during one sampling event. The reason for exceeding the discharge level is uncertain, since the system was capable of meeting the discharge levels during the other sampling events. Both vendors #2 and #3 had occasional hits on methylene chloride, 1,2-DCA, and TCE, but these values were near detection limits and are within the bounds of the analytical accuracy. Vendor #1 experienced difficulty in meeting the discharge limits for several VOCs, indicating that their system may not have been optimized because the vendor #1 system had sampled and met the discharge criteria during the system adjustment period.

C. Semivolatile Organic Chemical Analysis: The sample results for the semivolatiles (SVOCs) contained within the process flow are shown in Tables 9, 10, and 11. These data indicate that the pretreatment filters used by the vendors appeared to remove small amounts of aniline, while other SVOC concentrations did not appear to be affected. Vendors #2 and #3 were able to reduce the levels of the SVOCs to the required levels, while Vendor #1 experienced difficulties in the removal of several SVOCs. The Vendor #3 system did experience hits on benzidine and isophorone for a portion of the pilot testing. Vendor #3 indicated that the timing of those infractions was at the same time the systems hydrogen peroxide feed was experiencing mechanical problems. Both vendors #2 and #3 were effective in reducing the concentrations of tentatively identified compounds (TICs), while vendor #1 experienced limited success.

IX. Sole Source Procurement Strategy and Design Preparation: Based upon the data and the reports provided by the vendors, the Corps of Engineers selected a vendor around which the

design package would be prepared. Selection of a vendor was based upon a two phase screening process. The screening process relied upon two criterion to define the most appropriate vendor for the full scale system. The first criterion was defined as the ability of the vendors to effectively treat the waste constituents. Following this primary screening process, the second screening criterion was used to select the vendor to be used in the project design. The second criterion was cost related. The vendor which indicated the lowest life cycle cost was selected over the other vendors which met the first criteria. See Table 2A for data regarding cost data generated by the vendors during the testing period.

Following the report review, the vendors were contacted regarding the selection results. The groundwater treatment facility footprint was defined based upon dimensions provided by the UV Oxidation vendor. The selected vendor was also contacted periodically during the design phase to coordinate mechanical, electrical, and structural requirements.

A number of benefits associated with this contracting methodology became apparent as the process design continued. Specifically, the following items were streamlined or clarified as a result of this innovative contracting attempt:

a) The building footprint becomes easier to develop when the exact dimensions of the required equipment are obtained from the vendor.

b) The electrical loads, known to vary considerably depending upon the selected vendor, may be obtained early in the design. This facilitates the entire design and control sequence.

c) The process piping may be clearly defined and shown. Specific elevations may be coordinated with the vendor to insure compatibility with the remainder of the process train.

d) Pretreatment requirements, which may vary depending upon the vendor, can be

defined and incorporated into the process design.

e) The contract specifications are stream-lined when a specific vendor has been selected. This allows the designer to call for specific pieces of process equipment, provided that the appropriate approvals have been obtained prior to contract advertisement.

TABLE 2A: VENDOR PROJECTED COST DATA

Annual Cost Category	Vendor #1	Vendor #2		Vendor #3	
		Alt. #1	Alt. #2	Alt. #1	Alt. #2
$/year		with catalyst	without catalyst	with O_2 feed	with air feed
UV Energy[1]	772,660	735,000	572,000	44,300	44,300
Replace Lamps	90,000	189,000	147,000	22,600	22,600
Peroxide Use[2]	192,300	448,000	1,120,000	65,700	65,700
Acid	17,000	33,000	17,000	Not Used	Not Used
Base	74,000	147,000	74,000	Not Used	Not Used
Catalyst[3]	Not Used	19,000	Not Used	2,000	2,000
Ozone Elec.	Not Used	Not Used	Not Used	113,900	219,000
Liquid Oxygen	Not Used	Not Used	Not Used	441,700	Not Used
Total Annual	1,145,000	1,571,000	1,930,000	690,200	353,600
Total Capital	1,325,000	1,575,000	1,575,000	1,510,000	1,695,000
Life Cycle[4]	14.22 M	19.27 M	23.30 M	9.28 M	5.68 M

[1] Power costs based upon $0.06/kWh

[2] Hydrogen Peroxide costs ($/gal) vary with usage rate

[3] Catalyst costs represent proprietary additives or vapor phase treatment units.

[4] Life Cycle costs assume 30 year operating period at 8 percent interest.

Within the Army Corps of Engineers, special contracting efforts were required to insure that all appropriate FARs were complied with. The sole source justification to procure the selected vendor began shortly after receipt of the final vendor reports. A justification and approval (J&A) action was necessary to insure that the government was obtaining a system capable of meeting all necessary requirements. After approval is granted for sole source procurement, the contract documents are simplified by calling for a specific manufacturer. To insure that there were no other vendors capable of providing suitable equipment for this installation, a "Sources Sought" effort was initiated. The results of this request conclusively indicated that the three vendors targeted for the "treat-off" were the only vendors suitable for this application.

X. Conclusions: The predesign, design and contracting efforts performed for the procurement of the UV Oxidation equipment in the Bofors Nobel Groundwater Treatment Facility were shown to be extremely effective. This contracting technique allowed the government to attempt to procure proven process equipment, capable of meeting stringent discharge standards, and still provide a cost effective treatment system. The ability to allow all available vendors an opportunity to test their equipment concurrently has been shown to be an effective tool which facilitates the procurement of high cost equipment items. Although perhaps not suitable for all superfund sites because of project specific constraints, the "treat-off" technique proved to be very worthy of the high expectations originally targeted. In this specific instance, it is estimated that the use of the "treat-off" technique will save the government in excess of five million dollars during an estimated thirty year operating cycle, with the cost of the predesign treatability testing

recouped within six months. If traditional contacting techniques had been used in the procurement of a UV Oxidation vendor, the selected vendor would not have been awarded the contract because of higher initial capital cost. Although the selected vendor's equipment carries a slightly higher capital expense, the life cycle cost of the process has been shown to make this innovative contacting mechanism eminently suitable for the Bofors Nobel Superfund site.

TABLE 3
UV OXIDATION TESTING: METALS AND WATER QUALITY
VENDOR #1

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Arsenic	4.6	3.9	4.3	4.7	4.5	3.9	4.5	4.3	5.1	4.8	4.5	4.5	4.4
Calcium	-	-	108,000	-	-	86,600	-	-	-	-	-	87,000	-
Iron	1530	1440	1380	1070	1120	1220	1110	1050	1050	1180	1330	992	1420
Manganese	405	408	401	288	293	279	288	269	303	291	320	268	317
Magnesium	-	-	19,300	-	-	18,700	-	-	-	-	-	19,400	-
Zinc	38	44	38	<15	85	279	305	54	<15	517	37	54	26
ANALYTE Concentration (mg/l)													
COD (Total)	52	52	50	55	52	52	76	67	58	71	77	67	70
Alkalinity	248	236	230	11.8	68.2	74.9	58.3	63.3	9.06	51.0	87.5	63.4	71.7
Chloride	97.5	92.8	94.8	99.5	95.6	97.4	96.9	99.0	99.4	97.3	97.7	98.8	97.6
Sulfate	283	210	230	429	277	334	376	353	396	457	392	332	461
Ammonia Nitrogen	9.35	7.26	7.79	10.9	10.5	7.89	9.50	7.78	10.9	6.93	8.15	8.63	7.60
Nitrate Nitrogen	0.24	0.17	0.18	0.22	0.20	0.18	0.14	0.14	0.17	0.17	0.15	0.13	0.16
Nitrite Nitrogen	0.091	0.077	0.058	0.079	0.051	0.064	0.094	0.096	0.097	0.066	0.088	0.082	0.089
Total Kjeldahl Nitrogen	11.8	11.6	12.6	12.3	10.5	12.0	11.3	11.9	12.4	11.3	11.3	13.3	11.9
Phosphorus	0.16	0.16	0.18	0.14	0.14	0.15	0.17	0.14	0.15	0.14	0.16	0.14	0.15
TDS	743	717	740	1130	897	917	910	890	960	930	820	912	983
TSS	3	<2	<2	1	<1	<2	<2	<2	0	<2	<2	<2	<2
TOC I	14.2	12.6	14.0	14.8	12.5	12.2	12.4	11.9	13.2	12.0	12.0	11.9	12.7
TOC II (Dup)	15.0	12.8	14.0	14.0	12.4	12.2	12.6	11.9	13.1	12.0	12.1	11.8	13.0
pH, Laboratory	7.34	7.17	7.20	5.01	5.85	5.94	5.93	5.92	4.95	5.82	6.09	5.85	5.96

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #4 (67% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.
\- Not Analyzed For

TABLE 4
UV OXIDATION TESTING: METALS AND WATER QUALITY
VENDOR #2

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Arsenic	4.6	3.9	4.3	4.5	4.2	4.3	5.0	4.5	5.0	4.9	5.1	4.1	4.8
Calcium	-	-	108,000	-	-	113,000	-	-	-	-	-	112,000	-
Iron	1530	1440	1380	1780	1320	1320	13,700	13,600	1590	13,300	18,800	13,300	16,000
Manganese	405	408	401	404	413	410	487	500	386	491	523	492	509
Magnesium	-	-	19,300	-	-	18,400	-	-	-	-	-	18,300	-
Zinc	38	44	38	17	78	26	<15	41	58	45	78	140	35
ANALYTE Concentration (mg/l)													
COD (Total)	52	52	50	49	46	49	28	39	67	18	27	22	39
Alkalinity	248	236	230	248	236	237	<5	<5	229	<5	<5	<5	<5
Chloride	97.5	92.8	94.8	98.0	93.4	94.7	95.3	98.2	97.7	94.8	96.9	97.8	97.1
Sulfate	283	210	230	123	167	238	658	492	267	568	623	518	192
Ammonia Nitrogen	9.35	7.26	7.79	7.60	7.58	8.64	8.80	8.98	9.72	7.97	8.08	9.00	8.66
Nitrate Nitrogen	0.24	0.17	0.18	0.20	0.18	0.19	0.27	0.27	0.27	0.26	0.27	0.29	0.31
Nitrite Nitrogen	0.091	0.077	0.058	0.072	0.069	0.051	<0.050	<0.050	0.096	<0.050	<0.050	<0.050	<0.050
Total Kjeldahl Nitrogen	11.8	11.6	12.6	12.3	11.7	12.2	11.1	11.3	12.2	11.5	11.6	11.1	13.5
Phosphorus	0.16	0.16	0.18	0.19	0.17	0.15	0.59	0.66	0.85	0.59	0.66	0.67	0.80
TDS	743	717	740	750	714	723	977	967	813	937	1040	965	1010
TSS	3	<2	<2	<4	<2	<2	<2	1	1	3	3	6	4
TOC I	14.2	12.6	14.0	13.0	13.0	13.4	9.6	10.5	10.7	8.5	8.4	8.2	8.4
TOC II (Dup)	15.0	12.8	14.0	13.3	13.2	13.6	9.5	10.4	10.8	8.7	8.1	8.6	8.5
pH, Laboratory	7.34	7.17	7.20	7.37	7.24	7.26	2.55	2.41	7.00	2.53	2.57	2.42	2.47

[A] Intermediate Sampling Point after Lamp #2 (67% Retention Time)
[B] Intermediate Sampling Point after Lamp #1 (33% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.
- Not Analyzed For

TABLE 5
UV OXIDATION TESTING: METALS AND WATER QUALITY
VENDOR #3

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Arsenic	4.6	3.9	4.3	4.6	4.2	3.94.3	4.8	4.0	5.5	4.6	5.0	4.3	4.4
Calcium	-	-	108,000	-	-	113,000	-	-	-	-	-	117,000	-
Iron	1530	1440	1380	1600	1290	1520	1250	1240	1470	1190	1260	1350	1200
Manganese	405	408	401	400	405	410	408	406	391	394	399	417	416
Magnesium	-	-	19,300	-	-	18,400	-	-	-	-	-	19,200	-
Zinc	38	44	38	51	32	88	<15	49	29	243	649	93	61
ANALYTE Concentration (mg/l)													
COD (Total)	52	52	50	47	50	52	33	18	<8	16	21	15	32
Alkalinity	248	236	230	246	240	233	225	206	212	208	214	207	219
Chloride	97.5	92.8	94.8	97.5	96.3	94.8	93.4	95.7	97.1	91.8	94.0	95.3	94.3
Sulfate	283	210	230	239	200	207	259	265	280	252	135	279	124
Ammonia Nitrogen	9.35	7.26	7.79	11.20	8.65	7.73	8.52	9.08	9.84	9.50	7.51	8.30	8.45
Nitrate Nitrogen	0.24	0.17	0.18	0.21	0.19	0.18	0.31	0.39	0.67	0.37	0.34	0.40	0.31
Nitrite Nitrogen	0.091	0.077	0.058	0.075	0.053	0.065	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050	<0.050
Total Kjeldahl Nitrogen	11.8	11.6	12.6	12.2	11.2	11.3	11.3	11.5	11.9	11.1	11.6	11.3	10.6
Phosphorus	0.16	0.16	0.18	0.18	0.17	0.18	0.18	0.18	0.20	0.19	0.18	0.15	0.17
TDS	743	717	740	796	740	738	738	724	770	764	767	732	748
TSS	3	<2	<2	<4	<2	<2	<2	11	14	7	7	10	<2
TOC I	14.2	12.6	14.0	13.5	13.0	13.4	13.6	10.7	7.6	11.0	11.2	10.6	13.1
TOC II (Dup)	15.0	12.8	14.0	13.3	12.7	13.0	13.6	11.0	7.7	10.9	11.2	10.4	13.1
pH, Laboratory	7.34	7.17	7.20	7.30	7.18	7.19	7.07	7.30	7.55	7.09	7.16	7.23	7.41

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #5 (83% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.
- Not Analyzed For

TABLE 6
UV OXIDATION TESTING: VOLATILE ORGANIC COMPOUNDS
VENDOR #1

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Vinyl Chloride	110	120	150	77	60	34	20	18	10	<10	8	4	13
Methylene Chloride	47	53	200	24	16	73	10	8	17	3	4	4	5
Acetone	30	<140	<140	150	22	69	19	36	63	31	25	25	24
1,2-Dichloroethene (total)	170	200	180	140	120	91	47	45	23	13	19	21	30
1,2-Dichloroethane	<50	<68	<72	<31	<38	<33	<10	<5	<5	8	8	10	10
Trichloroethene	91	120	110	81	77	58	30	27	16	9	13	12	18
Benzene	1400	1900	1700	1100	1200	870	310	220	120	60	87	83	120
Tetrachloroethene	320	470	360	290	340	190	140	110	71	50	68	65	96
Toluene	1500	2000	1700	910	920	660	200	110	57	21	34	31	47
Chlorobenzene	160	220	190	120	120	100	35	26	14	7	10	10	15
Ethylbenzene	51	61	67	31	26	<33	6	4	2	<5	1	1	2
Xylene (total)	73	88	91	33	32	28	6	4	<5	<5	<5	<5	<5

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #4 (67% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

TABLE 7
UV OXIDATION TESTING: VOLATILE ORGANIC COMPOUNDS
VENDOR #2

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Vinyl Chloride	110	120	150	97	11	110	<10	<10	<10	<10	<10	<10	<10
Methylene Chloride	47	53	200	65	8	38	3	6	7	2	4	10	6
Acetone	30	<140	<140	260	16	<37	35	26	73	46	31	35	38
1,2-Dichloroethene (total)	170	200	180	150	18	150	<5	4	<5	<5	<5	<5	<5
1,2-Dichloroethane	<50	<68	<72	<50	<5	<18	5	7	4	4	4	4	3
Trichloroethene	91	120	110	92	10	88	<5	8	<5	<5	<5	4	<5
Benzene	1400	1900	1700	1400	170	1400	<5	9	<5	<5	<5	<5	<5
Tetrachloroethene	320	470	360	320	40	320	10	58	4	2	2	4	<5
Toluene	1500	2000	1700	1500	170	1500	<5	<5	<5	<5	<5	<5	<5
Chlorobenzene	160	220	190	160	19	170	<5	<5	<5	<5	<5	<5	<5
Ethylbenzene	51	61	67	50	5	51	<5	2	<5	<5	<5	<5	<5
Xylene (total)	73	88	91	70	8	81	<5	<5	<5	<5	<5	<5	<5

[A] Intermediate Sampling Point after Lamp #2 (67% Retention Time)
[B] Intermediate Sampling Point after Lamp #1 (33% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

TABLE 8
UV OXIDATION TESTING: VOLATILE ORGANIC COMPOUNDS
VENDOR #3

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Vinyl Chloride	110	120	150	<100	120	97	<10	<10	<10	<10	<10	<10	<10
Methylene Chloride	47	53	200	47	23	18	3	18	2	6	3	15	2
Acetone	30	<140	<140	180	130	<25	41	44	48	63	45	44	13
1,2-Dichloroethene (total)	170	200	180	180	200	140	9	<5	<5	<5	<5	<5	4
1,2-Dichloroethane	<50	<68	<72	<50	<50	<12	8	3	<5	5	4	3	4
Trichloroethene	91	120	110	97	110	86	7	<5	<5	<5	<5	<5	4
Benzene	1400	1900	1700	1500	1800	1200	35	1	<5	1	1	1	18
Tetrachloroethene	320	470	360	350	440	320	63	3	<5	6	7	2	32
Toluene	1500	2000	1700	1700	1800	1500	3	<5	<5	1	<5	<5	2
Chlorobenzene	160	220	190	170	220	170	5	<5	<5	<5	<5	<5	2
Ethylbenzene	51	61	67	55	56	48	<5	<5	<5	<5	<5	<5	<5
Xylene (total)	73	88	91	79	84	71	<5	<5	<5	<5	<5	<5	<5

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #5 (83% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

TABLE 9
UV OXIDATION TESTING: SEMIVOLATILE ORGANIC COMPOUNDS
VENDOR #1

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Phenol	8	<100	10	130	51	<10	100	<10	<10	32	39	35	<10
Aniline	230	110	160	64	85	<10	17	<10	<10	2	5	4	<10
2-Chlorophenol	3	<100	3	19	7	<10	20	<10	<10	8	10	10	14
Benzyl Alcohol	<10	<100	<10	6	1	3	5	5	<10	2	3	3	4
1,2-Dichlorobenzene	28	18	23	18	24	28	9	8	<10	1	3	3	5
2-Methylphenol	14	<100	12	48	23	19	89	67	<10	16	25	33	52
4-Methylphenol	6	<100	5	83	30	23	77	58	<10	16	26	29	43
N-Nitroso-Di-n-Propylamine	2	<10	1	<10	1	<10	<10	<10	<10	<10	<10	<10	<10
Isophorone	<10	<100	14	14	14	13	22	23	5	14	15	17	17
1,2,4-Trichlorobenzene	4	<100	3	3	3	4	1	1	<10	<10	<10	<10	<10
4-Chloroaniline	10	<100	7	3	7	9	<10	<10	<10	<10	<10	<10	<10
Benzidine	930	390	590	7	140	<50	<50	<50	<52	<50	<50	<50	<50
3,3'-Dichlorobenzidine	180	100	110	61	130	130	<20	<20	<21	<20	<20	<20	<20

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #4 (67% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

TABLE 10
UV OXIDATION TESTING: SEMIVOLATILE ORGANIC COMPOUNDS
VENDOR #2

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Phenol	8	<100	10	9	8	9	<10	<10	<11	<10	<10	<10	<10
Aniline	230	110	160	180	170	150	<10	<10	<11	<10	<10	<10	<10
2-Chlorophenol	3	<100	3	3	2	2	<10	<10	<11	<10	<10	<10	<10
Benzyl Alcohol	<10	<100	<10	1	<10	<10	2	2	<11	1	1	<10	<10
1,2-Dichlorobenzene	28	18	23	20	22	22	<10	<10	<11	<10	<10	<10	<10
2-Methylphenol	14	<100	12	15	11	11	<10	<10	<11	<10	<10	<10	<10
4-Methylphenol	5	<100	5	6	5	6	<10	<10	<11	<10	<10	<10	<10
N-Nitroso-Di-n-Propylamine	2	<100	1	1	<10	1	<10	<10	<11	<10	<10	<10	<10
Isophorone	<10	<100	14	9	<10	<10	2	<10	2	1	1	<10	<10
1,2,4-Trichlorobenzene	4	<100	3	3	3	3	<10	<10	<11	<10	<10	<10	<10
4-Chloroaniline	10	<100	7	8	7	7	<10	<10	<11	<10	<10	<10	<10
Benzidine	930	390	590	630	540	600	<50	<50	<50	<50	<50	<50	<50
3,3'-Dichlorobenzidine	180	100	110	130	130	120	<20	<20	<22	<20	<20	<20	<20

[A] Intermediate Sampling Point after Lamp #2 (67% Retention Time)
[B] Intermediate Sampling Point after Lamp #1 (33% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

TABLE 11
UV OXIDATION TESTING: SEMIVOLATILE ORGANIC COMPOUNDS
VENDOR #3

Bofors Nobel Superfund Site, Muskegon, Michigan
Predesign Testing

ANALYTE CONC. (ug/l)	Combined Purge Well Manifold			After Pretreatment UV Oxidation Influent			Intermediate		UV Oxidation System Effluent				
	9/27 1991	10/1 1991	10/2 1991	9/27 1991	10/1 1991	10/2 1991	9/27 1991[A]	10/2 1991[B]	9/27 1991[C]	10/1 1991	10/1 1991	10/2 1991	10/2 1991
Phenol	8	<100	10	16	<10	9	6	<10	<10	<10	<10	<10	2
Aniline	230	110	160	190	91	150	<10	<10	<10	<10	<10	<10	<10
2-Chlorophenol	3	<100	3	4	3	2	<10	<10	<10	<10	<10	<10	<10
Benzyl Alcohol	<10	<100	<10	5	<10	<10	1	<10	<10	<10	<10	<10	<10
1,2-Dichlorobenzene	28	18	23	25	22	21	2	<10	<10	<10	<10	<10	<10
2-Methylphenol	14	<100	12	24	12	11	2	<10	<10	<10	<10	<10	<10
4-Methylphenol	6	<100	5	6	7	5	4	<10	<10	<10	<10	<10	<10
N-Nitroso-Di-n-Propylamine	2	<100	1	<10	3	1	<10	<10	<10	<10	<10	<10	<10
Isophorone	<10	<100	14	<10	12	<10	10	<10	<10	1	2	<10	8
1,2,4-Trichlorobenzene	4	<100	3	3	3	3	<10	<10	<10	<10	<10	<10	<10
4-Chloroaniline	10	<100	7	9	7	7	<10	<10	<10	<10	<10	<10	<10
Benzidine	930	390	590	790	620	580	<50	<50	<50	<50	<50	63	<50
3,3'-Dichlorobenzidine	180	100	110	160	150	110	<20	<20	<20	<20	<20	<20	<20

[A] Intermediate Sampling Point after Lamp #3 (50% Retention Time)
[B] Intermediate Sampling Point after Lamp #5 (83% Retention Time)
[C] Effluent Sample taken on 27 September 1991 during equipment adjustment period.

Remediation of Groundwater Contaminated with Volatile Organic Compounds in the Saturated Zone at a California Superfund Site in Mountain View, California

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Historical Site Summary

This site, located in California's "Silicon Valley", was used for the manufacture of printed circuit boards from the mid-1960s to 1981. Various rinse waters were collected in five underground storage tanks along one side of a row of buildings. These washing and rinsing operations reportedly used chlorinated and other solvents. These concrete tanks have been recently removed and replaced with engineered fill. The buildings on the site are now occupied by a variety of small industries and service establishments.

The site is a California State Superfund Site. Investigations completed to date include a Remedial Investigation and a Feasibility Study. A Remedial Action Plan has been developed and approved by the California Environmental Protection Agency, Department of Toxic Substances Control. Regulatory oversight during the previous investigations and the implementation of the Remedial Action Plan has been provided by Department of Toxic Substances Control.

This paper will cover the remedial investigation, feasibility study, and engineering design of remediation facilities for the contaminated groundwater using a relatively new treatment method, which results in the destruction of contaminants, rather than their transfer to another medium.

Site Characterization

During the remedial investigation, approximately 30 monitoring wells and 25 soil borings have been completed at the site to characterize the extent of contamination. Figure 1 shows the site layout and locations of monitoring wells. Contamination extends through the vadose zone into two distinct aquifers, which are separated by an clay layer aquitard. There are two separate plumes; this discussion will cover only the eastern plume. Two extraction wells have been installed and used to field test an ultraviolet light hydrogen peroxide groundwater treatment process. Wells have been monitored for more than two years. The principal contaminants in the groundwater are shown in Table 1.

Setting

Mountain View is located about 40 miles southeast of San Francisco. The temperate climate is typical of California coastal areas, with an annual precipitation of 15 to 20 inches, predominantly in the period from November to March. Summer daytime temperatures are in the 70s to 80s, with nighttime temperatures in the 60s. Winter temperatures rarely drop below freezing.

The ground surface at the site is covered by buildings, pavement, and small landscape improvement areas. Surface topography is relatively flat, and has been locally modified by grading and other site improvements. The site is located geologically at the base of an alluvial fan, with the regional ground surface sloping gently to the north toward San Francisco Bay.

The site geology is characteristic of an alluvial environment which was periodically inundated by bay waters during interglacial periods. The lithology is characterized by interbedded unconsolidated sands, silts, and clays. Three aquifers have been identified and are referred to as Zones A, B, and C in order of increasing depth. Zone A is a shallow water table aquifer with a low hydraulic conductivity typical of silty sands. The present saturated thickness of this zone is only 3.0 ft, down from 6.5 ft in 1987, due to several years of drought.

Zone B is separated from Zone A by a clay unit 5 to 15 ft in thickness first appearing at a depth of about 25 ft. The conductive interval of Zone B is characterized by 10 to 15 ft of sand with varying amounts of clay and gravel, which is locally interbedded with sandy clay. The hydraulic conductivity of this zone is roughly 5 times that of Zone A. Pump tests characterize this aquifer as leaky with a hydraulic connection to Zone A. The piezometric surface of Zone B is approximately the same as the free groundwater surface of Zone A.

Zone C is separated from Zone B by 10 to 15 ft of clay which forms a hydraulic barrier between the two aquifers. The piezometric surface of this zone is approximately 1 ft higher than Zones A and B. Groundwater flow in the upper zones is generally to the north toward the San Francisco Bay with a gradient between 0.002 and 0.003 ft/ft. Figure 2 is a cross section showing conceptual lithology of the site.

Feasibility Study

A Feasibility Study considered a number of cleanup scenarios for both soil and groundwater. Chemical oxidation by means of ultraviolet light and hydrogen peroxide was selected as the treatment method. Extensive field testing has shown that a Perox-Pure LV-60 ultraviolet light hydrogen peroxidation (UV/PX) unit, manufactured by Peroxidation Systems Inc. to be effective in reducing concentrations of VOCs to less than 1 ppb and can meet the discharge limits set by a NPDES permit. The treated water will be discharged to the city storm sewer which ultimately flows into San Francisco Bay.

The UV/PX unit was tested at flows up to 50 gpm, hydrogen peroxide concentrations in the feed as high as 300 ppm, and power inputs up to 50 MW. Selected initial conditions will be 50 gpm feed, 200 ppm hydrogen peroxide, and four lamps operating (50 MW power).

Hydrogeologic modeling studies have shown that pumping from the Zone B aquifer at a sufficient rate will capture the contaminated plume in Zone B and simultaneously dewater Zone A. A parallel soil vapor extraction operation will be carried out in the vadose zone and the dewatered Zone A.

Facility Design and Construction

The criteria for design of the groundwater extraction and treatment system included:

- Use of the Perox-Pure UV/PX unit furnished by Peroxidation Systems Inc. which was used in the full-scale field tests. The reactor vessel has been modified with a new design to improve water flow patterns and minimize bypassing.

- Discharge limits as set by a NPDES Permit; the discharge is ultimately to San Francisco Bay. Discharge limits for VOCs are 5.0 ug/L each for 1,2-dichloroethylene, trichloroethylene, tetrachloroethylene, benzene, ethylbenzene, and xylenes, and 0.5 ug/L of toluene.

- Provision for discharge to the city sanitary sewer, ultimately to the Palo Alto Waste Water Treatment Plant. The Industrial Waste Discharge Permit with the City of Mountain View permits discharge of 750 ug/L of each VOC with a maximum of 1,000 ug/L total VOCs.

- Secondary containment for tanks or equipment containing untreated groundwater and 50% hydrogen peroxide solution, either double-walled piping or a bermed area

- Provision to enable unattended operation so that the facility may be serviced once a week, after the startup is complete

- Automatic shutdown for high water level in the untreated groundwater storage tank, water on the floor of the bermed process area, and misoperation or malfunction of the Perox-Pure unit. Conditions in the Perox-Pure unit causing a shutdown include low groundwater feed flow rate, low hydrogen peroxide solution pump discharge pressure, high temperature in any of several locations in the unit, and moisture in any of several locations in the unit.

A detailed design was prepared for the groundwater extraction and treatment system which included drawings and specifications. Contract documents were also prepared for a complete bidding package. Bids were received from several local contractors. Construction of the facility is essentially complete and the startup phase is beginning.

Estimated Costs

The estimated construction cost is $185,000; this does not include the UV/PX unit (it will be leased under a service agreement), or any engineering costs. Estimated operating and maintenance costs for the first year of operation are shown in Table 2 for the first year of operation.

Table 1. Principal Contaminants in Groundwater at the Plessey Site

Contaminant	Typical Concentrations (ug/L)
Ethylbenzene	300
Perchloroethylene	400
Trichloroethylene	8,000
Xylenes	700
1,2-Dichloroethylene	600

Table 2. Estimated O&M Costs at the Plessey Site (1st Year)

	$1000/yr	$/1000 gal
Startup (1)	20.7	0.93
Equipment Lease (2)	59.4	2.66
Utilities:		
Electricity	41.0	1.84
Storm Sewer Fees	10.5	0.47
Other	1.0	0.04
Operating and Maintenance (3)	30.5	1.37
Building Rent	13.6	0.61
Regulatory Activities		
Sampling/Analysis (4)	38.1	1.71
Hazardous Waste Fees	56.2	2.52
Special Reports	25.2	1.13
Total	297	13.3

Notes
(1) First year only
(2) For UV/PX unit; includes maintenance of the unit and hydrogen peroxide supply
(3) Routine checking each week and routine reports
(4) Includes sampling labor and analytical laboratory charges

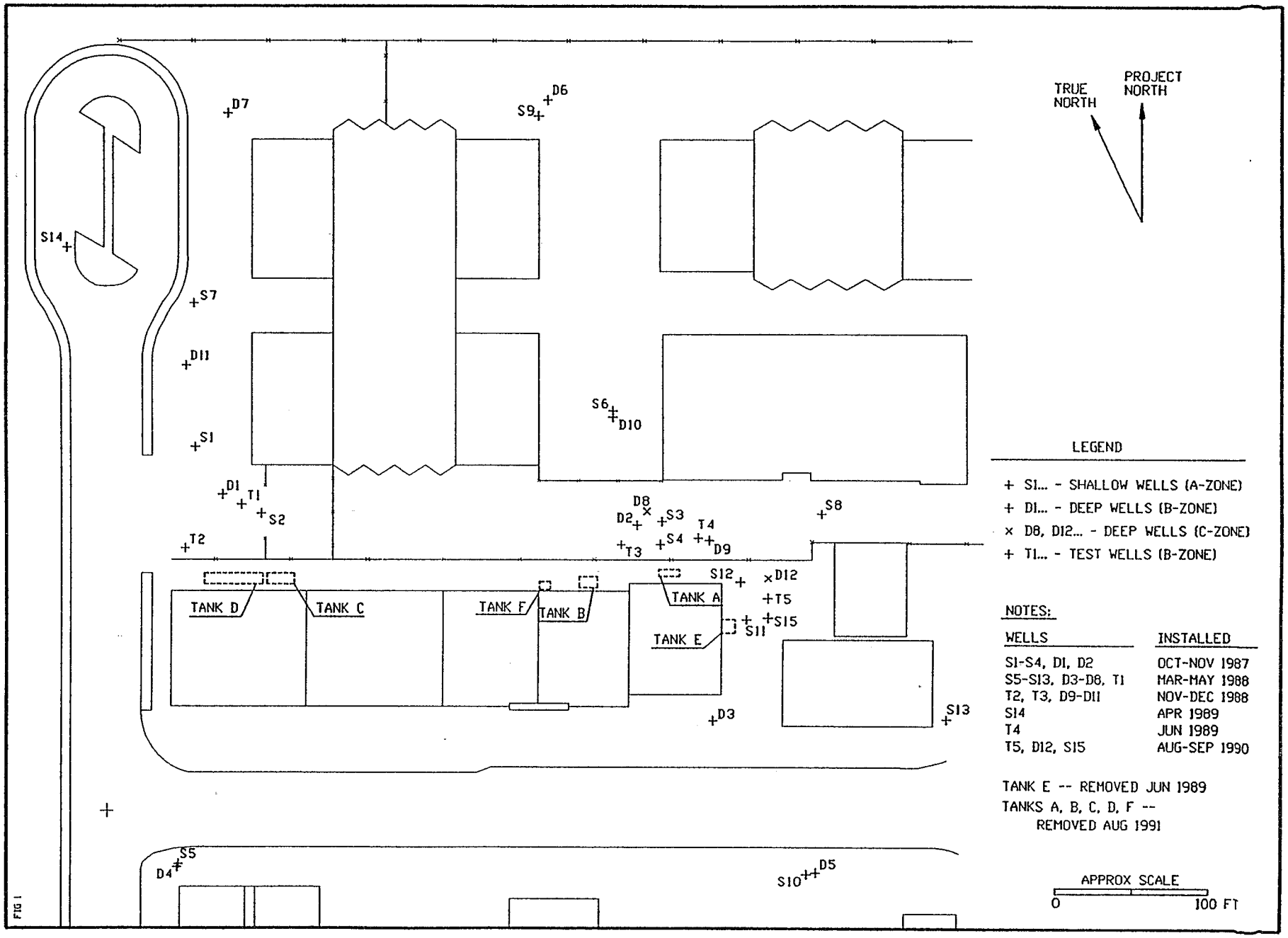

FIGURE 1. MOUNTAIN VIEW SITE MONITORING WELLS

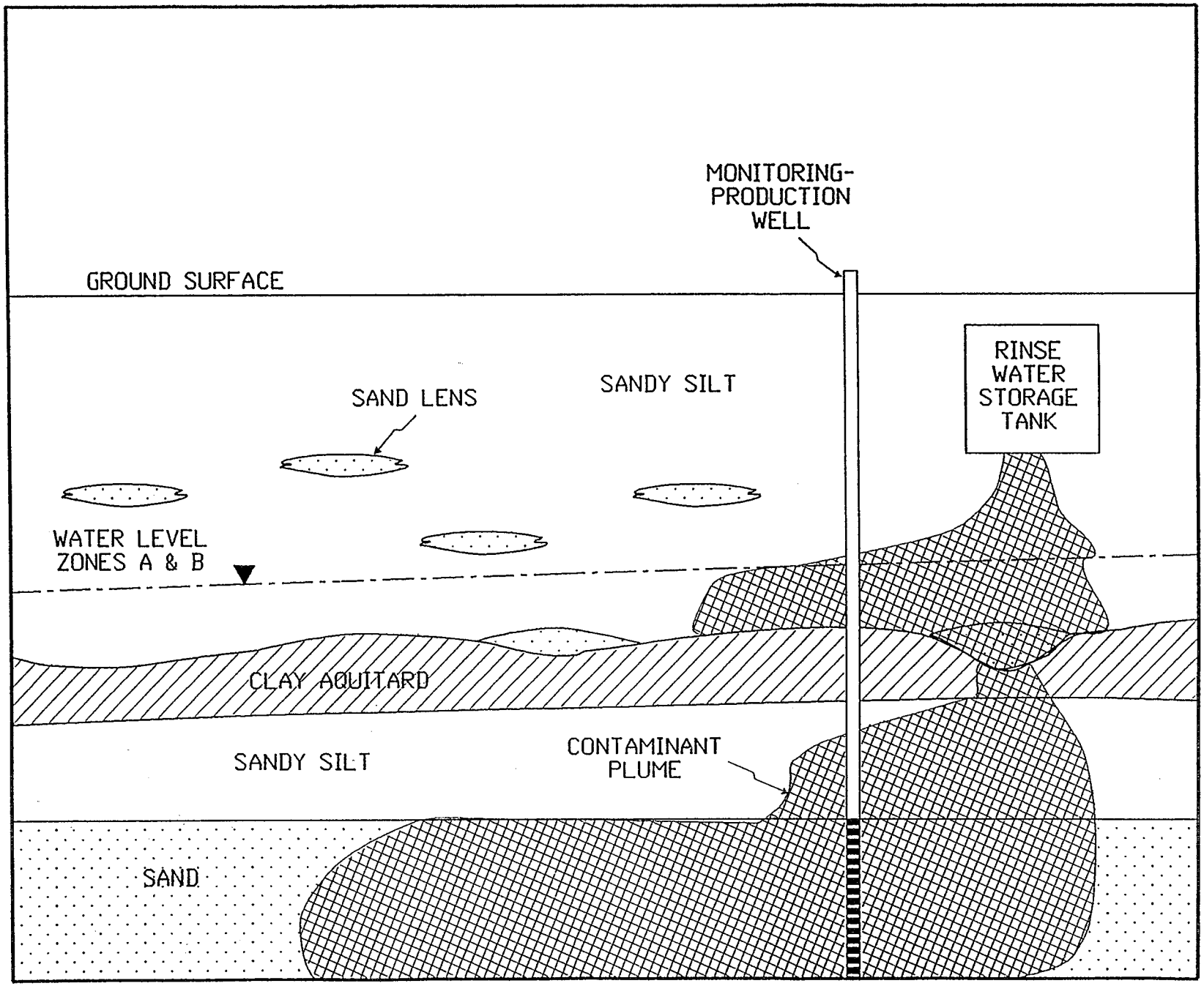

FIGURE 2. MOUNTAIN VIEW SITE CONCEPTUAL LITHOLOGY

SOIL WASHING OF LEAD-CONTAMINATED SOIL AT A FORMER GUN CLUB SITE

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Abstract

The subject site operated as a rifle range, a pistol range and a trapshooting area from 1976 to 1985. As a result of a preliminary site assessment, it was determined that surface soil contamination by particulate elemental lead in the form of spent bullets and shot existed in certain areas of the site.

Pilot studies performed on representative soil samples indicate that it would be feasible to separate and remove the lead shot, slugs and fragments from the stockpiled soil using a modified sand and gravel plant as the treatment plant. Approximately 15,000 cubic yards of contaminated soil were excavated from various areas of the site and field screened through a one-inch vibratory screen. The finer-grained material (approximately 9000 cubic yards) was processed in the treatment plant, which utilized the difference in specific gravity between the particulate lead and the soil to physically separate and remove the lead.

The treatment plant consisted of a hopper feeder above a jigging box used to capture the larger lead slugs and shot, and two sand screws that fed the contaminated soil onto three stacked screens. The fine material passing the smallest screen was sent through a three-foot-diameter centrifugal separator. The plant utilized approximately 300 gallons of water per minute, which was stored in two recirculation settling ponds. Clarified water from the settling ponds was recirculated as part of the soil washing and material transport water in the plant. The treated soil flowed along a drag tank and was discharged to ground (beached).

The goal of the treatment process was to remove the particulate elemental lead from the fine-grained soil so that a total lead concentration of less than 170 mg/kg for a given volume of sample was achieved. The test results showed a high degree of effectiveness in the removal of the free lead, although some lead remained bound to the silt, clay and organic fractions of the soil. Elemental lead particles ranging in size from coarse slugs down to approximately 100 mesh were recovered from the contaminated soil. The mean lead concentration for the treated soil was 181 mg/kg.

Twenty-one drums (31,970 pounds) of recovered lead were transported to a recycling facility. The treated soil and the coarse-grained, uncontaminated material from the screening operation were used as backfill beneath a road being constructed on site. The total cost of the soil washing operation, including all earthwork operations, was approximately one million dollars. The project team consisted of two consultants and a contractor who worked in conjunction with each other to oversee the remedial action, conduct the sampling, and to operate the treatment plant.

Introduction

This paper summarizes the investigation and remediation of lead-contaminated soil at a former gun club site in Folsom, California. The investigation and remediation were part of a Preliminary Endangerment Assessment (PEA) performed for the site; the PEA legislation was enacted in 1989, which allowed the State of California Department of Health Services (currently Cal EPA, Department of Toxic Substances Control) to oversee PEA projects.

The study site comprised approximately 40 acres in Folsom, Sacramento County, California, and the overall property is to be developed into a residential subdivision. The site was purchased by the Orangevale Sportsman Club, Inc. in February, 1976. Three relatively isolated areas of the site were used by the club for target shooting; the shooting was directed into soil berms designed to trap the spent bullets. The berms were constructed of on-site materials consisting primarily of sand, gravel and cobbles. Another portion of the site was used for trapshooting. The trapshooting operations resulted in particulate elemental lead contamination in the surface soil.

No specific measures were taken during the time of gun club operation to contain, store, treat, or dispose of the spent bullets and shot, except for construction of soil berms in the target area. Approximately 1,850 cubic yards of soil from the berms containing visible lead were removed from the site in October 1987.

The proposed development of the site required several site studies, including an *Environmental Impact Report* and a *Preliminary Site Assessment*. As a result of these studies, a determination was made that

surface soil contamination by particulate elemental lead in the form of spent bullets and shot remained in certain areas of the site.

Regulatory Perspective

The Department of Toxic Substances Control (Department) oversight was requested by the City of Folsom to ensure that a health based soil cleanup level was achieved. The Preliminary Endangerment Assessment (PEA) prepared by Wallace Kuhl and Associates, Inc. further characterized the site and defined the vertical and horizontal extent of the soil contamination after initial sampling confirmed elevated levels of lead in the soil. The PEA is an evaluation tool that assesses what remedial action is required to protect public health and the environment. Information and determinations gained through conducting the PEA included:

1) Site Description and History;
2) Apparent Problem;
3) Environmental Setting;
4) Sampling Activities and Requirements;
5) Human Health and Environmental Threat Assessment; and,
6) Conclusions and Recommendations.

The PEA also incorporated a description of the remedial action. The PEA presented information and data in a standard format to allow Departmental review of the potential for lead exposure from on-site soils.

The soil cleanup level for lead was determined for unrestricted use of the site. The type of contamination at the Folsom Gun Club site and the land use issue that designated change to residential development necessitated a treatment that was protective of human health. A Health Risk Assessment was conducted to predict whether the estimated residual concentrations of lead would pose a potential negative impact on the health of residents who would live in the development. A level of 170 ppm residual lead for the treated soil to be placed beneath an on-site roadway was established by a Department staff toxicologist based on risk factors to children and pregnant women, the most sensitive receptors.

Acceptable residual soil levels at the proposed residential lots from which the contaminated soil was excavated was determined using the U.S. EPA's Uptake/Biokinetic Model (Model) to estimate the total lead uptake (micrograms per day) in humans, in particular for infants and young children. This approach was developed by the U.S. EPA because there is a lack of empirical evidence for a threshold for many of the noncarcinogenic effects of lead in infants and young children. Therefore, the use of

traditional toxicity criteria (the reference dose; RfD) in assessing risk for lead is not considered adequate by the U.S. EPA. The Model provides a method for predicting blood lead levels in infants and children exposed to lead in multiple environmental media (air, diet, soil, indoor dust, water, etc.). The potential exposure pathways evaluated for the health risk assessment were:

1) ingestion of soil;
2) inhalation of fugitive dust originating from site soil;
3) ingestion of homegrown vegetables and fruit; and,
4) in utero exposure as result of maternal lead intake.

The Model, which used the residual lead concentration of 77 mg/kg for the residential lots, predicted blood lead levels in infants and children aged 0 to 7 years to be 3.89 ug/dL, which is less than the California Department of Health Services' threshold concentration of 5.0 ug/dL. The site exposure pathways contributing the greatest amount to blood levels in children are ingestion of homegrown vegetables and fruit, and ingestion of soil. Based on the results of the health risk assessment, future residents of the development will not be adversely impacted by residual concentrations of lead in site soil.

Another regulatory issue was to determine if lead, in essentially an elemental form, constitutes a hazardous waste. A related issue was also addressed -- do lead bullets and shot meet criteria under the Scrap Metal Exclusion? It was determined that the lead as a result of lead bullets and shot was not generated as a hazardous waste but was a hazardous substance. The lead in the surface soil, therefore, constituted disposal, and would have had to have been handled as a hazardous waste if it had been excavated and disposed of off site. Therefore, any remedial activity that involved moving the lead-contaminated soil triggered hazardous waste requirements in Title 22, California Code of Regulations (Title 22, CCR) and procedures mandated by the Department.

The Department is required under Title 22, CCR to implement regulations to manage hazardous substances and wastes in order to protect the public health and the environment. In Title 22, CCR Section 66261.24, Characteristic of Toxicity, the Total Threshold Limit Concentration (TTLC) for lead is 1000 parts per million (ppm) or mg/kg wet-weight. The TTLC is defined in Title 22, CCR as, "the concentration of a solubilized, extractable and nonextractable bioaccumulative or persistent toxic substance which, if equaled or exceeded in a waste, renders the waste hazardous." Any material with a lead concentration exceeding 1000 ppm TTLC is to be handled as a hazardous waste.

The leachability of the lead through the soil is determined by the Soluble Threshold Limit Concentration (STLC). The STLC is an indication of how soluble a substance or compound is through a medium. The STLC for lead is established at 5 ppm (milligrams per liter) in Title 22, CCR and

defined as, "the concentration of a solubilized and extractable bioaccumulative or persistent toxic substance which, if equaled or exceeded in a waste or waste extract...renders the waste hazardous."

The solubility test to determine the leachability is the Waste Extraction Test (WET). The WET was designed to reproduce leaching potential in a landfill. The WET is considered an aggressive solubility test for metals because it uses citric acid as a buffer. This tends to pull the metal out of solution and will not necessarily reflect what transpires in non-landfill environments subjected only to rainwater. Therefore, deionized water was substituted for the citric acid in a subsequent WET. The WET using the citric acid buffer on soils from the site exceeded the STLC limit of 5 ppm, whereas the test using the deionized water did not exceed the limit. Although neither test completely reflects what occurs in the environment, a comparison of the two allowed for a site management decision based on the results of both methods.

Another regulatory issue addressed whether or not lead bullets and shot classifies as scrap metal. Under Section 66260.10 Title 22, CCR, "scrap metal" is defined as one or more of the following:

1) Manufactured, solid metal objects and products;
2) Metal workings, including cuttings, trimmings, stampings, grindings, shavings, and sandings; or
3) Solid metal residues of metal production.

The definition also lists exclusions for metallic wastes that are not considered scrap metal. These exclusions include under Section 66260.10 subsection (b)(6), "Sludges, fine powders, semi-solids, and liquid solutions that are hazardous wastes." The argument has been made that based on the regulatory definition, lead bullets and shot are manufactured, solid metal objects or products and therefore are excluded from regulation as a hazardous waste. If the lead bullets and shot are found to have disintegrated into a fine powder (defined in Section 66260.10 as, "a metal in dry, solid form having a particle size smaller than 100 micrometers in diameter"), then based on the exclusion in subsection (b)(6), it would not be considered scrap metal. If the lead bullets and shot are mixed with a fraction of lead as a fine powder, then testing is required to determine whether it has any characteristics of hazardous waste. The site soils at Folsom did not meet the criteria for scrap metal exclusion because fines of 100 micrometers or less were extractable from the soils. The larger question of whether lead shot meets the definition of a scrap metal is not resolved.

Soil Sampling

A surface soil sampling plan was developed to assess the extent of the lead contamination. The results of this sampling confirmed that the areas of the site containing elevated levels of particulate elemental lead were near the soil berms originally constructed for the purpose of intercepting spent bullets, and in the trapshooting area that received spent shot. Concentrated sampling in these areas defined the limits of the surface soil contamination. The following phases of sampling for characterization, delineation, and confirmation were conducted:

Initial Sampling

The first phase of sampling took place on January 23 and 25, 1990. A total of 47 surface soil samples were obtained over the entire site to identify areas of potentially elevated lead concentrations and to determine background levels of lead in soil in areas of the site away from the former gun club operations. The samples were obtained from the upper six inches of soil. Laboratory analysis of these samples indicated that four areas of the site contained lead concentrations greater than background levels: three former soil berm areas and the trapshooting area.

Delineation Sampling

The second phase of sampling took place on February 14, 1990, and March 7 and 19, 1990. Fifty surface and subsurface samples from depths ranging from zero to four feet were obtained in the areas identified by the initial sampling as containing elevated levels of particulate elemental lead; the delineation samples were taken to determine the lateral and vertical extent of lead-contaminated soil in these areas.

Based on the laboratory analyses of the delineation samples, the lateral and vertical limits of elevated levels of lead (above 170 mg/kg) were defined.

Post-Excavation Confirmation Sampling

Subsequent to delineation of the four areas of lead contamination, the contaminated soil was excavated and stockpiled. The former soil berm areas were then resampled to confirm that the lead-contaminated soil had been removed. When confirmation samples indicated remaining isolated areas of residual contamination, the process was repeated -- the isolated areas were excavated, and the excavated

material stockpiled. Upon completion of the excavation process, confirmation sampling indicated that the highest concentration of lead remaining in the former trapshooting and soil berm areas was 77 mg/kg.

Stockpiled Soil

The entire stockpile of lead-contaminated soil, approximately 15,000 cubic yards, was field screened through a one-inch vibratory screen. The uncontaminated material retained on the screen (larger than one-inch diameter) was stockpiled separately and subsequently used as backfill beneath an on-site asphalt-concrete roadway. The finer-grained soil passing through the screen (less than one-inch in diameter and containing the particulate elemental lead) comprised approximately 9,000 cubic yards and was processed in the treatment plant.

The screened soil consisted of gravel, sand and silt. Sieve analysis data revealed that the gravel comprised approximately half of the final weight of the soil; an average of 70 percent by weight was retained on the No. 12 sieve and an average of five percent by weight passed the No. 30 sieve.

Treatment Plant

A modified sand and gravel plant was used to treat ("wash") the lead-contaminated soil. Sand and gravel plants operate on the principle that alluvial sand and gravel have an average specific gravity of approximately 2 to 3 grams per cubic centimeter (g/cc). The difference in specific gravity between the particulate lead (11.4 g/cc) and the soil was utilized to physically concentrate, separate and remove the lead from the soil.

The modified plant consisted of a hopper feeder above a jigging box used to capture the larger lead slugs and shot, and two sand screws which fed material onto three stacked screens (3/4", 1/4" and 1/8"). The fine material passing the smallest screen was sent through a three-foot-diameter centrifugal separator. The remaining material (treated soil) flowed along a drag tank until it dropped off the end of the plant; the treated soil was "beached" from this point outward in a triangular shape onto a gently sloping surface previously created by earthmoving equipment. The treated soil was contained at the furthest extent of the beached area by a three- to five-foot-high soil berm. The concentrated lead in the jigging box and centrifugal separator was removed and stored in sealed 55-gallon drums on site.

The treatment plant processed approximately 20 cubic yards of soil per hour and utilized approximately 300 gallons of water per minute; the water was stored in two recirculation settling ponds, described below.

Recirculation Ponds

The ponds were constructed using large Caterpillar scrapers by creating two trenches approximately 150 feet long by 15 feet wide. The excavated trenches were lined with 30-mil continuous plastic sheeting to form an impermeable barrier. Approximately 200,000 gallons of water from a hydrant on site was used to fill both ponds to a depth of approximately five to six feet.

The pond water initially became turbid with solids (silt and clay sediment), which increased its viscosity. The increase in water viscosity made it difficult for the lead to settle in the plant. This problem was solved by the addition of calcium chloride to the circulating water. Calcium chloride acted as a flocculent, causing suspended fines and clay particles in the processing water to lump together and drop out of suspension. Empirical observations in the field showed that approximately 40 pounds of calcium chloride added to the water were required per 100 yards of processed material.

When the level of settled fines in the lower pond rose to a point near the water pump intake, the fines were either pumped out with a trash pump, or removed using a large bucket excavator. The fines were placed against the soil berms constructed downslope from the ponds.

Results of lead analysis in water samples obtained from the recirculation ponds showed $< 10\ \mu g/\ell$ lead on October 8, 1990, and 46 $\mu g/\ell$ lead on October 17, 1990. Lead concentrations in the recirculating processing water were below the reporting limit of 10 $\mu g/\ell$ in four water samples taken March 4, 7, 15, and April 3, 1991.

Reconsolidation Process

Upon completion of the soil washing process, the fines from the recirculation ponds were combined with the treated soil (reconsolidated) using a Caterpillar D8 bulldozer equipped with three four-foot-long ripper teeth during early April, 1991. The reconsolidation process involved continuous mixing with the bulldozer in a grid pattern for five days (42 hours). The mixing area was approximately 630 feet long by 190 to 260 feet wide.

After mixing operations, the reconsolidated soil was sampled in place. The grid for the sample locations was based upon a minimum of fifty samples. At each sample location, a backhoe trench was excavated from the surface to the bottom of the reconsolidated soil, approximately three to four feet deep. Three discrete samples were collected from the top, middle and bottom of the trench at each sample location.

The treated soil, following the reconsolidation process, had a mean lead concentration of 181 mg/kg. The plastic pond liner was removed from the ponds by the excavator bucket. Three soil samples were obtained from below each of the former ponds. The test results for these samples showed lead levels in the native soil below the former pond sites well below 170 mg/kg.

Recovered Lead

Elemental lead particles ranging in size from coarse slugs down to approximately 100 mesh were recovered from the stockpiled soil. The recovered lead was in the form of slugs, shot and small particles. The slugs comprised eight to ten percent of the total weight of recovered lead. Of the remaining lead shot and particles, 98.5 percent passed the No. 8 mesh screen.

All recovered lead (slugs, shot and particles) was stored on site in covered 55-gallon drums. Twenty-one drums were transported on May 13, 1991 to a recycling facility. The net weight of lead as delivered was 31,970 pounds.

Cost

The total cost for the project was approximately $1,000,000, including excavation, field screening, recirculation pond construction, soil treatment and reconsolidation, and placement of the treated soil beneath the roadway.

Acknowledgments

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IMPROVEMENTS IN THE CONVENTIONAL HIGH TEMPERATURE ROTARY KILN INCINERATION TECHNOLOGY

1. INTRODUCTION

Ekokem Ltd operates two rotary kiln incinerators for hazardous wastes in Finland. Since 1984, when the first kiln started, the company has been developing the technology with Outokumpu Ecoenergy, a Finnish engineering firm. As a result of this co-operation, a second kiln was introduced in 1991.

The most significant difference compared to similar kilns, is the extremely high temperature used in a rotary kiln, 1.300 - 1.400 ˚ C (2.400 - 2.600 F) This results in several advantages: high combustion efficiency, slag vitrification and increased capacity. Refractory lining will normally be damaged when using increased temperature. This problem has been solved by installing a special cooling system around the kiln.

Another common source of disturbance in rotary kiln technology is inhomogeneity of waste feed. A shredder and feed homogenizer have been designed which allow for more solid organic material to be fed, as well as decreasing the need for auxiliary fuel (waste oil or solvents).

2. INCINERATION LINE II

Ekokem designed a new rotary kiln incinerator which has been in operation since April 1991. An activated carbon injection system with additional bag filter was installed in October 1992. Compared to the original incinerator this system has several new features which give better result in combustion, gas cleaning and solid material pretreatment.

The capacity of the new line is 25.000 tonnes/a of organic waste and 6.000 tonnes/a of waste water. The net value of the investment was approximately 30 MUSD.

Ekokem has created its own philosophy in respect of hazardous waste combustion, where:

- the temperature in the rotary kiln is extremely high (1.300 - 1.400 °C)
- waste is homogenized and fed uniformly to the kiln
- after burning chamber is designed to ensure complete mixing and sufficient retention time for the whole gas stream
- the gas cleaning technology is the best available to reach the extremely tight emission limits

The advantages of this method of operation are:

- to reach the highest possible combustion efficiency
- to have an insoluble vitreous slag resulting in lower costs of landfilling or utilization
- increased capacity of the kiln

2.1 The Kiln Cooling System

If a temperature of < 1.100 °C is applied in the kiln, the after burning chamber must be operated at a higher temperature using auxiliary fuel. These are normal operational conditions in most European incinerators. There are some disadvantages, such as, lower combustion efficiency in the kiln and the fact that some types of waste (for example PCB) cannot be incinerated efficiently. Also heavy metals will not evaporate from the slag. Moreover, the slag is not melted and a protective layer of molten slag is not formed.

Ekokem operates both kilns at 1.300 – 1.400 °C temperature made possible only by a special cooling system.

External cooling of the kiln has been in succesful operation at Ekokem since October 1987. The improvements have been the following:

- Lifetime of refractory lining has more than doubled
- Capacity has increased 10 – 20 % on an annual basis
- Operating hours per year have increased
- The thickness of refractory lining can be reduced
- PCB waste can be incinerated due to increased temperature
- Heavy metals such as lead are totally evaporated from the slag
- Steel barrels are oxidized and dissolved
- Thermal stress on refractory lining and shell is reduced

The main objective of the cooling system is to keep all parts of the kiln shell at a constant temperature. Cooling must also be maintained during power failures. Inside the refractory lining, the formation of a layer of solid and high viscous slag takes place, which protects the lining from erosion and corrosion.

An important factor of the control of kiln operation is the understanding of molten slag chemistry. The viscosity and other properties can be influenced by proper feed and additives thereby avoiding disturbances caused by uncontrolled slag properties.

The quality of slag is shown in Table 1. The low solubility means that the material is not classified hazardous or toxic and it can be used in construction of roads, etc.

2.2 Pre–Treatment and Feed to the Kiln

Pre–treatment starts with the reception of waste and a rigid laboratory control on incoming materials. Waste oil and oily wastes should be treated to separate oil, water, paste and solid fractions and then individually fed to the incinerator. Chlorinated solvents should be separated from normal solvents.

Barrels form the most difficult handling problem in the pre–treatment area. The main difficulties are the disposal of empty barrels and barrels that cannot be emptied because of solidified content or risk of polymerization of the contents.

The trend is towards a highly automated barrel handling system which meets the requirements of the working environment and fire safety regulations. Handling includes a shredder system for the steel barrels which allows the steel scrap to be added to the bulk material.

The contents of the barrel are separated into different fractions to be fed separately to the incineration line. In the future, feeding of complete barrels will virtually be unknown, with the probable exception of infectious waste and some special wastes.

The bulk material is usually fed to the incinerator with a grab crane, typically in 1 ton batches. Even though the bulk material is well blended, the batch introduced to the kiln will cause variations in the oxygen content of the flue gases and consequently problems in CO emissions. A solid waste feed homogenizer has been installed resulting in stable combustion and a better control of emissions. Table 2 shows emission standards for both the Ekokem kilns.

The patented cooling system has already been adapted to several European rotary kilns.

Table 1

Slag Suitability After EPA-Test

EPA limits mg/l		Ekokem slag mg/l
Ba	100	0,2 – 0,3
As	5	0,005 – 0,018
Cd	1	0,001 – 0,004
Cr	5	0,001 – 0,004
Pb	5	0,01 – 0,03
Se	1	< 0,01
Ag	5	< 0,002
Hg	0,2	< 0,0005

Table 2

Limit Values for Incineration Lines 1 & 2 (dry, 12 % O_2)

		Incinerator 1	Incinerator 2
Dust	mg/m^3	30	10
HCl	mg/m^3	50	20
HF	mg/m^3	2	2
CO	mg/m^3	70	70
$C_x H_y$	mg/m^3	20	20
Hg	$\mu g/m^3$	50	50 (1)
TCDD-ekv	ng/m^3	1,0	1,0 (2)

(1) Obligation to study the possibility to reach value 30 $\mu g/m^3$

(2) Obligation to study the possibility to reach value 0,1 ng/m^3

EVALUATION OF GROUTING TECHNOLOGY: DOE PERSPECTIVE

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ABSTRACT The US Department of Energy (DOE) must make a variety of decisions within their environmental management (EM) program regarding (1) development and transfer of improved EM technologies and (2) application of the optimum EM technologies at specific sites. To assist in this decision-making process, a methodology has been developed for evaluating EM technologies in terms of (1) the degree to which they would accomplish specific EM activities and satisfy specific requirements, under various conditions, if they were available, and (2) the costs and risks (if any) associated with their becoming available. For demonstration purposes, this methodology was applied to (1) the preliminary evaluation of the generic application of a Ukrainian clay-based grouting technology to the DOE complex, and (2) the detailed evaluation of the specific application of a French silicon-based grouting technology to DOE's underground storage tanks at Hanford, Washington. Based on these evaluations, justifiable recommendations regarding further development and transfer of these technologies were made.

INTRODUCTION

The US Department of Energy (DOE) manages an extensive complex of facilities throughout the United States which are concerned with radioactive and hazardous wastes. DOE is responsible for environmental management (EM) of these facilities. In this role, they must make significant decisions regarding (1) application of the optimum available EM technologies at each site, and (2) improvements in available EM technologies. The potential consequences of poor decisions in these areas include unnecessary hazards (short- and long-term), expense, and/or delays, as well as possibly inadequate performance. Hence, a methodology is needed to help ensure that appropriate decisions are made. As discussed herein, this methodology consists essentially of evaluating EM technologies with respect to specific DOE needs, both for individual facilities and the complex as a whole.

The context of the methodology within the DOE EM program is first discussed. The application of the methodology to the evaluation of two grouting technologies is then presented.

DOE EM PROGRAM

The US Department of Energy (DOE) is responsible for environmental management (EM), consisting of waste management (WM) and environmental restoration (ER), at a number of facilities throughout the US.

EM Activities - The various types of EM activities have been identified through a simple EM system process chart, as illustrated in Figure 1. Although broadly defined, this chart is believed to represent a comprehensive set of EM activities (DuCharme et al, 1992a):

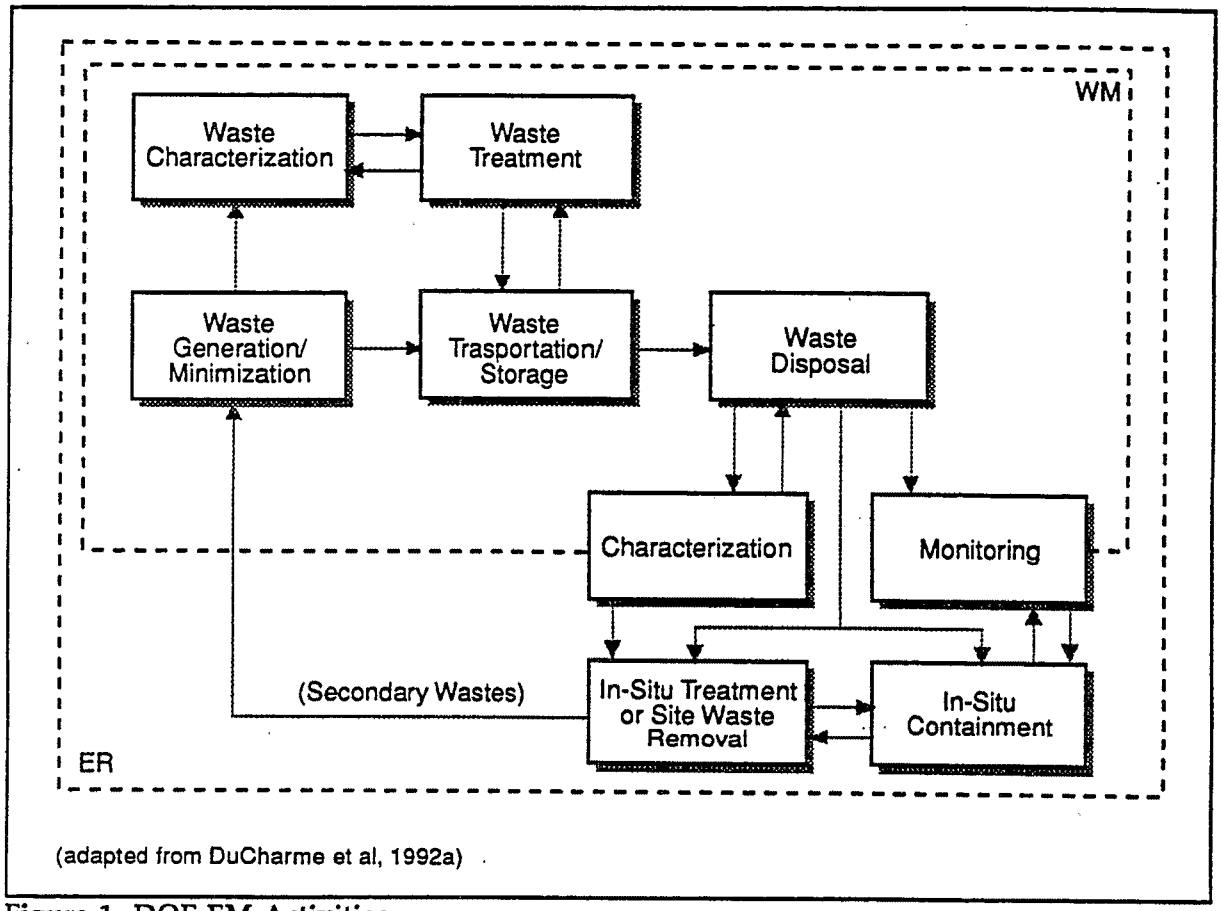

Figure 1 DOE EM Activities

- **Waste Management (WM)** - An initial waste stream is generated through various processes. During generation, the amount of waste can be minimized through specific procedures. The waste should be characterized and can possibly be treated, where treatment may include further waste minimization and require additional post-treatment characterization. Such treatment may be conducted off-site, thus requiring transportation of the waste to the treatment facility. Whether treated or not, the waste must ultimately be transported to a disposal facility. The disposal facility, in turn, must be characterized prior to disposal and monitored after disposal.

- **Environmental Restoration (ER)** - If an operating disposal facility is found by monitoring to not perform adequately, or if an existing contaminated site (e.g., a closed disposal "facility") is found by characterization to not perform adequately, it can be: (1) remediated (cleaned up) to various degrees by in situ treatment or by removal of the contaminated

materials; and/or (2) mitigated (contained). Containment may: (1) precede remediation, either as a stop gap measure until remediation can be conducted or to prevent further contamination during the remediation process; or (2) follow remediation if the remediation process is incomplete and residual contamination remains on-site. If mitigated, then monitoring must continue to ensure adequate performance, with subsequent additional mitigation or remediation possible. If remediated, a secondary waste stream is generated, which must be characterized, treated, transported and disposed of in similar ways as the primary waste stream.

EM Conditions - EM activities will be conducted under specific conditions at each site. These conditions have been broadly but comprehensively categorized as follows (DuCharme et al, 1992a):

- Waste
  - specific types of waste (i.e., contaminants);
  - amount of each type (e.g., in terms of an operating period and rate of newly generated wastes, and/or in terms of current concentrations and volumes of previously disposed wastes); and
  - waste form (e.g., dissolved in groundwater, packaged in barrels, vitrified, etc.).

- Site (see Figure 2)
  - waste environment;
  - transport characteristics from the waste to potential receptors, which in turn are a function of the engineered barriers, the geology, the geohydrology, and the climate; and
  - potential receptors, including distance and demographics.

- Waste-site relationship (configuration, Figure 2)
  - release rates; and
  - pathways.

- Infrastructure (framework within which the waste/site system operates)
  - regulatory;
  - institutional; and
  - public.

EM Program Requirements - EM activities must be conducted within specific requirements:

- Technical - Functional requirements (eg, minimum capacity) may be established for specific activities (eg, waste disposal). Similarly, performance requirements (eg, maximum allowable dose) may be established for other activities (eg, in situ containment). In addition, cost and schedule, as well as safety, will generally be of concern, and may be mandated (eg, by negotiated agreement).

- Institutional - As policy, there will be a minimum acceptable level of confidence, either implied or stated, that the technical requirements will be satisfied. This requires high confidence that the proposed approach for conducting the EM activities will work as anticipated, which in turn suggests high confidence that the technologies involved will

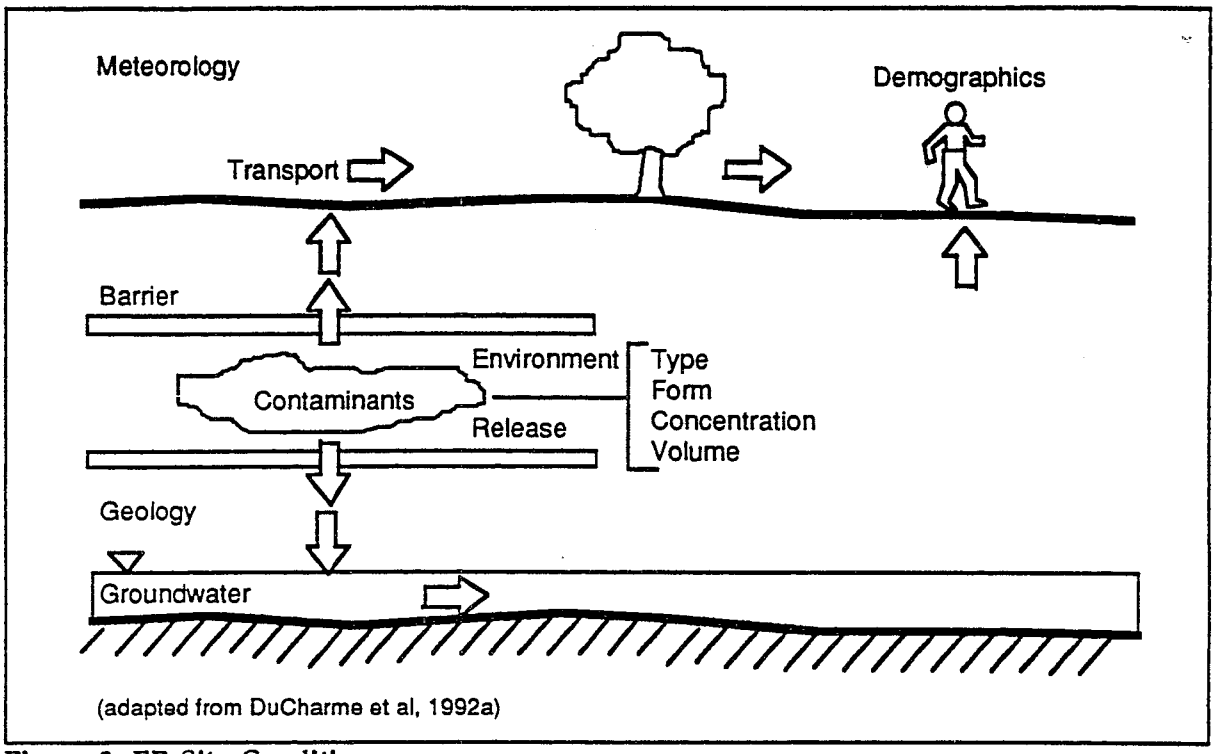

Figure 2 ER Site Conditions

be available when needed and moreover will be accepted (eg, by the regulators and the public).

<u>EM Program Decisions</u> - A wide range of technologies are currently available for conducting the various EM activities and satisfying the specified requirements. Improvements on these technologies, as well as new innovative technologies, can be developed and/or transferred (if necessary), and thus become available in the future. Significant decisions must be made by DOE regarding: (1) programs for developing and/or transferring EM technologies; and (2) technologies for conducting EM activities at specific sites.

<u>Technology Attributes</u> - The various technologies can accomplish specific activities and satisfy specific requirements to various degrees, depending on the specific conditions involved. For example, advanced incineration can be used to treat primary organic wastes, thereby reducing the volume for disposal, while meeting air emission requirements. Each technology has a specific set of relevant "attributes", which include:

- effectiveness in satisfying specific activities/requirements under various conditions;
- application cost (fixed and variable);
- rate of application;
- hazards associated with its application; and
- acceptability (ie, to regulatory agencies, institutions, public, etc.) of application.

If the technology is not yet available, then the cost and time associated with it becoming available (eg, through research and development, and/or transfer), and the likelihood of it ever becoming

available, must also be considered. The likelihood of future availability is a function of the current status of development/transfer, the plans for completing development/transfer, and potential problems associated with development/transfer.

Evaluation Process - Decisions on technologies for site specific applications and for development/transfer programs can be made based on comparative evaluations of their attributes with those of "base case" technologies, in conjunction with tradeoffs made among the attributes. For example, one technology might be preferred over another even though it is less effective because it can be applied faster and cheaper. As illustrated in Figure 3, the evaluation approach consists of first screening the technologies with respect to applicability to specified EM activities/conditions. The potentially applicable technologies are then comparatively evaluated against Base Case alternatives in terms of their relative effectiveness in solving the specific EM problems, and the costs, schedule, safety issues and acceptability issues associated with their application, assuming that they are available (ie, fully developed and transferred). These comparative evaluations can then be combined with value judgements regarding tradeoffs among the various factors to establish a rating for the specific application of that technology. If the application rating is positive, the technology (once available) would be preferred to the Base Case alternative. If the application rating is not positive, the technology would not be preferred to the Base Case alternative, regardless of availability, so that any remaining development/transfer should not be carried out. However, if the technology is preferred over the Base Case alternative but is not yet available, then the likelihood of successfully completing development and transfer of the technology, and the associated cost and schedule, must also be considered. These evaluations can then be combined with the application rating, the priority of that application, and value judgements regarding tradeoffs among the various factors to establish an overall rating for the development, transfer, and application of the technology. In this evaluation, the cost of making such a technology available should not necessarily be borne by any one site, but spread among all those sites where it would be used. Based on the overall rating, a decision would be made whether to continue development and transfer of a specific technology.

International Program - Within EM and complementary to other programs in accomplishing DOE's EM mission, DOE instituted the International Program Division (IPD), previously called International Technology Exchange Program (ITEP), with the following primary goals:

- **Import** - Transfer foreign EM technologies which are more effective ("better"), cheaper, faster, safer or more acceptable to apply to DOE's EM activities/conditions/requirements than those technologies currently available in the US.

- **Export** - Identify foreign EM needs (ie, specific site activities, with associated conditions and requirements) for which currently available US technologies are more effective ("better"), cheaper, faster, safer or more acceptable to apply than those foreign technologies currently available (ie, market opportunities).

Within IPD/ITEP, a methodology has been developed for definitively evaluating candidate technologies, consistent with the above evaluation process (DuCharme et al, 1992a). Such evaluations are done at two levels: (1) preliminary evaluations with respect to generic, system-wide applications for screening a large number of candidates for potential development (if necessary) and transfer; and (2) detailed evaluations with respect to site-specific applications.

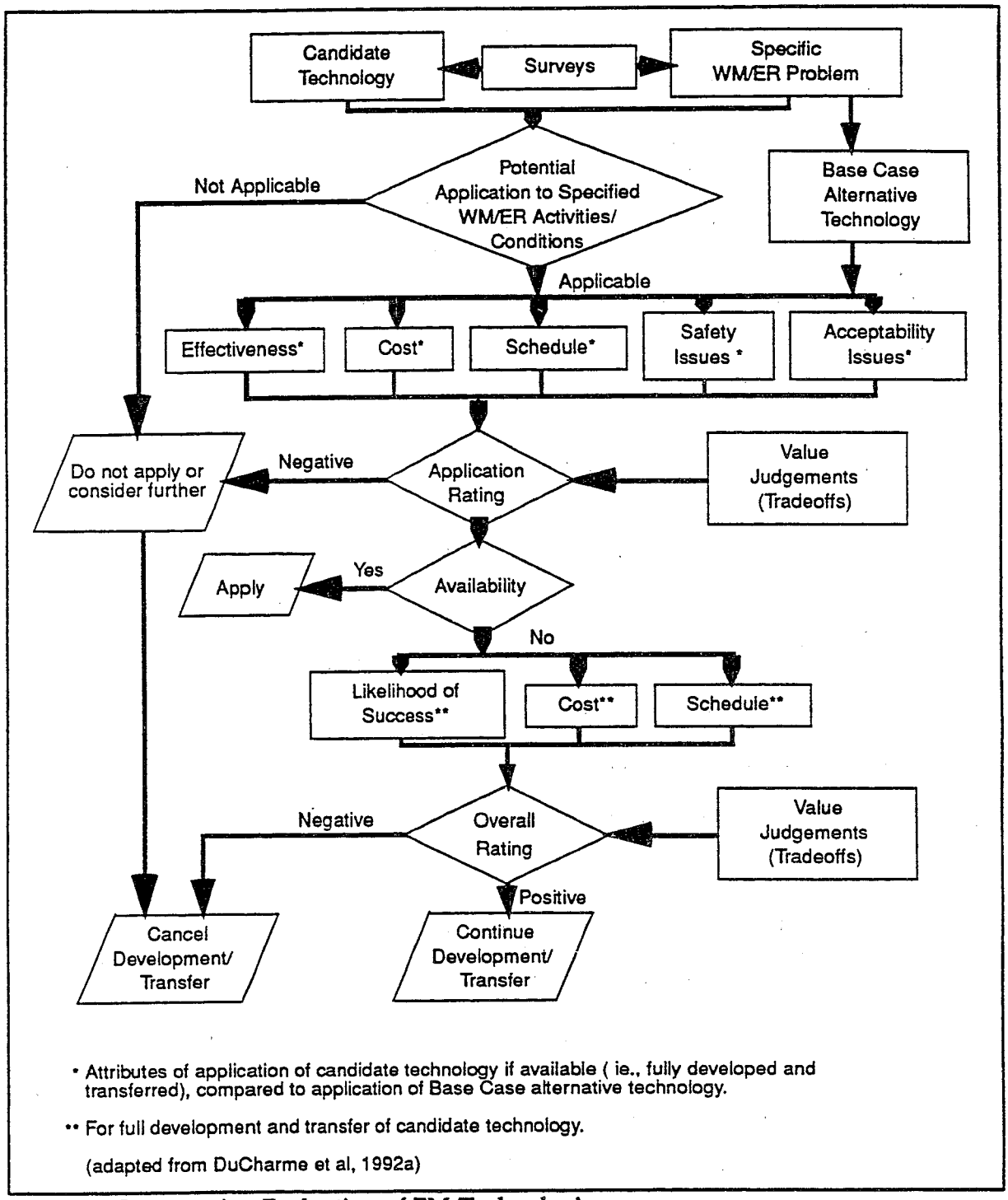

Figure 3 Comparative Evaluation of EM Technologies

EnviroTRADE - Ultimately, the site-specific evaluations will be accomplished through a computerized relational data base (ie, EnviroTRADE) which is being developed within IPD/ITEP

by Sandia National Laboratories for DOE (Harrington and Harlan, 1992). EnviroTRADE will consist of the following compatible modules:

- World-wide EM needs data base, describing the relevant conditions and requirements for various EM activities at sites around the world (including the responsible parties), categorized by country;

- World-wide EM technology data base, describing the relevant attributes of technologies (including application parameters, availability and contacts); and

- Decision module for matching EM technologies and EM needs, either to identify and rank appropriate technologies for user-specified needs, or to locate potential applications (ie, markets) for user-specified technologies.

GROUTING TECHNOLOGY EVALUATION

In order to demonstrate the use of the methodology for evaluating EM technologies and thereby assisting DOE to make rational and informed decisions regarding (1) development and transfer of foreign technologies and (2) application of technologies at specific sites, similar but different technologies have been evaluated at various levels:

- The Ukrainian clay-based grouting technology is adequately described in other papers (Spickelmier, 1992; Verma, 1992). Its attributes are briefly summarized, and then the technology is evaluated in a preliminary fashion for generic applications to determine whether its development and transfer should continue.

- A French silicon-based gel grouting technology is described. It is evaluated in a detailed fashion with respect to application at a specific site, ie, to provide containment of the single shell underground tank wastes at Hanford, Washington, to determine whether it should be considered further for this application.

Grouting in general can be used to create a low permeability barrier for in situ containment, eg, prior to remediation as a stop gap measure, during remediation to prevent transport of mobilized wastes, or for the long-term. Grouting can also be used to redirect and concentrate a contaminant plume for remediation. The resulting seals are applicable to containment of various contaminants from basins/ponds, storage tanks, trenches/cribs, containerized wastes, and leaks/spills.

UKRAINIAN CLAY-BASED GROUTING TECHNOLOGY

A specific clay-based grout which may provide improved containment has been identified through ITEP (DuCharme et al, 1992a and b). The clay-based grout was developed by the Ukrainian company SPETSTAMPONAZHGEOLOGIA (STG), which translates to "grouting and geological enterprise". This grouting technology can and has been applied to a variety of problems, especially to provide relatively impermeable barriers (eg, during construction of shafts) in fractured or karstic water-bearing rocks. Of particular interest is its potential application in

providing a barrier to contain hazardous wastes at similar sites managed by DOE.

Properties - The clay-based grout consists of the following components:

- 89% clay slurry at densities up to 87 pcf, which in turn consists of kaolin (or possibly illite if kaolin is unavailable) mixed with water;
- less than 10% cement or processed tailings; and
- 1 to 2% of structure-forming reagents, such as sodium silicate.

The resulting grout is reported to have the following beneficial properties:

- chemically stable in a variety of conditions;
- long-term pliability so that small ground displacements can be accommodated without compromising barrier characteristics;
- low shrinkage and erodability so that barrier characteristics are not compromised by changes in groundwater conditions;
- non-toxic; and
- low cost relative to other chemical- or cement-based grouts.

Evaluation - The clay-based grout is very viscous, and thus can only be applied effectively in "open" geologic systems, ie, fractured or karstic rock. In such cases, compared to other chemical- or cement-based grouts, application of the clay-based grout is believed to have the following attributes, based on preliminary subjective evaluations:

- more effective because it is more pliable and long-lasting;
- cheaper;
- similar rate of application;
- similar safety issues; and
- more acceptable (once transferred and demonstrated) due to its better performance and use of natural, geologic, non-toxic materials.

Due to a lack of experience with this technology in the US, however, there are significant uncertainties in these attributes, especially in the range of site and waste conditions for which the grout would be effective and the duration of such effectiveness. Such issues must be adequately resolved, eg, by demonstration testing in the US, before development of the technology can be considered complete and it can be used for DOE projects. Such a demonstration has been proposed, and has been estimated to take on the order of two years to complete. In addition to completing technical development, the technology must also be transferred to the US before it is available for application. This has been at least partially effected by STG forming a joint venture with Morrison-Knudsen to market the technology in the US.

Recommendation - Based on the preliminary evaluation of the clay-based grouting technology, it appears that it should be considered further, once it becomes available, where containment in "open" geologic systems is needed at DOE sites.

FRENCH SILICON-BASED GROUTING TECHNOLOGY

A specific inorganic, silicon-based grout which may provide improved containment has also been identified through ITEP (DuCharme et al, 1992a and b). The silicon-based grout ("KLEBOGEL") was developed by the French company Société Française Hoecsht (SFH). This grouting

technology has been applied to a variety of problems, primarily to provide additional strength for granular soils during excavation, but it has reportedly also been used successfully in oil reservoir secondary recovery to plug a permeable zone around an oil reservoir, under extreme conditions (60-80°C and 1000m depth). It is now being considered as a means to provide a barrier to contain hazardous wastes around underground storage tanks (USTs) at Hanford Washington for Westinghouse Hanford Company (WHC), a DOE contractor.

Evaluation Process - The detailed evaluation of the silicon-based grout for this specific application involved significant interactions between the evaluators and the technology owner (ie, SFH), and between the evaluators and the potential users (ie, DOE/WHC). As illustrated in Figure 4, this was accomplished through the following steps:

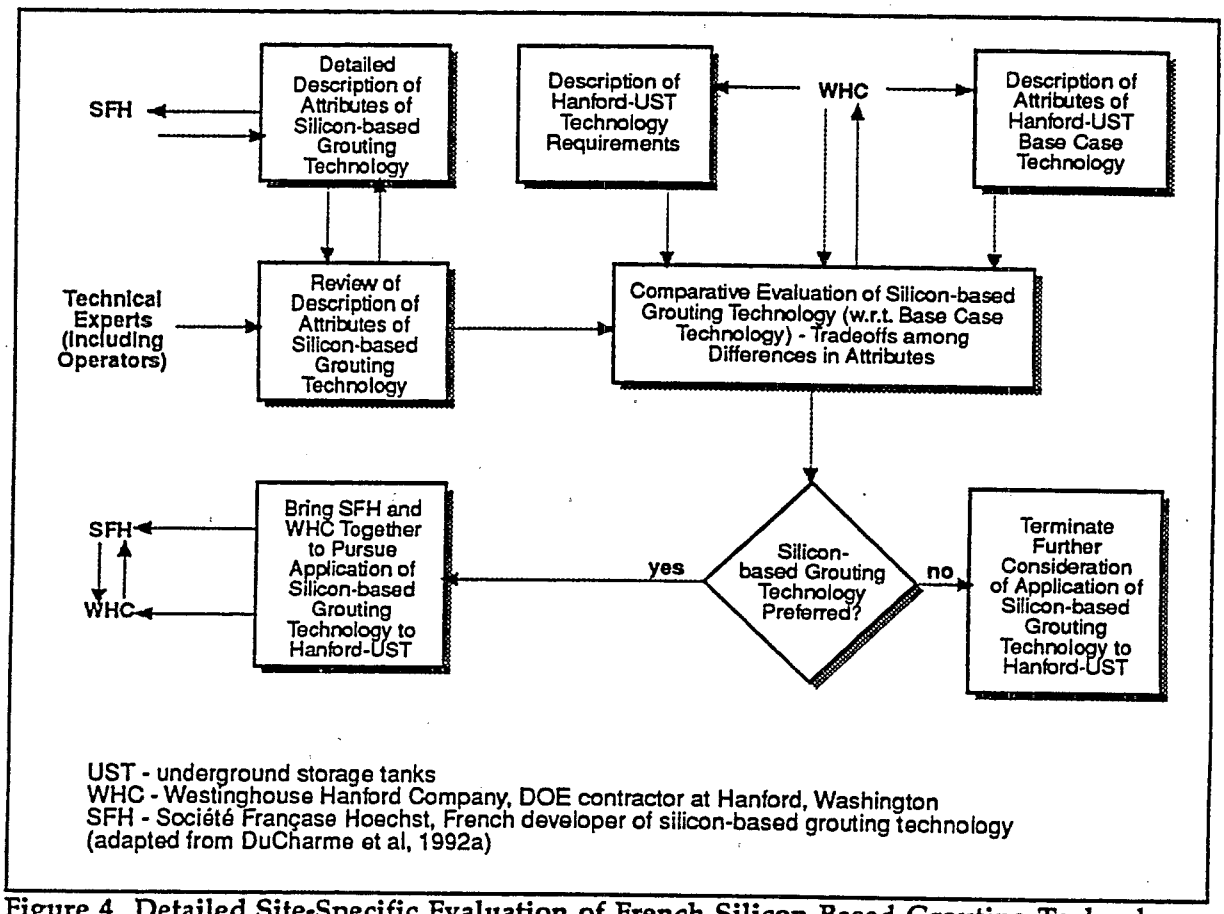

Figure 4 Detailed Site-Specific Evaluation of French Silicon-Based Grouting Technology

1. The list of relevant technology attributes was sent to the technology developers (ie, SFH) for them to fill out.

2. Technical experts (including operators) reviewed the foreign participants' description and assessment of their technology's attributes. These reviews were then resolved with the foreign participants.

3. The end users (ie, WHC) identified and described (in similar terms) their specific technology requirements for the USTs, and the domestic base case for comparison.

4. A quantitative comparative evaluation (i.e., differences in attributes) of the silicon-based grouting technology with respect to the base case technology for the Hanford USTs was conducted, involving WHC in determining appropriate tradeoffs among the attributes.

5. If the evaluation of the silicon-based grouting technology is favorable (ie, it is potentially better, safer, cheaper, faster, and/or more acceptable compared to the base case technology), then SFH will be brought together with WHC to pursue application of their technology to the Hanford USTs. Otherwise, application of the silicon-based grouting technology would not be pursued further for the Hanford USTs, although it may still be applicable for USTs at other DOE sites or for other facilities (eg, cribs, trenches, or ponds) at various sites (including Hanford).

Generic Properties - The silicon-based grout consists of various portions of sodium silicate, "silica sol" (a dispersive suspension of very fine silica particles), "glyfix" (acid-based hardener) and tap water. They produce an amorphous, silicon-dioxide gel, with about 5-10% solids. The recipe is proprietary and confidential, and can be varied on-site to suit observed conditions. As demonstrated in the laboratory, the resulting grout has low permeability (ie, less than 10^{-9} m/s), is very flexible, has low shrinkage (even under high temperatures) and is chemically stable, as long as it is not allowed to dry out. The materials are non-toxic and EPA/NEPA approved (although for other purposes). Prior to setting, the grout has very low viscosity (ie, 5 cPoise, similar to water), which allows it to be injected in relatively low permeability ground (including very fine sands); conceptually, grouting in highly permeable ground may require a first stage grouting using fast sets or more coarse, viscous types of grout (eg, bentonite). The viscosity increases rapidly at setting (to an amorphous gel). The setting time can be controlled over a wide range (from minutes up to 2 days), in order to achieve proper penetration during injection, by changing the mixture. The cost of the grout material is a function of the mixture, which in turn is determined by the desired setting time. A fast set mix (up to 2 hours) does not include silica sol and costs about $1/gal, whereas a slow set mix (up to 2 days) includes silica sol and costs about $2/gal.

Generic Procedures - Access and equipment for drilling boreholes, and mixing and injecting grout on site are necessary. Boreholes are drilled around and possibly below the site at an appropriate spacing. These boreholes must be sufficiently stable and porous to allow subsequent grout injection, and spaced closely enough to ensure adequate overlap. The thickness and continuity of the barrier will be a function of borehole spacing and grout penetration characteristics. For lateral containment, the boreholes are vertical whereas for vertical containment (eg, below tanks), the boreholes must be inclined or even horizontal. Such inclined or horizontal boreholes are typically much more difficult to drill and especially stabilize. A promising technique for drilling horizontal boreholes below the site is "micro-tunnelling". It should be noted that drilling will produce secondary wastes (contaminated soil) which must be disposed of.

The grout is mixed per specification (proprietary and confidential) in a standard batch plant, and injected into specific zones of the boreholes. The penetration distance of the grout into the ground around a borehole is a function primarily of the following:

- **Grout Viscosity** - As previously noted, the viscosity of the grout is initially very low until it sets, at which point it increases rapidly and penetration effectively ceases; hence, the penetration distance is a function of the setting time, which can be varied over a wide range. Injection conditions (eg, increased temperature, dissolved organics, aluminates and salt content) may modify the setting time.

- **Ground Permeability** - The ground must be sufficiently permeable (ie, more permeable than clay) to allow adequate grout penetration at injection pressures below those which cause hydraulic fracturing, and yet not too permeable (ie, less permeable than gravel) which would cause excessive grout loss. If the ground is too permeable (ie, $>10^{-3}$m/s), then a first stage of grouting with bentonite cement or clay suspension, for example, may be necessary. The permeability of the ground will be a function of a variety of factors, including the moisture content in the vadose zone. Variability in soil or moisture conditions can cause preferential penetration, resulting in incomplete barriers. Similarly, injection in the saturated zone requires water displacement, which may be incomplete, and may result in dilution of the grout.

- **Injection Pressure** - The injection pressure should be maintained below that which would cause hydraulic fracturing.

The general penetration characteristics of the grout are known to be relatively good from "soil consolidation" applications, although uniform penetration is not as important an issue in that case. It is anticipated that grout penetration of several meters can be obtained with an appropriate mix.

In order to be effective, the grouted zone must be continuous across the potential contaminant transport paths and maintain a low permeability (over the required time frame). Hence, the resulting barrier must be verified and possibly monitored with time. During injection, this might be done by monitoring injection pressures and volumes. After injection, this might be done by geophysical testing, eg:

- by ground penetrating radar in the grout holes or in nearby monitoring wells; and/or
- by DC resistivity surveys using sensors embedded in the grout holes
  - for cross-hole analyses in the plane of the barrier, and
  - for borehole-to-surface analyses across the barrier at various locations, although this might not be appropriate for horizontal barriers below a site.

<u>Generic Issues</u> - Grouting can be used in ground which is sufficiently permeable to achieve adequate penetration (eg, silty fine sands through coarse sands), although it may be difficult to drill stable open holes in such ground especially if not vertical. However, the sealant may not be chemically compatible with all wastes or site conditions. Also, uniform penetration may be difficult to achieve in heterogeneous site conditions (ie, soils, moisture, stresses), although two-stage grouting might be effective. It may be difficult under any conditions to install and verify a continuous grouted zone over large areas, especially below a site.

The specific technical issues associated with the generic application of the silicon-based grouting technology to containment of hazardous wastes include:

- **Horizontal Drilling** - Although vertical drilling procedures are well established, horizontal drilling techniques (including micro-tunneling) have not been applied in contaminated granular soils. Hence, there is a question whether stable horizontal grout holes can be drilled. This is a generic grouting issue, rather than specific to the silicon-based grout.

- **Injection Conditions** - The penetration distance for specific site conditions is uncertain until field-tested. Similarly, the uniformity of penetration in heterogeneous conditions (ie, relating to soils, moisture/water, and stress) is also unknown. Again, these are generic grouting issues, rather than specific to the silicon-based grouting technology. However, the effects of various injection conditions (eg, presence of non-neutral pH, dissolved organics, aluminates and/or salts) on the gelation process have not yet been determined. Adverse injection conditions might be modified by neutralizing (eg, with other chemicals) or removing (eg, by sweeping with deionized water), although this might mobilize existing contamination.

- **Verification** - The geophysical methods required for verification have not yet been tested on the grout. Again, this is a generic grouting issue, rather than specific to the silicon-based grouting technology.

- **Long-term Integrity** - The potential chemical reactions of the grout with various wastes and injection conditions have not yet been determined. Although the grout properties, both short-term (including setting times) and long-term, are anticipated to be good, based on general chemical stability considerations, they may be affected by the following: (1) interactions with the waste, either during injection or subsequently; (2) biodegradation in the vadose zone; (3) dehydration; and (4) other chemical-physical reactions (eg, diffusion). For example:
  - If the site is highly acidic or alkaline, the gelation process could be affected or the gel could dissolve over time.
  - Water soluble organics might diffuse into the gel, or be contained within the gel if not displaced during injection, and the gel might then be subject to biodegradation.
  - The gel might diffuse ionically into very low salt content water over time.
  - The gel might dissipate if evaporation is possible, although this is considered to be a very slow process at the depths of interest.
  - The characteristics might change with time if subject to hydrolysis (eg, due to radiation).
  - The gel may be affected by changes in temperature, although based on limited testing such effects (eg, shrinkage) are not significant for moderate changes in temperature and as long as evaporation does not occur. High temperatures affect the setting time, but apparently not the other properties.
  - Cations may react with the silicates to form salts, although if the salts are formed on the outer boundary only, they may be beneficial and inhibit any dissolution of the gel with time.
  - The presence of aluminates, caustic soda, sodium hydroxide, or potassium oxide, for example, during injection may have significant negative effects.

<u>Availability</u> - The issues identified above must be adequately resolved before development can be considered complete.

SFH, which is a subsidiary of Hoechst AG (Germany), has developed the silicon-based grout mixture (KLEBOGEL) and considers it to be proprietary and confidential. Hoechst AG also has an American subsidiary, Hoechst Celanese Co. in Charlotte NC, which is thus affiliated with SFH. SFH has expressed the desire to work with DOE. Hence, transfer of the technology to the US should pose few problems.

No special equipment or expertise is needed for installation, so that a competitive environment exists for contractor services. Special contractors may be needed, however, for drilling horizontal grout holes and for geophysical verification.

Generic Alternatives - The alternative to KLEBOGEL is other clay-, paraffin-, chemical- or cement-based grouts. Depending on the specific grout being compared, KLEBOGEL is generally: more effective in reducing permeability (due to its low viscosity and extremely small particle size, which allows greater penetration) although it may be less stable over the long-term; more costly; possibly less acceptable, although it is NEPA-approved, due to long-term integrity issues; and equally fast and safe to apply.

Hanford USTs - The DOE has 334 USTs for storing radioactive and hazardous wastes at their operations across the US, with 149 single shell tanks (SSTs) and 28 double shell tanks at Hanford. A total of 79 of these tanks, 66 of which are located at Hanford, are either known or are assumed to leak, thereby contaminating the soil and groundwater. In addition to the USTs, other facilities (eg, cribs, piping and trenches), either at Hanford or elsewhere (eg, INEL), experience similar problems.

The Hanford SSTs are single shell reinforced concrete with carbon steel liners, which are of various dimensions and buried at shallow depth. Some of them have corroded and otherwise deteriorated over the years to the point that they are now leaking their contents into the subsurface. The contents are liquid mixed wastes, which were relatively well known at the time of placement (due to controlled procedures), with the possible exception of some additional undocumented solvents. However, over time, (1) the supernates were pumped off, but not characterized, so that some wastes may have been selectively removed, (2) water was added (sometimes many 10,000s of gallons) when the contents leaked, possibly removing the more soluble wastes, and (3) chemical reactions have occurred, changing the remaining wastes. For example, several tanks are of special concern: one tank has high heat, so that 8000-10000 gallons of water are added per month for cooling, which presumably evaporates; one tank experiences hydrogen gas buildup, which vents (or "burps"); and another gas has relatively high concentrations of ferrocyanide which (if high enough) could be explosive.

The subsurface consists primarily of more than 100 feet of permeable soils (sands and gravels with some fines), overlying fractured basalt. The soil around and to some depth (about 8 feet) below the tanks was excavated and reworked during tank construction. The groundwater is relatively deep (about 200 feet), with a significant gradient towards the Columbia River several miles away. Near the tanks, the pH is generally somewhat alkaline (pH of 8-10), with elevated temperatures (up to 60-75°C). Below leaking tanks, there is a vertical plume of contaminants, extending to various depths depending on the extent of leakage but generally contained within the vadose zone.

Requirements for Hanford USTs - The Hanford USTs are to be totally remediated according to a specific schedule, per the Hanford Federal Facility Agreement and Consent Order (ie, the "Tri-Party Agreement - TPA"). In the TPA, the DOE has committed to a demonstration of a full-scale closure method for the USTs by 2004. This will require the following activities: (1) characterization of waste, tanks, and the site; (2) treatment and disposal, either insitu or retrieval; and (3) site closure and monitoring, depending on whether any wastes remain in-place. Options for insitu treatment/disposal consist of stabilization, grouting or in situ vitrification, all of which would result in residual wastes in-place when closed. Options for retrieval and treatment/disposal include mechanical excavation or hydraulic sluicing followed by various treatment/disposal options, which may result in mobilization of wastes during removal and some residual wastes in-place when closed. Waste separation techniques could be implemented as part of treatment, to reduce the amount of wastes to be disposed of.

Functional requirements for remediation are currently being developed (Rouse et al, 1992; Boomer et al, 1990). The primary performance requirements for the technology include occupational safety (e.g., dose), public safety (e.g., dose), and groundwater protection (e.g., concentrations). The long-term performance requirements are currently being considered for a period of 300-1000 years after closure.

Base Case Technology for Hanford USTs - Consistent with the specified requirements, the reference base case technology is as follows:

- Removal of the wastes within the tanks by hydraulic sluicing followed by treatment and disposal. Treatment and disposal consist of mixing the wastes with cementitious grout to stabilize it, and placing the grout in vaults in the 200 Area.

- No subsurface containment is currently planned at the tank sites, because all of the waste is supposed to be removed. However, following treatment/disposal, the site would be closed per RCRA requirements (ie, an engineered cover), unless complete remediation has been effected and verified.

Potential Application of Technology to Hanford USTs - The candidate technology, as described above, can be applied to help satisfy the Hanford UST requirements by enhancing specific treatment/disposal options, as well as closure. Specifically, the silicon-based grouting technology can be applied to the following areas:

- **Retrieval and Treatment/Disposal** - Create barrier below site to reduce leakage into the groundwater to acceptable levels, during retrieval (especially hydraulically). Such a barrier is an additional feature, since none is currently contemplated, and might make the hydraulic retrieval option much more attractive. Such a barrier could incorporate a sump to collect and remove any contaminants.

- **In Situ Treatment/Disposal Options** - Create barrier below site to reduce leakage into the groundwater to acceptable levels, both during and after treatment. During treatment, such a barrier is an additional feature, since none is currently contemplated. Similar to above, such a barrier could incorporate a sump to collect and remove any contaminants.

- Site Closure - If residual wastes remain in-place from retrieval and treatment/disposal, then the site must be closed as a landfill. Similarly, if the in situ treatment/disposal option is adopted, then the site must be closed as a landfill, assuming that residual wastes will remain in-place. In either case, a barrier below the site will supplement a cover to reduce leakage into the groundwater to acceptable levels. Conversely, if no residual wastes remain in-place (above the potential subsurface barrier), then the subsurface barrier would not contribute to meeting system performance requirements, and would be unnecessary.

Concerns with the base case (or any other) technology include increased waste volume (including secondary waste such as drill cuttings or leachate) and increased mobilization of waste (eg, due to drilling fluid), as well as other aspects of short- and long-term performance.

Application Costs - The primary cost components for application of the silicon-based grouting technology are the material costs and the drilling costs. These and the total costs have been estimated for a bowl-shaped subsurface barrier with a nominal diameter of 75 feet and a nominal depth of 50 feet (ie, similar to a barrier surrounding a typical individual tank at Hanford), as illustrated in Figure 5, as a function of borehole spacing and grout type (ie, fast or slow set), based on the following assumptions:

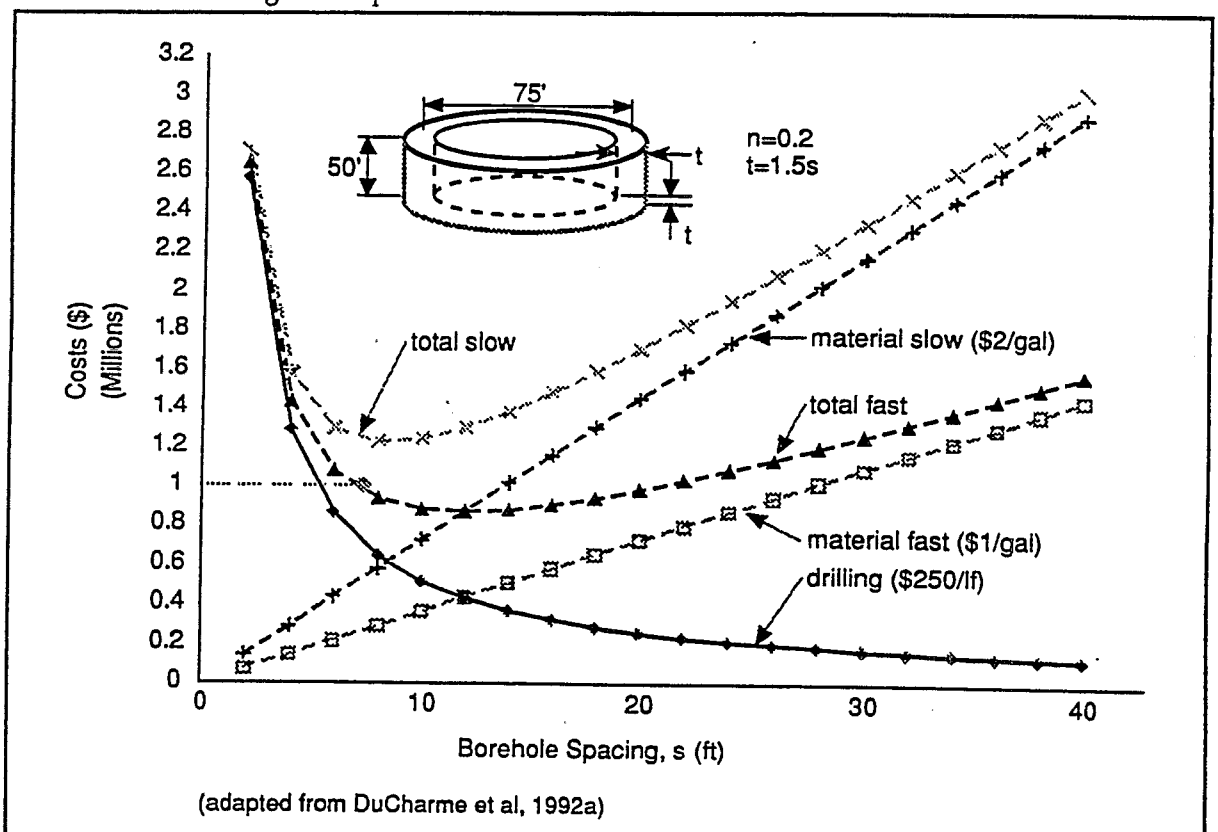

Figure 5 Costs of French Silicon-Based Grouting Technology Applied to Hanford USTs

- average soil porosity of 0.2;
- grouting overlap of 33% with the grouted zone on either side (along the plane of the barrier, assuming a cylindrical grouted zone) in order to ensure barrier continuity, so that the average barrier thickness is about 1.5 times the borehole spacing;

- average drilling costs of $250/lf (although the typical costs for conventionally drilling vertical 2.5-4 inch diameter boreholes in contaminated material at Hanford is reported to currently be approximately $1500-2000 per linear foot, the total footage involved and the use of streamlined techniques should bring this cost down);
- total material costs of $1/gallon for fast set grout and $2/gallon for slow set grout; and
- all other costs (eg, for shipping, mixing, injecting and verifying) are insignificant.

The optimal (ie, lowest total cost) borehole spacings would thus be 12 and 8 feet for the fast and slow grouts, respectively. However, it must be recognized that there is a maximum allowable borehole spacing for each grout type, depending on its maximum penetration distance. For a 33% overlap between adjacent holes, the maximum spacing cannot exceed 6/5 of the maximum penetration distance, or the designed overlap will not be achieved and "windows" in the barrier may occur. The penetration distance, in turn, depends on the site conditions, but might reasonably be expected to be on the order of 6 and 12 feet for the fast and slow grout, respectively, in soils similar to those at the Hanford UST. Hence, although the optimal spacing (ie, 12 feet) for the fast grout cannot be achieved, the maximum possible spacing (ie, 7 feet) results in a lower total cost ($1.0 million vs. $1.2 million) than the achievable optimum spacing for the slow grout and would be preferred. Different optimal spacings and total costs would result for different maximum penetration distances.

Application Rate - The rate of application is determined primarily by the rate of drilling. The grout can generally be mixed and injected in less time than it takes to drill the borehole and the drill rig is not necessary for this procedure. Hence, the drill rig can be drilling boreholes continuously while previously completed boreholes are grouted. This process may be accelerated by using multiple drill rigs. The total time required to install the bowl-shaped subsurface barrier described above, with a borehole spacing of 7 feet, would be about 93 days if the combined rate of drilling is, for example, about 50 ft per day (ie, considering multiple shifts and multiple drill rigs) and if other activities (eg, drill rig setup) result in about a one day delay per borehole. This would increase to about 93 days if the borehole spacing decreased to 7 feet.

Safety of Application - There are no significant safety issues associated with the grout itself, since it is non-toxic and US EPA National Environmental Policy Act (NEPA) approved. However, there are the normal operating safety issues associated with drilling, mixing and injection operations, especially at a hazardous waste site, although these operations are generally carried out at the periphery of the site in order to contain the waste. The grout materials are nonflammable, inorganic, alkaline or acid chemicals, which after mixing are weakly alkaline.

Acceptability of Application - The technology is relatively cost-effective, ie, potentially improving site performance at reasonably low cost. In addition, the grout material will be US supplied, can be installed by local contractors, has been used previously in the US (for other purposes) and is EPA NEPA approved (although for other purposes). However, it may be difficult to construct and verify seal continuity over large areas and for long times. Hence, although such seals might be acceptable for short-term containment (eg, prior to or during remediation), they might not be acceptable as the sole barrier for long-term containment but only as a supplement to other

technologies; it should be noted that it may not be acceptable in any case to leave any waste in-place. Natural analogues and especially successful field demonstrations (eg, for the UST-ID) would make this technology more acceptable (from an institutional, regulatory, and public standpoint).

Comparative Evaluation of Technology Applied to Hanford USTs - The candidate technology has been evaluated with respect to the base case in terms of their likely differences in attributes. These assessed differences in attributes are very approximate, based on judgement, and should subsequently be analyzed in greater detail if found to be important. These assessments are summarized below and in Table 1:

Table 1 Comparison of Candidate Technology with the Base Case Technology

ATTRIBUTES	ESTIMATED FRACTIONAL IMPROVEMENT IN ATTRIBUTES RELATIVE TO BASE CASE	RELATIVE WEIGHTS		
		Performance	Cost	Acceptability
Performance	+0.6	0.6	0.1	0.1
Costs*	-0.2	0.1	0.6	0.1
Schedule*	-0.1	0.1	0.1	0.1
Safety*	-0.1	0.1	0.1	0.1
Acceptability	+0.4	0.1	0.1	0.6
Total Score		+0.36	-0.04	+0.26

* Includes additional costs associated with development and transfer, but does not include additional savings associated with decreased likelihood of subsequent remediation.

- **Performance** - Releases to groundwater and thereby dose to the public will be reduced significantly (about 60%) over the long term due to the presence of a subsurface barrier, even considering issues regarding installation and long-term integrity.

- **Costs** - Costs will be increased slightly (about 20%) due to activities associated with in situ grouting (including development and transfer costs), although the expected total life cycle costs would not increase as much due to a decreased likelihood of subsequent expensive remediation.

- **Schedule** - The schedule will be increased slightly (about 10%) due to the additional activities associated with in situ grouting (including development and transfer time), although the expected total life cycle schedule would not increase as much due to a decreased likelihood of subsequent remediation.

- **Safety** - Operating hazards will be increased slightly (about 10%) due to the additional activities associated with in situ grouting, although the expected total life cycle hazards would not increase as much due to a decreased likelihood of subsequent hazardous remediation activities.

- **Acceptability** - Acceptability will be increased moderately (about 40%) due to the improved long-term performance and decreased likelihood of subsequent remediation provided by the supplementary subsurface barrier.

Tradeoffs among the various attributes can be made by assessing and applying relative weights to the differences in attributes, and then summing the weighted differences (DuCharme et al, 1992a). The relative weights, however, will be a function of the absolute level of the attributes of the Base Case technology, so that a specific percentage improvement in an attribute will have greater weight if the initial value is larger. In the absence of such information for the Base Case Technology, several sets of relative weights have been used to cover the possible range in values, as summarized in Table 1:

- **Performance Dominated** - If improvement in performance is six times more important than improvement in any of the other factors, which are otherwise equally important, the total score for the candidate technology is +0.36, and it is thus strongly preferred.

- **Cost Dominated** - If improvement in cost is six times more important than improvement in any of the other factors, which are otherwise equally important, the total score for the candidate technology is -0.04, and it is thus slightly <u>not</u> preferred.

- **Acceptability Dominated** - If improvement in acceptability is six times more important than improvement in any of the other factors, which are otherwise equally important, the total score for the candidate technology is +0.26, and it is thus moderately preferred.

Hence, based on the assessed differences in attributes between the candidate technology and the Base Case technology and on various sets of relative weights (where each set reflects an emphasis on improving a different factor), it can be concluded that the candidate technology is preferred unless cost improvement is more than about 5 times as important as improvements in other factors.

It should be recognized that this evaluation did not include the additional savings associated with a decreased likelihood of subsequent remediation. The sensitivity of these results to the assessed differences in attributes (including consideration of such potential savings), as well as to relative weights, should also be evaluated.

<u>Proposed Issue Resolution</u> - Issues associated with the application of the silicon-based grouting technology relate primarily to waste compatibility, long-term integrity, grout penetration (distance and uniformity), and barrier verifiability. In addition, for horizontal barriers, issues relate to the ability to drill stable horizontal grout holes.

Laboratory and field tests for barrier construction are necessary to resolve these issues and complete development of this technology for this application, and are being proposed for the UST ID. This would include three phases: (1) laboratory bench scale testing to determine waste

compatibility, long-term integrity and post soil injection performance; (2) single borehole injection tests to determine penetration characteristics under field conditions; and, if warranted, (3) multiple borehole injection tests to determine barrier characteristics. The laboratory tests would include enhanced 90/90 testing, as recommended by EPA guidelines, supplemented with radiation and high heat. Accelerated testing would use simulated wastes for the Hanford UST, which is a Battelle-PNL recipe and is itself hazardous. All the testing phases would include consideration of verification, ie, testing of the electrical resistivity and dielectric properties of the grout in the laboratory and calibration of the geophysical testing in the multi-hole field test (eg, by subsequent drilling and sampling, or even excavation and inspection, of the barrier). The field tests would be conducted, for safety and economics, at a similar but uncontaminated site. Additional work may be necessary to customize the material for specific soil/waste conditions and for refining the horizontal drilling and verification techniques. Natural analogues (if any) for the grout will be investigated.

The time to complete development of this technology (ie, demonstration at Hanford UST) is estimated to be on the order of less than two years. This does not include development of horizontal drilling techniques or new geophysical verification techniques.

Recommendation - The detailed evaluation suggests that the silicon-based grout represents an improved technology for application to the Hanford USTs, and thus warrants further consideration.

CONCLUSIONS

DOE must make a variety of decisions within their EM program regarding (1) development and transfer of improved EM technologies and (2) application of the optimum EM technologies at specific sites. To assist in this decision-making process, a methodology has been developed for evaluating EM technologies in terms of (1) the degree to which they would accomplish specific EM activities and satisfy specific requirements, under various conditions, if they were available, and (2) the costs and risks (if any) associated with their becoming available. For demonstration purposes, this methodology was applied at different levels of detail to two grouting technologies:

- The generic application of a Ukrainian clay-based grouting technology was evaluated in a preliminary fashion. It was determined that this technology, if available, represents a potential improvement over other grouts in "open" geologic systems. Hence, development and transfer to the US should be completed if containment in such conditions is a large enough problem for DOE to justify the development/transfer costs.

- The specific application of a French silicon-based grouting technology to the Hanford USTs was evaluated in a detailed fashion. It was determined that this technology, if available, represents a potential improvement over the current base case technology for the Hanford USTs, even when the costs of making the technology available are considered. Hence, development and transfer to the US should be completed, and if successful its application to the Hanford USTs should be strongly considered.

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DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY (SITE)

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Abstract

The novel Du Pont/Oberlin Microfiltration Technology has recently been demonstrated in EPA's Superfund Innovative Technology Evaluation (SITE) program. Its key features are fine microfiltration at low cost using Du Pont's new Tyvek®* T-980 flashspun olefin filter media coupled with Oberlin's reliable automatic pressure filter (APF) and Enviroguard's PROFIX** filter aid for metals stabilization.

This new microfiltration technology is best suited for contaminated heavy metal wastewaters and groundwaters. The SITE demonstration (1990) actually removed Zn, Cu, Cd, Se and Pb from the Palmerton, PA Zinc smelting Superfund site. Basically, 99.95% removal of Zinc and Total Suspended Solids (TSS); and firm, dry (41% solids) cakes that passed both the "Paint Filter Test" and TCLP were demonstrated. Thus, this new technology provides low cost metals removal/stabilization all in one simple operation.

This paper will describe this new technology in detail, and will present some typical application results. It will also detail where it has been applied since the SITE demonstration.

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* Du Pont's trademark for its flashspun HDPE nonwoven filtration media.

** Enviroguard's trademark for its patented filter aid/stabilization agent.

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TYVEK• T-980 MEDIA

Du Pont has commercialized a new filter media based on flash spinning technology for Tyvek spunbonded olefin. It has an asymmetric pore structure, a greater number of submicron pores, and a smaller average pore size [1]. As a consequence, it has superior filtration properties and longer life, and in many instances it can compete with microporous membranes, PTFE laminates, and various melt-blown media [1]. Its key property is its tight pore structure at a very low cost compared to competitive products. Table I outlines the media cost per gallon of waste filtered and shows that the T-980 grade, which is the lowest basis weight manufactured (0.9 oz/yd^2) and the only grade evaluated here, is very cost effective. In most applications the T-980 grade was sufficient so the added cost for a higher basis weight grade was not warranted. For example, T-980 produced slightly poorer effluent quality than the 'standard' 0.45μ microporous membrane at a fraction of the cost; equivalent effluent quality to the PTFE laminate at a fraction of the cost; and much better effluent quality than typical 1- and 5- micron melt-blowns at equal or significantly lower cost (depending on application [2]). Tests with actual wastes showed the greatest cost benefit (Table I). A similar cost benefit was obtained in operation with a low-level radioactive plating waste at the Savannah River Plant [2,3]. This installation realized almost a $350M annual savings when T-980 media was used with a more efficient filter aid. An added benefit is its superior strength compared to microporous membranes and the PTFE laminate media. This strength permits its use in robust automatic pressure filters [4]. The high strength [5] coupled with the tight, ~1- micron pore structure [1] led to its use in the EPA Superfund SITE program [6-9].

OBERLIN AUTOMATIC PRESSURE FILTER (APF) **

T-980 media requires a suitable filter housing. The Oberlin Filter Company's automatic pressure filter (APF) was chosen for its simplicity and fully automatic operation [10]. Their APF has other advantages, namely:

- Completely automatic, unattended operation save for disposable media roll replacement and chemical treatment makeup. Standard PLC control.
- Enclosed operation for safety and handling of hazardous wastes.
- Fairly high operating pressure (up to 60 psig).

- Complete in-line treatment-chemical addition, ie, filter aids and polymer flocculants.
- Automated shutdown flushing capability.
- Cake washing capability to remove hazardous filtrate, if required.
- Automatic, positive dry cake discharge.
- Direct submicron filtration without the need for further downstream processing.
- Reliable, low-maintenance performance.
- Completely automatic safety interlocks and enclosures and/or purging, if required.
- Explosion-proof design, if required.
- Completely integrated pumping system(s), if required.
- Dirty-media takeup and doctoring, brushing, or washing, if required (automatically accomplished during takeup); and, optional media reuse if desired.

DU PONT TYVEK®/OBERLIN MICROFILTRATION TECHNOLOGY

Thus, the Du Pont Tyvek/Oberlin Microfiltration technology has some unique advantages, especially its completely automatic submicron, low-cost filtration and its dry cake discharge [6]. This dry cake discharge feature is precisely why the resultant cakes pass the modified EPA "Paint Filter Test" for land disposal [11] and in some instances pass the new EPA TCLP (Toxic Characteristic Leaching Procedure) test for hazardous components [12-15], provided a stabilization agent is used (i.e., Profix*** was used in the SITE program [9]). Dry cake/submicron filtration in one operation is why the Microfiltration technology was selected at Savannah River over conventional crossflow microfilters and ultrafilters. In plating-waste treatment the simple, one-step Microfiltration technology replaced the conventional three-step clarifier/overflow sand filter/underflow recessed filter press process. However, the purpose of this paper is to highlight case histories where the Microfiltration technology has been successfully applied. The technology is most suitable for hazardous wastewater where the solids loading is not too high (i.e., generally less than about 5000 ppm). Examples include contaminated groundwater, plating wastewaters, low-level radioactive wastes, plant equipment/floor washings, cyanidic wastes, plant wastewaters that contain heavy metals, and metal grinding wastes [2, 3 & 6]. In most of these cases Profix was used per the SITE technology [9] to accomplish automatic, submicron, low-cost microfiltration and stabilization all in one simple operation.

*** Enviroguard's trademark for its patented filter aid/stabilization agent.

CASE HISTORIES

Many successful case histories have been presented previously [2], but a few are worth repeating here, especially those involving heavy metals removal and stabilization. Other new applications are also presented.

Savannah River Operation

Table II details actual Savannah River plant wastewater treatment specifically aimed at aluminum and uranium removal [3]. The data were obtained from two T-980/Oberlin units which had been operating for about four years. Aluminum forming and metal finishing operations generate a high content of solids, aluminum, and turbidity. These solids can be reduced below the National Pollution Discharge Elimination System (NPDES) limits with the Microfiltration technology at very high 1200 gfd (gallons/sq ft/day) rates [16]. This rate is about six times higher than the ultrafilter (UF)/reverse osmosis (RO) system (200 gfd) originally considered. Pilot testing also showed that the UF/RO system repeatedly fouled with this waste, requiring aggressive cleaning agents which significantly added to the waste volume. Plans are now underway to evaluate Profix in this operation.

Electronics Manufacturing Plant Wastewater

This plant's effluent exceeded the local sewer authority's lead discharge limit. As a consequence, the plant was mandated to cease discharge and dispose of their wastewater in an off-site hazardous waste landfill at a $0.55/gallon cost. Two Microfiltration systems were installed instead of crossflow microfilters because their dry cake feature significantly reduced waste volume. These units repaid their cost in three months of operation based on disposal cost savings alone [16].

Table III details actual plant operation and compares the Microfiltration effluent with the plant's discharge limits. As shown, these units reduced the effluent Total Suspended Solids (TSS) and lead levels to well below the plant's required discharge limits at high 800 gfd flux rates. In addition, these units routinely achieved >50% solids dry cakes that could be disposed of in a RCRA-approved landfill (at significant cost savings compared to the concentrate from the crossflow microfilters). Subsequent evaluation of the Profix filter aid/stabilization agent per the SITE technology [9] actually improved flux and resulted in stabilized cakes (passed TCLP).

Electronics Plant Cartridge Replacement

This plant's effluent had to be polished by absolute 0.45-micron cartridge filters to meet heavy-metal discharge limits. Cartridge costs exceeded $1200 daily plus significant labor charges [16]. A Microfiltration system was installed at significant cost savings compared to these cartridges or a crossflow microfilter which was also considered. Payback was on the order of three months; the system produced dry cakes suitable for landfilling off-site, and significant labor savings resulted.

Table IV demonstrates that the Microfiltration system easily met the TSS and lead discharge limits at very high 1500 gfd flux. Cakes were also quite dry at ~50% solids.

Clarifier Underflow Heavy Metals Removal

This plant was faced with a land ban of their main clarifier metal hydroxide underflow sludge (2-3% solids) because it did not pass the EPA "Paint Filter Test" [11]. This clarifier treated the entire plant effluent and removed primarily lead, zinc, and copper. To satisfy the RCRA land ban restrictions, the plant hired an expensive ($400/day) mobile dewaterer who used a manual, recessed-chamber filter press that produced sloppy cakes. These cakes had to be shovelled into dumpsters for off-site disposal. The Microfiltration technology was installed about three years ago. Table V shows excellent effluent quality at very high, 10,000 gpd capacity and 900 gfd flux. The cakes were sufficiently dry (50% solids vs. 40% requirement) to pass the "Paint Filter Test" and were acceptable to the hauler/landfill operator at a significant cost saving to the plant. The Microfiltration system operates automatically at significant labor savings compared to the manual press. Profix has been evaluated here and was implemented recently since the resultant cakes pass TCLP particularly for lead (Table V). As a result, off-site disposal costs were reduced about $200M annually.

Battery Manufacturing Heavy Metals Removal

This plant consistently exceeded their permitted discharge limits from their conventional clarifier/underflow press system and considered an overflow polishing sand filter. Simultaneously, they heard of our Microfiltration technology and decided to evaluate it as a polishing filter. Testing showed that it could replace the entire clarifier/press installation. Table VI shows excellent metals removal, TSS reduction, and excellent effluent turbidity (0.5 NTU). Flux is quite high at 2400 gfd and capacity from the single system exceeds 60,000 gpd. These benefits are in addition to dry cakes that could be easily disposed of in a RCRA-approved landfill.

Heavy Metals Removal from Chemical Plant Wastewater

This plant was faced with severe heavy metal discharge restrictions based on recent EPA chronic toxicity regulations (ie, 15 ppb Cu, 60 ppb Pb, 130 ppb Ni, 150 ppb Cr, and 300 ppb Zn). In addition, this mixed heavy metals waste had to be stabilized to meet the "third-third" EPA BDAT (Best Demonstrated Available Technology) regulations for land disposal [2, 12 & 13]. Ion exchange was first evaluated, but it could not meet the low ppb limits for all the metals and its regenerant required off-site stabilization at high cost. As a result, the Microfiltration technology was next evaluated since it could produce dry, stabilized cakes, but previously it never achieved these low metals limits. An extensive pilot testing program was conducted and finally, it was demonstrated that these limits could be achieved quite routinely (Table VII). In addition, these low metals limits were obtained at a very high 3600 gfd flux; and the resultant "dry" cakes passed the TCLP test for all eight toxic metals (per EPA "third-third" regulations issued May 8, 1990 [12 & 13]). As a consequence, the Microfiltration technology was selected and one large system (along with a Profix addition system) has been operating successfully for one year; and a second system is being installed now.

Groundwater Lead Removal

A RCRA hazardous site required lead removal from contaminated groundwater to a level of less than 50 ppb to meet primary drinking water standards as well as the chronic toxicity criteria. The responsible party hired an outside consulting firm to study and recommend a suitable treatment scheme. Unfortunately, their piloted treatment process could only achieve

4 ppm; and their recommended activated carbon polishing step also could not achieve the low required 50 ppb lead discharge limit. The Microfiltration technology was then evaluated and outstanding <10 ppb lead removals were obtained (Table VIII). As a result, this technology will be used and a single large system is being installed. Profix was used here and the cakes passed TCLP for lead.

Chemical Plant's Groundwater Metals Removal

This plant had groundwater contaminated with metals and organics, and hired an outside consulting firm to study and recommend a suitable treatment scheme. Unfortunately, their piloted sand filter scheme couldn't achieve the required low metals levels; and as a result the Microfiltration technology was evaluated. As can be seen from Table IX, it achieved outstanding metals removal (i.e., below detection limits) at a very high 4000 gfd flux. In addition, filtrate turbidity, TSS, and cake % solids were all excellent; and the cakes passed TCLP. As a result, the system is now being installed to treat this groundwater.

Groundwater Hexavalent Chrome Removal

This Superfund site required groundwater chrome removal to the 50 ppb level. Simple sodium bisulfite chrome reduction followed by Microfiltration resulted in excellent chrome removal to below the 50 ppb detection limit, as well as excellent filtrate TSS and turbidity (Table X). Flux was very high at 3600 gfd and the resultant cakes were stabilized. However, the client opted for ion exchange (IX) since only one metal was present and it reduced solid waste volume. In this case, IX was a better choice for the client; and illustrates that all metals removal technologies have their niche.

Groundwater Mixed Metals Removal

This mixed organics/metals contaminated groundwater was chemically treated to destroy the toxic organics and the resultant effluent was treated by the Microfiltration technology (Table XI). As can be seen from Table XI, excellent metals removals were obtained basically to the detection limits. Flux was reasonable (1750 gfd) considering the high 50 ppm Fe content; cakes passed the new TCLP test; and filtrate turbidity and TSS were outstanding at 0.05 NTU and 0.03 ppm, respectively (i.e., better than distilled water). In this case, the regulatory limits were later relaxed so direct discharge was possible; and the Microfiltration technology was not required.

Wastewater Mixed Metals Removal

This plant required stringent heavy metals removal to meet chronic aquatic toxicity criteria. A variety of technologies were evaluated, but the Microfiltration technology provided the best overall metals removal of this waste (Table XII) as most were removed to below detection limits. The resultant cakes also passed TCLP, which was also a big factor since other technologies required additional post-treatment to produce stabilized solids.

Wastewater Zinc Removal

This wastewater required zinc removal to 1 ppm prior to discharge; and in this case, only the Microfiltration technology was evaluated because selective ion exchange could not achieve the 1 ppm limit. Table XIII shows that the Microfiltration system easily achieved the 1 ppm Zn

limit as well as excellent Cd, Pb, and Cu removals like in the SITE demonstration [9] where these metals are normally associated with Zn smelting. In addition, filtrate turbidity and TSS were excellent and flux was reasonably high (1000 gfd) for this high 3000 ppm TSS waste. Cakes again passed the TCLP test. In this case, despite the promising microfiltration results the plant opted to incinerate this waste.

Explosives Plant Pb Removal

This plant sends their Pb wastewater off-site for treatment and stabilization at considerable expense. They heard of the Du Pont/Oberlin Microfiltration technology and evaluations in Table XIV demonstrated complete feasibility as Pb was removed to well below the proposed discharge limits and cakes passed TCLP at a reasonably high 2000 gfd flux. As a consequence, a small system has been started up recently.

Chelated Wastewater Cu Removal

This plant had two wastewater streams which required Cu removal to meet the 50 ppb toxic discharge limit as well as to protect the on-site biological waste treatment system. One stream contained chelated Cu (Case II) while the other was chelated as well as heavily contaminated with organics (Case II). Ion exchange and oxidation with iron were tried on Case I stream with little success while hot sodium sulfide precipitation was successfully demonstrated for Case II after the organics were removed. However, it was later found that complete organics removal could not be assured so the Microfiltration technology was evaluated on both streams. Table XV shows that Cu removal to 10 ppb was obtained at high 4200 gfd flux (Case I) and <200 ppb Cu at 300 gfd flux for Case II. The higher ~200 ppb Cu in Case II was due to the copious ~50% organics present, but combined waste discharge was below 50 ppb. In addition, both cakes passed TCLP and even organics were stabilized when a mixed Profix/organic stabilizer (FO1) was used. Economics showed that Case I treatment costs amounted to low $1.60/1000 gallons while Case II about $130/1000 gallons, but Case II disposal cost savings amounted to about $1350/1000 gallons due to the high level of organics present that could be recovered and recycled. As a consequence, a project is being implemented to install a Microfiltration system.

ACTUAL EPA SITE DEMONSTRATION

The Du Pont/Oberlin microfiltration technology was demonstrated by the EPA under the SITE program in April - May, 1990 at the Palmerton, PA Superfund site [7, 8, 9, & 16]. This site's groundwater is contaminated with heavy metals by runoff from a huge 2.5 mile long cinder bank as a result of a zinc smelting operation. As expected, the groundwater contained high concentrations of zinc as well as manganese, lead, cadmium, copper and selenium (Table XVI). The Microfiltration system was able to remove 99.95% of the zinc, 99.95% of the TSS, produce dry cakes that passed the "Paint Filter Liquids Test", 41% cake solids, filtrate that met NPDES discharge limits, and cakes that passed both the EP Toxicity and the new TCLP test, because the new filter aid / stabilization agent (Profix) was used [7, 8, 9, & 16].

SUMMARY

These cases and actual operating applications demonstrate the utility of the Du Pont/ Oberlin microfiltration technology to remove heavy metals at very high flux rates <u>and</u> to simultaneously produce dry cakes that pass the EPA "Paint Filter Test", and in some cases, the

new EPA TCLP leaching test (if Profix filter aid/stabilization agent is used per SITE demonstration - Refs. 2, 6, 7, 9). This technology is quite competitive when compared to microfilter cartridges, crossflow microfilters, and ultrafilters. In some instances, the system can replace the conventional three-stage metal finishing treatment process of clarifier, underflow filter press, and overflow polishing sand filter. Thus, the waste engineer/consultant now has a simpler, one-step process for treating and stabilizing hazardous metal-bearing wastewaters and groundwaters.

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TABLE I

MEDIA COST PER GALLON WASTE FILTERED

Media	Nom. Rating (µm)	Overall Filtrate Quality	Actual Costs/Gallon Filtrate (cents/gal)*		
			600 ppm ACFTD**	Low-Level Radioactive Waste	Lead-Bearing Waste
Microporous Membrane	0.45	Excellent	29	69	14
Tyvek® T-980	1	V. Good	1.3	1.7	0.3
PTFE Laminate	0.8	V. Good	41	63	12
Melt-blown PP	1	Good	2.4	6.5	1.3
Melt-blown PP	~5	Poor	1.5	4.0	0.8

* Based on actual media costs, flux rates, and measured life cycles.
** AC Fine Test Dust (ACFTD) challenge tests.

TABLE II

ACTUAL SAVANNAH RIVER PLANT OPERATION WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Waste	T-980/ Oberlin	NPDES Limits*
Turbidity (NTU)	110	0.32	--
TSS (ppm)	687	1.4	31
Aluminum (ppm)	127	0.95	3.2
Lead (ppm)	1.6	0.2	0.43
Zinc (ppm)	0.5	< 0.1	0.32
Copper (ppm)	2.0	< 0.1	0.21
Uranium (ppm)	2.3	0.01	0.5
Capacity (gpd)	35,000	60,000	--
Flux (gfd)	--	1,200	--

* Actual State discharge permit values.

TABLE III

ACTUAL ELECTRONICS MANUFACTURING PLANT WASTEWATER WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Waste*	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	>1,000	0.3	NR
TSS (ppm)	1,000	<1	26
Lead (ppm)	20	0.04	1.0
Barium (ppm)	25	<1**	NR
Cadmium (ppm)	2	<0.05**	NR
Capacity (gpd)	2,500	4,500	---
Flux (gfd)	---	800	---
Cake % Solids	---	54	---
Cakes Pass TCLP?	No	Yes	Must pass

TABLE IV

ELECTRONICS PLANT CARTRIDGE FILTER REPLACEMENT WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Waste*	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	2,400	0.43	NR
TSS (ppm)	5,500	1.0	20
Lead (ppm)	2,300	0.18	0.7
Capacity (gpd)	2,000	11,000	---
Flux (gfd)	---	1,500	---
Cake % Solids	---	50	---

* Includes floor washings also.
** Detection Limit
NR = Not Regulated.

TABLE V

CLARIFIER UNDERFLOW HEAVY METALS REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Waste*	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	>1,000	1.0	NR
TSS (ppm)	17,000	2.5	20
Lead (ppm)	40	<0.01**	5.0
Zinc (ppm)	410	0.2	5.0
Copper (ppm)	1,050	1.2	5.0
Capacity (gpd)	6,800	10,000	---
Flux (gfd)	---	900	---
Cake % Solids	---	50	40
Cakes Pass TCLP?	No	Yes	Must pass

TABLE VI

DIRECT FILTRATION FOR HEAVY METALS REMOVAL FROM A BATTERY MANUFACTURING PLANT WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY ***

Property	Raw Waste	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	175	0.5	NR
TSS (ppm)	1,600	<1	20
Nickel (ppm)	30-50	<0.10	2.27
Cadmium (ppm)	15-40	<0.05	0.4
Zinc (ppm)	0.2-1.0	<0.10	1.68
Cobalt (ppm)	0.4-1.5	<0.05	0.22
Capacity (gpd)	40,000	60,000	---
Flux (gfd)	---	2,400	---

* Existing plant clarifier underflow sludge was previously hauled off-site to hazardous landfill.
** Detection limit
*** Replaced clarifier and underflow press.
NR = Not Regulated.

TABLE VII

HEAVY METALS REMOVAL FROM CHEMICAL PLANT WASTEWATER WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Waste	Du Pont Oberlin	Discharge Limits**
Turbidity (NTU)	>100	0.06	<0.2
TSS (ppm)	100	<0.2	<1
Copper (ppb)	2,000	<5	15
Lead (ppb)	100	<5 *	60
Zinc (ppb)	3,500	<10 *	250
Nickel (ppb)	400	<5 *	130
Chromium (ppb)	1,000	< 100 *	150
Capacity (gpd)	75,000	130,000	---
Flux (gfd)	---	3,600	---
Cakes Pass TCLP?	No	Yes	Must Pass

TABLE VIII

GROUNDWATER LEAD REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Groundwater	Du Pont/ Oberlin	Discharge Limits **
Turbidity (NTU)	≤10	0.1	NR
TSS (ppm)	120	<0.2	30
Lead (ppb)	20,000	≤10	50
Flux (gfd)	—	1,400	---
Cakes Pass TCLP?	No	Yes	Must Pass

* Detection limits.
** Based on EPA Chronic Toxicity tests
NR = Not Regulated

TABLE IX

CHEMICAL PLANT GROUNDWATER METALS REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Groundwater	Du Pont/ Oberlin	Discharge Limits **
Turbidity (NTU)	100	0.17	NR
TSS (ppm)	80	0.3	20
Fe (ppm)	40	<0.1*	NR
Ba (ppb)	900	500	NR
Cr (ppb)	45	<10*	150
Ni (ppb)	50	<5*	130
Zn (ppb)	300	<10*	250
Cake % Solids	---	56	---
Flux (gfd)	---	4000	---
Cakes Pass TCLP?	No	Yes	Must Pass

TABLE X

GROUNDWATER CHROME REMOVAL FROM SUPERFUND SITE WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Groundwater	Du Pont/ -Oberlin	Discharge Limits **
Turbidity (NTU)	30	0.07	NR
TSS (ppm)	40	0.3	NR
Cr (ppm)	3-12 (hexavalent)	<0.05*	0.05
Cake % Solids	---	56	---
Flux, (gfd)	---	3600	---
Cakes Pass TCLP?	No	Yes	Must Pass

* Detection Limit
** Based on EPA chronic toxicity standards
NR = Not Regulated

TABLE XI

GROUNDWATER METALS REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Groundwater	Du Pont/ Oberlin	Discharge Limits **
Turbidity (NTU)	160	0.05	NR
TSS (ppm)	180	0.03	30
Fe (ppb)	50,000	<100*	NR
Cr (ppb)	40	10	150
Ni (ppb)	300	<5*	130
Zn (ppb)	14,000	<10*	300
Flux (gfd)	---	1750	---
Cakes Pass TCLP?	No	Yes	Must Pass

TABLE XII

MIXED WASTEWATER METALS REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Groundwater	Du Pont/ Oberlin	Discharge Limits **
Turbidity (NTU)	<1000	0.2	NR
TSS (ppm)	1200	0.4	20
Fe (ppm)	80	<0.1*	NR
Cr (ppb)	1800	50	150
Cu (ppb)	1000	<5*	15
Zn (ppb)	14,000	<10*	250
Cake % Solids	---	51	---
Flux (gfd)	---	400	---
Cakes Pass TCLP?	No	Yes	Must Pass

* Detection limit
** Based on EPA Chronic Toxicity Tests.
NR = Not Regulated

TABLE XIII

WASTEWATER ZINC REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Wastewater	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	>1000	0.06	0.2
TSS (ppm)	3000	0.13	20
Zinc (ppm)	1500	<0.01*	1
Cd (ppm)	0.15	<0.01*	NR
Pb (ppm)	0.70	<0.005*	NR
Cu (ppm)	0.25	<0.005*	NR
Flux (gfd)	---	1000	---
Cake Pass TCLP?	No	Yes	Must Pass

TABLE XIV

WASTEWATER Pb REMOVAL FROM EXPLOSIVES PLANT WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Wastewater	Du Pont/ Oberlin	Discharge Limits
Turbidity (NTU)	9000	<1	-
TSS (ppm)	3300	<1	<20
Pb (ppm)	110	0.3	5
Flux (gfd)	-	2000	-
Cakes Pass TCLP?	No	Yes	Must Pass

TABLE XV

WASTEWATER Cu REMOVAL WITH DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY

Property	Raw Wastewater	Du Pont/ Oberlin	Discharge Limits
1. Chelated Case:			
Turbidity (NTU)	20	<0.3	-
TSS (ppm)	25	<0.2	-
Fe (ppb)	500	20	-
Cu (ppb)	2,500	10	50
Flux (gfd)	-	4200	-
Cakes pass TCLP?	No	Yes	Must Pass
2. Organics Case:			
Turbidity (NTU)	>1000	<10	-
TSS (ppm)	30,000	2	-
Cu (ppm)	1600	<0.2	0.2
Flux (gfd)	-	300	-
Cakes pass TCLP?	NO	Yes	Must Pass
- with PROFIX		(Metals Only)	
- with PROFIX FO1		(Metals & Organics)	
Organics Recovery (Vol %)	~10%	98.6%	Cannot Discharge

TABLE XVI

DU PONT/OBERLIN MICROFILTRATION TECHNOLOGY DEMONSTRATION BY EPA AT PALMERTON, PA SUPERFUND SITE

Property	Raw Waste	Du Pont/ Oberlin	Discharge Limits**
Turbidity (NTU)	>1,000	0.1	NR
TSS (ppm)	1,700	0.8	30
Zinc (ppm)	500	0.25	2.4
Manganese (ppm)	50	<0.1*	NR
Lead (ppm)	0.1	0.025	0.7
Cadmium (ppm)	0.5	0.005	0.2
Copper (ppm)	0.2	0.003	NR
Selenium (ppm)	0.1	0.040	NR
Cake % Solids	---	>40	NR
Cakes Pass EP Tox?	No	Yes	NR
Cakes Pass TCLP?	No	Yes	Must Pass

* Detection Limit.
** NPDES discharge limits.
NR = Not Regulated.

U.S. ARMY CORPS OF ENGINEERS

TOXIC AND HAZARDOUS MATERIALS AGENCY

Composting of Explosives-Contaminated Soil at the U.S. Army Umatilla Depot Activity

Composting Technology

Composting is a controlled biological process by which biodegradable materials are converted by microorganisms to innocuous, stabilized by-products. In most cases, this is achieved by the use of indigenous microorganisms. Explosives-contaminated soils are excavated and mixed with bulking agents such as wood chips, and organic amendments such as animal, fruit and vegetative wastes. Maximum degradation efficiency is controlled by maintaining moisture content, pH, oxygenation, temperature and the carbon to nitrogen ratio. There are three process designs used in composting; aerated static piles, windrowing, and mechanically agitated in-vessel composting (Figure 1). This technology requires substantial space to conduct the composting operation and results in approximately a two fold volumetric increase in material due to the addition of amendment material.

The first composting demonstration for explosives-contaminated soils conducted at Louisiana Army Ammunition Plant (LAAP) demonstrated that aerobic, thermophilic composting is able to reduce the concentration of explosives (TNT, RDX and HMX) and associated toxicity to acceptable health based clean-up levels. However, an economic analysis determined that full scale implementation of composting of explosives-contaminated soils using previously investigated design parameters was not economically competitive with incineration. An optimization field demonstration was initiated at a National Priority List (NPL) site at Umatilla Depot Activity, Hermiston, OR, to investigate several process design parameters that would make this technology more cost effective. In addition, extensive chemical characterization and toxicity studies were conducted on the final composted product.

General Site Information

Umatilla Depot Activity (UMDA), Hermiston, OR, was selected as the site for the compost optimization field study. Between 1950 and 1965, a washout facility for recovering explosives from unserviceable munitions was operated at UMDA. Pressurized hot water was used to melt out explosives from munition bodies and, upon cooling and settling, the explosives were recovered. Large quantities of water were contaminated with explosives in this operation. It was standard practice, at the time, to discharge this water into unlined settling basins. Explosives contained in these waters consisted of TNT, RDX and HMX. In 1987, these washout lagoons were placed on Environmental Protection Agency's EPA National Priorities List (NPL) because of the presence of explosives in the water table aquifer some 50 feet beneath the lagoons. The explosives concentration levels in the washout lagoons soils approach a maximum concentration of 10% (100,000 mg/kg). Explosives contaminated soils from these lagoons were hand excavated for this composting optimization study. The mean concentrations of TNT, RDX and HMX were 13,380, 1,071, and 274 mg/kg, respectively.

Optimization Field Study Objectives and Design

The primary objective of this composting optimization field study was to increase the quantity of soil processed in a composting treatment system per unit time. Since soil throughput is dependent on the rates of degradation and the percent soil loading, the key variables investigated in this study were amendment mixture composition and percent contaminated soil loading. In addition, two technologies were evaluated, aerated static pile and mechanically agitated in-vessel composting systems.

Amendment selection was based on adiabatic testing using a combination of fifteen readily available agricultural wastes. The amendments selected and their approximate cost are provided in Table 1. Percent soil loading was investigated using seven 3 cubic yard aerated static pile systems which were constructed from fiberglass to model actual static pile conditions (Figure 2). The tests were used to investigate soil/amendment ratios using 0, 7, 10, 20, 30 and 40 volume percent of explosives-contaminated soil and composted for 90 days. Different soil amendment ratios and amendment mixture compositions were investigated using a special seven-cubic yard pilot scale mechanically agitated in-vessel (MAIV) system which was constructed according to rigorous explosive safety standards by Fairfield Engineering Co., Marion, Ohio (Figure 2).

The mechanical pilot system uses rotating augers attached to the rotating cover to mix the compost. The first two tests investigated two different amendment compositions using 10% contaminated soil volume. The final two tests were used to investigate soil/amendment ratios using 25 and 40 percent volume of explosives contaminated soil with the optimum amendment composition selected from the previous tests. The MAIV tests were composted for 44 days.

The static pile systems and the MAIV system were housed in greenhouses to protect them from the environment and prevent the spreading of contamination from explosives contaminated dust. A computer-based data acquisition and control system was used to monitor and regulate the environment in each of the compost systems. Temperatures were kept from exceeding 55°C using forced aeration and the moisture content maintained between 45 - 50 percent. Compost samples were taken at various time intervals, homogenized and split into two fractions. Chemical analysis for the presence of TNT, RDX and HMX were conducted by High Performance Liquid Chromatagraphy methods on the first fraction while the second fraction was subjected to toxicity testing.

Since the implementation of this technology will be based on it's ability to meet health based clean-up criteria, the second objective was to conduct a chemical characterization and toxicological evaluation of the resultant composted material. Leachates from the EPA Synthetic Precipitation Leachate Test (referred to as the "Clean Closure Leaching Test or CCLT) and organic solvent leachates were subjected to Ames bacterial mutagenicity tests, acute and chronic toxicity tests using the aquatic crustaceans Ceriodaphnia dubia, and a rat oral toxicity screening of finished compost. Characterization included determination of the explosives and TNT metabolites in the composts and organic solvent extracts.

Optimization Study Results

The composting optimization study confirmed the LAAP composting study results which indicated that composting can effectively treat TNT, RDX and HMX contaminated matrices. The optimization study indicated that both static pile and MAIV composting technological approaches for implementing composting are effective in degrading explosives. The percent reduction of explosives observed in the tests are provided in Table 2. In the static pile tests, the majority of the degradation occurred in the first 44 days of composting while in the MAIV tests the majority of the degradation occurred in the first 10 days. The results of this optimization

study indicated the amendment composition is an important parameter in achieving maximum reduction of RDX and HMX. The maximum loading level for both technologies appears to be 30 volume percent and mixing is important in achieving rapid and extensive destruction of explosives. Since mixing is an important process design parameter, a composting windrow field demonstration has been initiated.

Chemical characterization and toxicity testing on the finished compost sponsored by the U.S. Army Biomedical Research and Development Laboratory and conducted by the Oak Ridge National Laboratory (ORNL) concluded that composting can effectively reduce the concentrations of explosives and bacterial mutagenicity in explosives-contaminated soil, and can reduce the aquatic toxicity of leachable compounds. The CCLT leachate toxicity to humans was estimated by comparing the concentrations of TNT, RDX and HMX with 100 times their EPA Drinking Water Equivalent levels (a 100 fold dilution of leachate in drinking water supplies was assumed, as in RCRA). The CCLT leachates from the composts met this criteria indicating the toxicity to humans is not a serious concern. The ORNL noted that small levels of explosives and metabolites, bacterial mutagenicity, and leachable toxicity do remain after composting; however, they do not pose a serious health concern. In fact, no mortality or toxic effects were observed in a rat oral toxicity screen.

Chemical analysis of the finished compost indicated that the nitro groups in TNT were reduced to amino groups, producing first the monoamino-dinitrotoluenes and then diamino-mononitrotoluenes. These metabolites have been shown to be less mutagenic than the parent compound in previous studies. The observed TNT metabolites did not quantitatively account for the decreases in TNT concentrations. The ultimate fate of the biotransformed explosives still remains unknown; however, extensive organic extraction and alkaline digestion of a compost inoculated with radio-labelled TNT suggested that a major portion of the biotransformed TNT was chemically bound to the compost and not mineralized. The nature and significance of the biotransformation product-soil binding will continue to be investigated.

UMDA Washout Lagoon Feasibility Study

As the composting optimization study was concluding at UMDA in 1991, the Remedial Investigation (RI) of these washout lagoons was also nearing completion. The washout lagoons soils were broken out from the other sites in the RI and made the subject of a separate Risk Assessment and Feasibility Study (FS). An FS was conducted in accordance with the Comprehensive Environmental Response,

Compensation, and Liability Act of 1980, as amended by the Superfund Amendments and Reauthorization Act of 1986. The FS summarized the baseline risk assessment, the remedial action objectives, screened potential remedial technologies and evaluated in detail the most promising remedial technologies. Since there are no federal cleanup standards for explosives contaminated soils, the cleanup standards were developed based upon the remedial action objectives in the Risk Assessment and the evaluation of various treatment alternatives.

The remedial action objectives were used to determine a range of soil volumes and treatment standards to be considered for remediation. Four potential excavation scenarios, including a cleanup to background, were considered thus providing varying degrees of contaminant removal and risk reduction. The state cleanup standard requires that soils should be cleaned up to background if possible, or if not, to a level which is protective of human health and the environment. Soil sample analysis within the lagoons determined that 90% of the explosives contaminants were in the 5 feet of soil below the bottom of the lagoons. Cleanup to background (i.e., excavation to groundwater at 47 feet deep) was evaluated, but the small amount of additional protection provided would be very expensive ($14 million). It was determined that excavation of the soil to a depth of approximately 5 feet below the lagoons to a cleanup standard of 30 parts per million for TNT and RDX would reduce the excess lifetime cancer risk to 7×10^{-6} in a future industrial land use scenario; well within the acceptable ranges specified by EPA (i.e., between 1×10^{-4} and 1×10^{-6}). This represents a volume of soils of approximately 6,800 tons.

The remedial alternatives evaluated in detail were no action, excavation followed by incineration, and excavation followed by composting. Incineration is a proven method of destroying explosives contaminants and could reduce the concentrations and associated toxicity by 99.99 percent. Composting is an innovative bioremediation technology for which extensive site-specific treatability studies have been conducted. The optimization study demonstrated the MAIV composting can reduce the TNT and RDX concentrations by greater than 97 to 99 percent and reduce the toxicity by 90 to 98 percent. Windrow composting is expected to be comparably effective. Static pile composting was not considered because of it's inability to meet the established cleanup criteria in the treatability studies. The FS evaluated the cost of implementing MAIV composting, windrow composting and incineration for several excavation scenarios. Table 3 provides the estimated cost of implementing these remedial alternatives at UMDA.

The alternatives were evaluated for overall protection of human health and the environment; compliance with applicable or relevant and appropriate requirements (ARARs); long-term effectiveness; reduction in toxicity, mobility, and volume; short-term effectiveness; implementability; and cost. The no action alternative failed to provide overall protection to human health and the environment and did not comply with ARARs. The FS showed that windrow composting would be expected to meet the remedial action goals at a cost of approximately $2 million, as compared to $4.1 million for incineration. The FS indicated that windrow composting may be the most cost-effective application of this technology due to the high capital costs of MAIV. Composting was proposed to the public and regulatory agencies and was selected as the final source control remedial action of the washout lagoons in a Record of Decision on September 1992. A composting windrow field demonstration is currently being conducted at UMDA to obtain design information for the full-scale remediation contract. The U.S. Army Corps of Engineers - Seattle District will initiate the implementation of the remedial action in 1993.

Conclusion

Composting is an emerging, innovative technology for the remediation of explosives-contaminated soils. Treatability studies have demonstrated that composting is able to reduce the concentration of explosives (TNT, RDX and HMX) and associated toxicity to acceptable health based clean-up levels. The UMDA Washout Lagoon FS has provided a cost analysis which indicates composting is a cost effective alternative to incineration for sites with less than approximately 20,000 tons of contaminated soil. The implentation of composting to remediate the explosives contaminated washout lagoon soils at the U.S. Army Umatilla Depot Activity will be the first application of bioremediation at an NPL site for explosives-contaminated soils.

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CETHA-BC-CR-92017, Feasibility Study for the Explosives Washout Lagoons (Site 4) Soils Operable Unit Umatilla Depot Activity, Hermiston, Oregon, April 1992.

Technology Contacts

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Table 1: Amendment Mixture Composition and Cost

Amendment	Mixture A	Mixture B	Mixture C
Sawdust	30 %		22 %
Apple pomace	15 %		6 %
Chicken manure	20 %		
Chopped potato	35 %		17 %
Horse manure/straw		50 %	
Buffalo manure		10 %	
Alfalfa		32 %	22 %
Horse feed		8 %	
Cow manure			33 %
COST PER TON	$15	$200	$11

Table 2: Results of Umatilla Composting Optimization Tests

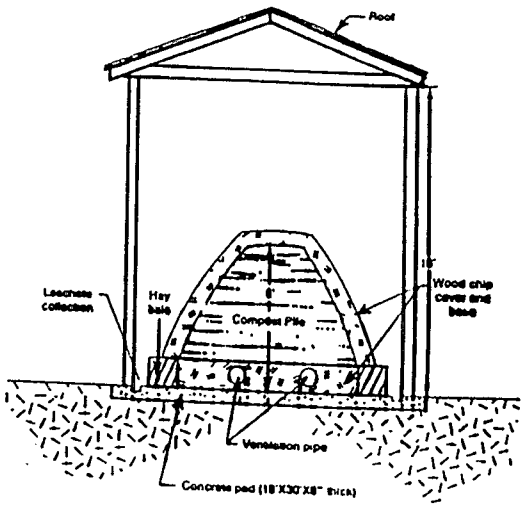
Test % Soil	Amend-ment Mix	Initial conc. TNT mg/kg	Final conc. TNT mg/kg	% Reduction TNT	RDX	HMX	half-life days
static pile							
0	A	0	0	N/A	N/A	N/A	0
7	A	1144	107	91	73	39	6.6
10	A	1008	200	96	46	21	6.4
10	C	3850	41	99	93	80	6.9
20	A	5716	331	94	16	5	14.8
30	A	7908	174	98	22	11	16.1
40	A	9858	2086	79	0	2	24.9
MAIV							
10	A	3452	90	97	90	29	5.2
10	B	3126	5.6	99	99	95	5.1
25	C	5208	14	99	97	68	6.4
40	C	6950	209	97	18	0	14.9

Table 3: Estimated Cost per Ton to Implement Remedial Alternatives

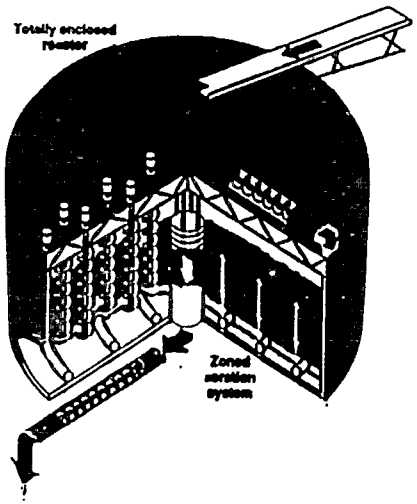
Depth of Excavation Tons of Soil	Windrow	MAIV	INCINERATION
2 Feet / 3,700	$386/ton	$651/ton	$740/ton
5 Feet / 6,800	$288/ton	$481/ton	$660/ton
20 Feet / 30,000	$206/ton	$330/ton	$280/ton
47 Feet / 47,000	NA[a]	NA[a]	$300/ton[b]

Notes: [a]Composting was not considered a viable alternative for this large volume of soil due to the requirements for large quantities amendments. [b]Includes the cost for special construction techniques used for vertical sided excavation.

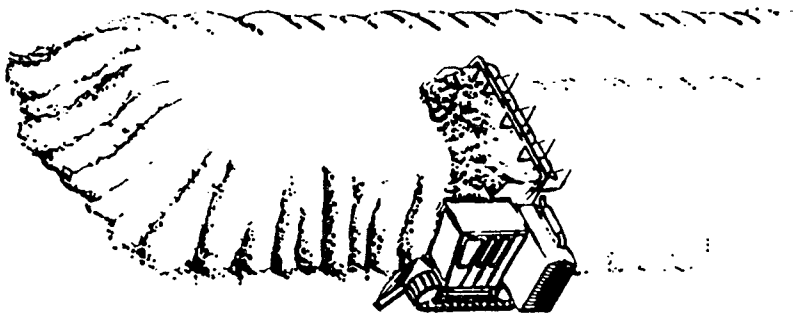
FIGURE 1: COMPOSTING PROCESS DESIGNS



STATIC PILE COMPOSTING

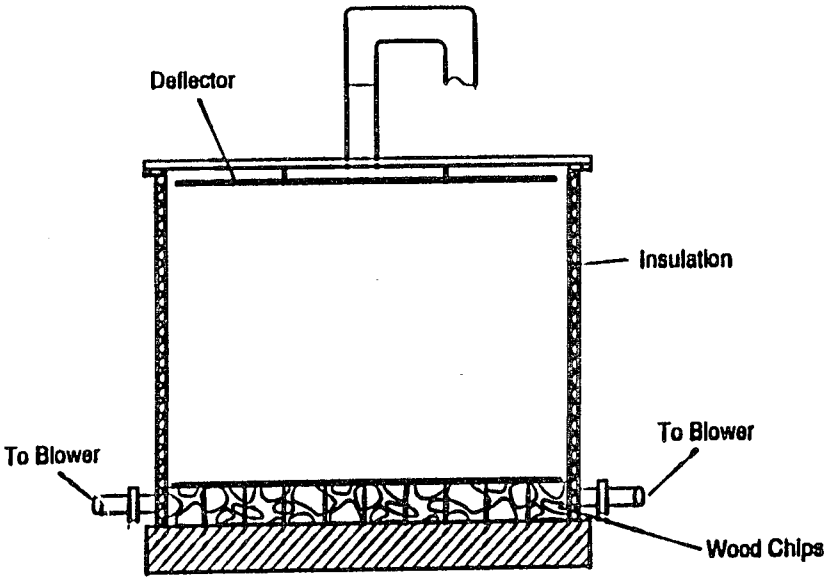


MECHANICALLY AGITATED IN-VESSEL COMPOSTING

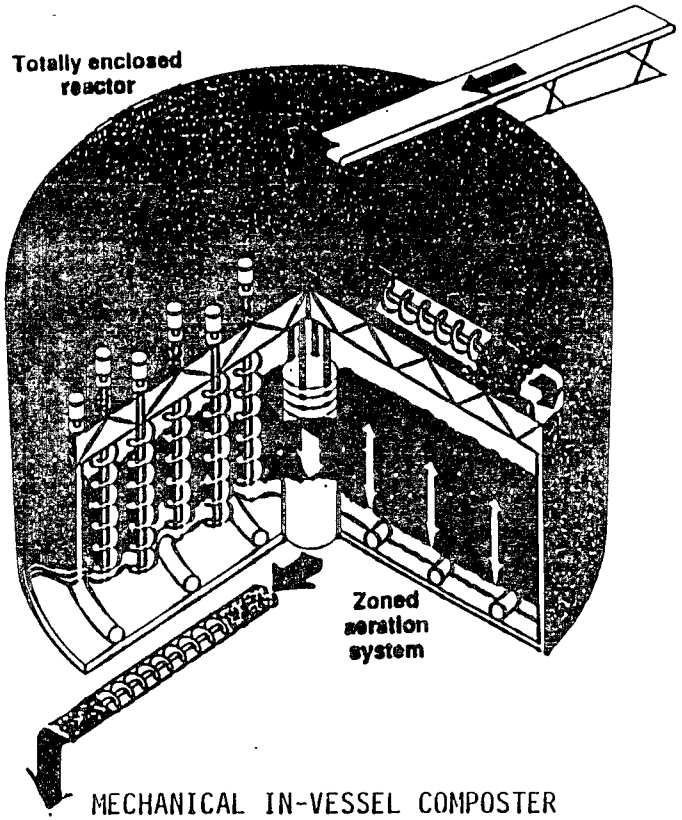


WINDROW COMPOSTING

FIGURE 2: COMPOSTING PROCESSES DEMONSTRATED DURING THE UMDA OPTIMIZATION STUDY



AERATED STATIC PILE SCHEMATIC



MECHANICAL IN-VESSEL COMPOSTER SCHEMATIC

United States/German Bilateral Agreement on Hazardous Waste Site Clean-up Projects

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The problem of contamination to land and groundwater from improper disposal of hazardous materials/waste are common to all industrialized countries. Research and the development of technologies to deal with these environmental problems is very costly and requires the highest level of creativity and ingenuity. All countries resources and technical talents are limited. Good researchers do not operate in a vacuum. Sharing technical ideas and the expenses of developing new and innovative technologies for dealing with contaminated land and groundwater appears to be a good idea based on past experience. Cooperation at an international level is an economically cost effective way to access hard-to-get and very worthwhile information. To complicate the situation a wide variety of local and national circumstances/ factors lead to the development of varying standards and techniques used to determine the effectiveness of various technologies to deal with these environmental problems. In order to reduce environmental overload, close international cooperation is indispensable, both in terms of measures implemented and in the field of research and development, including the exchange of information and experiences. Furthermore coordination of environmental demands in different countries lessens the everpresent, potential trade barriers and imbalances in competitiveness.

Against this backdrop a United States/German Bilateral Agreement on hazardous waste site cleanup projects has been developed. The two lead agencies are the United States Environmental Protection Agency (USEPA), Office of Research and Development (ORD), and the Federal Republic of Germany (FRG), Federal Ministry for Research and Technology (BMFT). By leveraging existing resources and programs within the bilateral agreement each agency will enhance the potential impact of these activities to the overall hazardous waste site problems within their respective countries.

The goals of this bilateral agreement are:

- Facilitate understanding of each side's approach to the remediation of contaminated sites ("as if-approach": as if the foreign project had taken place in their own country)
- Demonstrate innovative remedial technologies
- Compare quality assurance programs
- Facilitate technology transfer

The technical approach to remediating a hazardous waste site is subject to a different set of environmental and social factors in each country; therefore, the usefulness of a particular technology can only be determined if it has been evaluated in the light of these considerations within both countries.

Six sites on each side were selected for the cooperation. Detailed executive summary reports on each of the German sites are being prepared by the contractors working for the BMFT. These reports will be reviewed by designated USEPA/RREL Technical Program Managers to determine what additional analytical-type Quality Assurance (QA) and Quality Control (QC) measures should be incorporated into the remedial action demonstration by the Germans to meet the U.S. EPA Superfund Innovative Technology Evaluation (SITE)) criteria for determining the effectiveness of the individual technologies being utilized at the sites.

The USEPA/RREL has prepared similar reports for the U.S. sites. The BMFT will

review these reports to determine what additional analytical QA/QC measures should be implemented into these remedial action demonstrations to meet German criteria for determining the effectiveness of the individual technologies being utilized at the EPA sites.

In the Federal Republic of Germany support for environmental related research and development has a central function in the Federal Government's environmental policy. In its environmental research program the Federal Ministry for Research and Technology defined priority areas for the awarding of research grants in fields particularly interfering with the environment. The present promotion concept for the area of waste management and abandoned hazardous sites (1989 - 1994) presents the future research and development priorities in accordance with environmental priorities. In 1989 a special program, the "Model remediation of representative hazardous waste sites" was launched. The aim of this program is to develop further the state of the art and to demonstrate new clean-up technologies as well as to assess their applicability to actual hazardous waste sites. For the practical demonstration the remediation projects are funded where physical-chemical-thermal and biological techniques or combinations of these techniques are applied. Special emphasis is given to their efficiency of clean-up, their ability to generate a reusable soil, their costs and their environmental impact. Six of these R&D projects were selected for the EPA/BMFT bilateral cooperation on hazardous waste site clean-up projects.

In order to obtain results within a given time frame the schedule of the remediation projects affects the selection. The German project sites, the remediation technologies being applied, and the types of contamination being remediated are listed in table 1. (The technologies likely to start in 1993 and therefore that will be preferentially studied in the bilateral agreement are underlined)

Table 1: German Remediation Projects

German Sites	Technologies	Type of Contamination
GASWERKE MUNCHEN	Soil-Washing + Volume Reduction of Residuals	PAH, Cyanides, Lead
VARTA SUD, Hannover	Soil-Washing (+ Acid Extraction)	Pb, Sb, As, Cd
KERTESS, Hannover	Ground Water Pump + Treat, Soil Vapor Extraction In-situ Soil-Washing	CHC + Degr. Products, CFC, HC, Monoaromatics
HAYNAUERSTRASSE 58, Berlin	Soil-Washing, Microbiology (ex situ), Rotary Kiln Thermal Treatment, Fluidized Bed Incineration of Residuals	CHC, PHC, Monoaromatics, PAH, PCB, PCDD, PCDF
BURBACHER HUTTE, Saabrucken	Thermal Treatment, Soil-Washing, Microbiology	Sulfides, Cyanides, Pb, Hg, Phenols, HC, Monoaromatics
TNT STADTALLENDORF	Soil-Washing + Incineration of Residuals	Munitions, TNT + Degradation Products, heavy metals

A brief description of the activities at these sites is as follows:

Gaswerke Munchen

The remediation of a former coal-gasification and gas-distribution facility in Munich, Germany, is coordinated by an interdisciplinary working group comprised of the site-owner, the city and state authorities and various technical consultants. The entire site of the former gas-works is about 32.5 hectare (81.25 acres) in size and is located about 1 km northeast of the city center. Various site investigations since 1982 showed that both the soil and the ground water are contaminated with PAHs and the top most layer of soil is further contaminated by lead. Slightly elevated concentrations of aliphatic hydrocarbons and cyanides were found throughout the site, with some higher peaks in limited areas. One of the hot-spots of the contamination (the "C 1 area", approx. 1 acre) was found to pose a substantial hazard to the ground water and will be remediated in a first phase of the overall site remediation which is subsidized by the Bundesminster für Forschung und Technologie (BMFT).

Soil washing was identified to be the appropriate remediation technology. 25,000 t of gravel will be treated on-site using a soil washing process that will be selected out of five optional technologies which are presently in an off-site pilot scale testing-phase. The five plants apply batch processes with or without detergents. Different systems are used for the separation of

the clean soil from the contaminant bearing fines. To supplement the treatment process, innovative treatment technologies like steam desorption and vacuum distillation will be applied in parallel with soil-washing for the treatment of the soil-washing residues.

Data on the contamination and the cleanup criteria identified are listed in table 2:

Table 2

	Soil-Contamination in mg/kg		Cleanup Criteria	
	maximum	average	soil mg/kg	eluate (pH7) µg/l
Pb	> 5,000	100 -1,000	< 150	-
CN total	> 1,000	> 50	< 50	< 50
PAH	> 7,000	≤ 500	< 20	< 0.2
HC alipbatic	> 10,000	≤ 500	< 500	

VARTA-Sud, Hannover

The goal of this project is the remediation of the "Varta-Sud" area which was contaminated by emissions from an adjacent battery factory between 1938 and 1989. The remediation of the site owned by the City of Hanover is being coordinated by a consultant with the support of the "Varta-Sud Assessment Group" which consists of independent scientists and engineers. The site is located northwest of Hanover and covers an area of 4.5 hectare (approx. 11 acres). From October 1989 to April 1991 the site investigation was performed showing lead, antimony and cadmium as main contaminants in the soil. Major hot spots are deposits of sediments from a creek ("Roßbruchgraben") which was used for waste water discharge by the battery factory. Slags from smelting and coal firing are distributed unhomogenously throughout the area and are of concern, as well as, landfills of debris, slags and residues from the battery production. Besides the heavy metals, a PAH contamination of unknown origin was detected in the south-eastern part of the site. The groundwater is not yet substantially contaminated with heavy metals. Some typical values are presented in table 3.

Table 3

	landfill material maximum concentration [mg/kg]	slag/soil mixture range of concentrations [mg/kg]
Pb	38,000	120 - 5,000
Sb	11,000	3 - 380
Cd	1,300	0.1 - 14
Σ PAH	1,000	0.05 - 10

At present (November 1992), the results of investigations and trial runs of different physical treatment technologies (water extraction, high pressure soil washing, chemical extraction, or combinations) are being evaluated. Concepts for the volume reduction of residues are designed. Decisions concerning the further proceeding in the project are expected by winter 1992.

KERTESS, Hannover

The project involves the remediation of an industrial area which was used for the handling and storage of organic solvents and detergents, as well as aromatic and halogenated hydrocarbons from 1946 until 1985. The owner of the site is the DB German Railroad (Deutsche Bundesbahn). The area is about 1 hectare (2.5 acres) in size and is located in the southern part of the City of Hannover. Site investigations in 1975 detected groundwater contamination and in 1976 the first remediation attempt (groundwater extraction and treatment) started. Due to the lack of efficiency of these measures the project management was reorganized and a new remediation concept was designed.

Major contaminants are chlorinated and aromatic solvents found in the vadose zone and on the bottom of the underlying aquifer (DNAPL). Table 4 lists average concentrations of selected contaminants as well as cleanup criteria identified by the State Secretary of Environment:

Table 4

	ground water [mg/m^3]	soil gas [mg/m^3]
trichloroethene	4,160	4,185
perchloroethene	6,050	2,150
chloroform	65	80
vinyl chloride	410	120
benzene / toulene	110 / 310	230 / 270
Σ CHC / Σ VOC*	18,300 / -	- / 14,935
Σ BTX	1,220	200
Cleanup Criteria Σ CHC	< 10 - 20 mg/m^3	< 1 mg/m^3

* chlorinated

Berlin: Haynauer Str.58

The site "Haynauer Straße 58" is situated in the south of Berlin, in the district of Steglitz and has an overall size of 3,100 m^2. The site was used for the reconditioning of solvents, chemical wastes and waste oils. The contamination of the site happened between 1952 - 1960. In 1980, the company was closed down. Major contaminants are petroleum hydrocarbons (PHC), BTEX, volatile chlorinated hydrocarbons (CHC), polychlorinated biphenyls (PCB), PCDD/F were found in the debris of demolition works.

Clean-up standards for soil are fixed by the "Berlin List":

- petroleum hydrocarbons (PHC) 150 mg/kg
- BTEX 2.5 mg/kg
- total high-volatile chlorinated hydrocarbons (CHC) 2.5 mg/kg
- total PCBs 0.5 mg/kg.

For ground water the following clean-up standards are fixed:

- CHC 25 µg/l
- BTEX 10 µg/l
- PHC 250 µg/l
- PCBs 0.25 µg/l.

The remediation concept for this site is a combination of different individual

technologies:

- PCDD/F-contaminated debris are treated thermally in a rotary kiln
- full-scale, off-site soil washing plant will be used for the main portion of the contaminated soil (40,000 t)
- residuals will be incinerated in a fluidized bed process or treated microbiologically
- slightly contaminated soil will be treated microbiologically
- full scale soil vapor system is used for the decontamination of soil vapor
- ground water is treated.

The soil of the site will be excavated emission-free in three phases. Remediation phase 1 was started in fall 1991 and finished in August 1992. In this step an overall contained third of the site (approx. 700 m^2) was excavated to a depth of 7 m below ground level. An amount of 7,100 m^3 soil was treated by soil washing, 600 t microbiologically. The cleaned soil was reembedded on site.

Soil vapor extraction has been performed since 1990. In the first half of 1993 the thermal treatment process will be started for the residuals and debris as well as the ground water treatment.

In fall 1992 the 2nd remediation phase was prepared. About 1,600 m^2 of the site was covered in order to avoid emissions during excavation. Work was finished in October 1992. Soil excavation was started in November 1992. Again the contaminated soil is treated by soil washing and microbiologically.

Burbacher Hütte

The "Burbacher Hütte", founded in 1857 is located in the western part of Saarbrücken. In times of peak productivity the Burbacher Hütte reached its maximum size with approx. 60 ha (600,000 m^3).

Contamination of the soil started when the steelworks was founded in 1857 and continued until the end of the 1980's when all production plants were demolished. In the past, there were different individual production plants, e.g. coke factories, benzene works, gas generation plant etc. which caused specific contamination at the Burbacher Hütte site. The following main contaminants were found in different parts of the site:

- BTEX
- phenols
- PAHs
- heavy metals (e.g. lead and mercury)
- sulfides and cyanides.

In addition, in some areas of the site ammonium has been detected at elevated concentrations.

In 1991 - 1992 full-scale pilot-tests were performed with different technologies on-site and off-site:

- soil extraction

- bioremediation
- soil washing and
- high temperature incineration.

At present the results of these pilot-tests are being evaluated. The remediation concept will be a combination of these different technologies for the various, individual groups of contaminants.

A decision on a suitable combination of technologies is expected to be made in late fall of 1993. Start of the actual remediation will be in 1994 after passing the permitting process.

Stadtallendorf

The former ammunition and explosives factory Stadtallendorf is located approx. 100 km north of the city of Frankfurt. The production area of the former DAG-site had a size of ca. 4.2 km^2 with 413 buildings having an overall base of ca. 62,000 m^2. In March 1941, the TNT production was started. Within the following 3 years the production raised from zero to 5,400 tons per month. The overall production and processing amounted to ea. 126,000 tons of TNT and 27,000 tons of other explosives. Production stopped on March 28, 1945. After World War II the U.S. Army used the site as storage for ammunition, gear and tools. Between 1946-1949 almost all production plants were demolished or blasted. Today, the site of Stadtallendorf is mainly characterized by mixed use including residential areas, industrial sites and the former ammunition and explosives factory. About 3,000 inhabitants of Stadtallendorf are living and working in the former bunkers or in the converted production buildings or related facilities remaining on the site.

Between 1938 and 1945 the site of the ammunition factory was contaminated with:

- explosives, e.g. TNT, H.N.D., RDX;
- raw materials and pre-fabricates of the explosives production, e.g., toluene, mono-and dinitrotoluenes;
- degradation products, e.g. (di-)nitro-aminotoluenes;
- miscellaneous pollutants like phenols, heavy metals and others.

Contamination of soil and groundwater at Stadtallendorf was caused by unsafe production methods, uncontrolled waste disposal, insufficient waste water treatment, accidents, leakages and others.

The envisaged remedial technology for contaminated soil is a combination of soil washing with a high-temperature combustion of the contaminant-bearing residues. For soil decontamination the clean-up targets are defined as 1 mg/kg for explosive-related contaminants. Soil washing and thermal treatment is to be started in 1995.

At present additional investigation of a 6 ha hot spot area are being conducted. In a trianguarily shaped grid additional borings are being carried out at the former production plants (TNT Groups 1-3 ruling plants). First results indicate that the main contamination with varying concentrations was found at a depth of 0-1m below ground level. The detailed results of this investigation phase will be the foundation of the future remedial concept.

Furthermore, a new analytical method for the analysis of TNT by means of HPLC and electro-chemical detection was performed by a scientific expert team because there was no analytical standard procedure for TNT in Germany. This analytical method will be published in January 1993.

The United States sites are summarized with their main characteristics in table 5.

Table 5. U.S. Remediation Projects

U.S. Sites	Technologies	Types of Contamination
Waukegan Harbor Site (Outboard Marine Corp.), IL	Anaerobic Thermal Treatment on Site	PCB, Oil & Grease
Kelly Air Force Base San Antonio, TX	Radio Frequency Induced Heating	VOC'S, SVOC'S, TPH
Electro-Voice NPL Site Buchanan, MI	Subsurface Volatilization and Ventilation System (SVVS)	BTEX, PCE, TCE, 1, 1-DCE
Lawrence Livermore, Site 300, GSA Altmont Hill, CA	Advanced Oxidation, Perox-Pure	VOCs, TCE, PCE
Indiana Wood Preservers Site Bloomington, IN	Bioremediation	Creosote/Coal Tar, PAHs Naphthalene, Anthracene
Pennsylvania Power & Light (PP&L) Brodhead Creek Site Stroudsburg, PA	Contained Recovery of Oily Waste (CROW)	Organic Liquids, Coal Tars, PAH, Phenols

A brief description of these activities at these sites is as follows:

Outboard Marine Corporation (OMC), Waukegan, Illinois

Outboard Marine Corporation (OMC) used PCBs as a hydraulic fluid at the Waukegan Harbor facility. As a result of leaks and spillage major parts of Waukegan Harbor's 37 acres and parts of the manufacturing facility were contaminated with PCBs up to 10,000 ppm (mg/kg). The OMC site remediation included dredging and excavating the PCB contaminated sediments and soils; treating the high PCB concentration soils and sediments; and placing low concentration PCB soils and sediments in one of several isolation cells.

Thermal desorption was the selected treatment technology for the high concentration PCB soils and sediments. SoilTech's Anaerobic Thermal Processor (ATP) treated these solids after natural dewatering occurred. The ATP system mixes and heats the solids in the processing unit, which consists of four

zones; preheat, retort, combustion and cooling. Temperatures in the preheat zone (400 - 650^0) cause the water and volatile organic compounds (VOCs) in the solids to vaporize. The higher temperatures in the retort zone (900 - 1,150^{0}F) cause (1) heavy organics to vaporize and (2) thermal cracking of hydrocarbons creating coke and low molecular weight gases. In the combustion zone the coked solids are combusted and either recycled to the retort zone or passed into the cooling zone. Gases from the preheat and retort zones are cooled and condensed to recover the water and organics; while the noncondensable organics are burned in the combustion zone.

In June 1992 a USEPA SITE Demonstration was performed on the SoilTech ATP system operating at the OMC Waukegan facility. Three replicate test runs were conducted at the typical operating conditions used during the OMC site remediation. Each test run consisted of 8.5 hours of solids and liquids sampling and 8 hours of stack sampling. A total of 224 tons of PCB contaminated soil and sediment was treated during the Demonstration. Extensive process operating data were collected to document the ATP operating conditions. Key findings from the OMC/SoilTech SITE Demonstration included:

1) PCB concentrations were reduced from an average of 9,761 ppm in the untreated solids to an average of 2 ppm in the treated solids.

2) Approximately 0.12 milligrams of PCBs were discharged from the ATP stack per kilogram of PCBs fed to the ATP (0.12 mg/kg or 99.9999% DRE).

3) The majority of PCBs removed from the solids during treatment were accumulated in the organic storage from the gas condensation.

4) No dioxins, other than a low concentration (0.1 nanograms (ng) per dry standard cubic meter (dscm) of octachlorinated dioxin, were detected in the stack gas from the ATP system. Tetrachlorinated furans were found in both the untreated (88 ng/g) and treated (5 ng/g) solids and the stack gas (0.07 ng/dscm).

5) Leachable VOCs, semivolatile organic compounds (SVOCs) and metals in the treated solids were below RCRA toxicity characteristic standards.

6) No operational problems affecting the ATP's ability to treat the contaminated solids were observed.

KELLY AIR FORCE BASE - San Antonio, Texas

Site S-1, located near the northern boundary of Kelly Ait Force Base was used from 1960 to 1973 as an intermediate storage area for wastes awaiting off-base reclamation. Waste liquids consisting of mixed solvents, carbon cleaning compounds and petroleum oils and lubricants were hadled here. Spills and storage tank flooding resulted in soil contamination from these chemicals. At the conclusion of waste handling operations in 1973, the area was backfilled and regraded. This resulted in soil contamination at depths of up to 27 to 30 feet. The vadose zone extends to this depth.

Volatile and Semi-volatile organic contamination at the site occurs at concentrations ranging from 8.5 to 104,000 ppb. Total Petroleum Hydrocarbon (TPH) concentrations range from 20 to 17,000 ppm. Specific contaminants found

at the site include a variety of short chain chlorinated hydrocarbons such as 1,2-Dichlorobenzene, 1,4-Dichlorobenzene and 1,3-Dichlorobenzene, aromatic hydrocarbons such as benzene, ethylbenzene, chlorobenzene and styrene and polycyclic aromatic hydrocarbons such as Dibenzo Anthracene, Benzo Pyrene and Benzo Fluoranthene. Some very low concentrations of PCBs have also been detected.

In-Situ Radio-Frequency Heating will be studied at site S-1 to determine its efficacy in removing volatile and semi-volatile organic contamination from vadose zone soils. This technology was developed by the Illinois Institute of Technology Research Institute (IITRI) and will be demonstrated for the Air Force with the assistance of Haliburton NUS. The system consists of a 120kW RFH power source, excitor and ground electrodes, a vapor barrier and a vapor treatment system.

For the test, the excitor and ground electrodes will be placed in the ground at S-1 in a predetermined array. Thermocouples will be placed in the ground with the electrodes to monitor ground temperature. Heat generated by radio-frequency radiation will heat the soil to approximately 150^{0}C. The elevated temperature combined with steam distillation resulting from the vaporization of soil moisture will sweep organic contamination from soil. A vacuum will be maintained on the soil area under treatment in order to capture released contamination. A vapor barrier installed atop the soil treatment area will prevent the release of contaminant laden gasses to the atmosphere. These gasses will be captured by the vapor barrier and treated by both condensation and carbon filtration.

Development of the demonstration plan is currently under way. Electrode placement and pre-test soil sampling should occur in early 1993. System set up and treatment of 500 cubic yards of contaminated soil from S-1 will take place in mid-1993. Post test soil sampling will be completed by the end of July 1993. Data analysis and reporting will be completed as soon as possible thereafter.

SVVS Demonstration, Buchanan, Michigan

This SITE Program Demonstration will assess the effectiveness of the Soil Volatilization and Ventilation System™ (SVVS™) developed by Billings & Assoc., Inc. of Albuquerque, NM and offered under license through Halliburton NUS. The technology is a combined air-sparging/soil-vacuum-extraction technique which moves air into the water table through injection wells and draws air from the vadose zone through extraction wells. At some installations, one injection and multiple vacuum wells are placed in the same soil boring, resulting in a "well nest." In this installation, injection and vacuum wells are placed in individual borings. The movement of air through the subsurface stimulates the activity of aerobic microorganisms resulting in a quicker remediation of organic contamination than by soil vacuum extraction (SVE) alone. Vapors collected in the SVE portion of the system can be treated in Biological Emissions Control™ (BEC™) units reducing or removing the need for carbon adsorption or other expensive emissions controls.

The Demonstration site chosen is the Electro-Voice site, a Superfund (National Priority List [NPL]) site in Buchanan, Michigan. This site in southwestern Michigan is an operating factory producing electrical sound

amplification equipment. Formerly, liquid painting residues were discharged to a "drywell," a lined pit backfilled with gravel, next to the factory facility. This practice was discontinued and the drywell filled with soil and construction debris in 1973.

Sampling conducted during the NPL process revealed a sludge-like layer at the bottom of the former drywell. Initially, peak soil concentrations were observed for alkylbenzenes (454,000 ppb), benzene (350 ppb), 2-butanone (4,900 ppb), 1,1-dichloroethane (200 ppb), 1,2(cis)-dichloroethene (200 ppb) ethylbenzene (95,000 ppb), styrene (3,400 ppb), tetrachloroethene (14,000 ppb), toluene (330,000 ppb) trichloroethene (590 ppb), and total xylenes (710,000 ppb). During sampling prior to the Demonstration, peak soil concentrations were sought for toluene (96,000 ppb), ethylbenzene (64,000 ppb), m,p-xylene (190,000 ppb), o-xylene (29,000 ppb), benzene (210 ppb), 1,1-dichloroethene (130 ppb), trichloroethene (18,000 ppb), and tetrachloroethene (16,000 ppb).

The SVVS™ technology is to be evaluated for its ability to meet a claimed 30% reduction in seven combined contaminants (benzene, toluene, ethylbenzene, xylene [BTEX], tetrachloroethene [PCE], trichloroethene [TCE], and 1,1-dichloroethene [DCE]) in the vadose zone within 12 months of operations. Further, data collected during the SITE Demonstration will investigate the relative contribution of the two primary mechanisms of removal: bioremediation and air-stripping. Finally, the effectiveness of the BEC™ unit at meeting State of Michigan air emissions standards will be evaluated. Vinyl chloride levels in the soil will also be monitored. In order to assess the claimed 30% reduction, twenty soil borings will be located within the 113 m^2 area before the start of operation, and twenty more soil borings will be obtained following 12 months of operation. From each soil boring, seven soil samples will be obtained for Volatile Organic Contaminant (VOC) analysis with special quality assurance/quality control measures performed for the seven "critical analytes" and vinyl chloride. Analyses of the gasses entering and leaving the BEC™ unit will be conducted periodically throughout the 12 months. Additionally, soil gas measurements, groundwater analyses, soil VOC levels from the saturated zone, and *in-situ* biological respiration data will be obtained.

Lawrence Livermore National Laboratory; Site 300 Demonstration, Altamont Hill, California

The perox-pure™ technology is designed to destroy dissolved organic contaminants in groundwater or wastewater through an advanced chemical oxidation process using ultraviolet (UV) radiation and hydrogen peroxide. Hydrogen peroxide is added to the contaminated water, and the mixture is then fed into the treatment system. The treatment system contains four or more chambers in the reactor. Each chamber contains one high-intensity UV lamp mounted in a quartz sleeve. The contaminated water flows in the space between the chamber wall and the quartz tube in which each UV lamp is mounted.

UV light catalyzes chemical oxidation or organic contaminants in water by its combined effect upon the organics and reaction with hydrogen peroxide. First, many organic contaminants that absorb UV light may undergo a change in their chemical structure or may become more reactive with chemical oxidants. Second, and more importantly, UV light catalyzes the breakdown of hydrogen

peroxide to produce hydroxyl radicals, which are chemical oxidants.

Site Description:

Site 300 is a high-explosive test area, established by LLNL in 1955. It is comprised of 11 square miles and is about 60 miles east of San Francisco, and 15 miles east of Livermore, California. Operations at Site 300 include hydrodynamic testing; charged particle beam research; physical, environmental, and dynamic testing; and high-explosive formulation and fabrication. The demonstration took place in a section of Site 300 called General Services Area (GSA). This area is contaminated with VOCs, including trichloroethane (TCE), tetrachlorethane (PCE), 1,1-dichloroethane (1,1DCE), 1,2-dichloroethane (1,2-DCE), and 1,1,1-trichloroethane (1,1,1-TCA).

Additional monitoring measures included the following:

- VOC Purge and Trap GC-MS (method 8240), additionally to the target compounds, TIC (10 largest peaks) are identified applying NBS-search
- SVOC Method 8270 (GC-MSO, additionally to the target compounds, TIC (10 argent peaks) are identified applying NBS-search.
- AOX/TOX During each run of the plant at the fed-line and at the effluent-line on sample each is taken for TOX (method 9020). "AOX" including the purging step was performed with 20% for the samples additionally. Thus, a basis for a comparison between the two methods will be available, the risk of errors due to poor data quality is minimized. A summary of the results will be supplied.

Indiana Wood Preservers (IWP) Site, Bloomington, Indiana

The IWP site was operated from 1976 to 1987. A solution of creosote/coal tar was used as an agent for preservation of railroad ties. IWP utilized the Boulton process which involves the application of an initial vacuum, the pressure impregnation of the creosote/coal tar solution into the railroad ties. There is a total of 35,000 gallons of liquid and 355 cubic yards of sludge/contaminated soil existing in two holding ponds, as well as 890 cubic yards of contaminated debris in a waste pile on site.

Bioremediation was chosen for the treatment of the contaminated soils removed from the holding ponds. Because of the limited amount of space available at the site, it was decided that the biodegradation would take place in constructed compost piles. This treatment process would also add additional organic sources to allow co-metabolism to assist in the degradation as well as the direct mineralization of the polynuclear aromatic hydrocarbons (PAHs) present in the contaminated soil. Preliminary studies were conducted at the laboratories of International Technology Corporation in Knoxville, Tennessee. It was determined that the soils contained between 1.0×10^5 to 1.0×10^7 hydrocarbon degraders per gram of soil and that the PAHs could be degraded.

The compost piles are made of a mixture of 17 parts of soil, 4 parts of horse manure, and one part of straw. Each compost pile is 20 meters long, 10

meters wide, and 2.5 meters high. As the pile was being built, hollow plastic piping was placed from the outside of the pile leading into the heart of the pile. This piping was added all around the pile and at different heights in order to allow air into the pile to supply oxygen for the microbial degradation of the PAHs. Laboratory studies had shown an average oxygen consumption rate of 64.8 mg O_2/kg hour.

The compost piles have been built and are in operation. The analytical test results have not yet been received. Consideration is being given to a series of treatments consisting of biological treatment, followed by chemical treatment with Fenton's reagent (hydrogen peroxide and ferrous iron salt, which is a powerful radical oxidant), followed by additional biodegradation to attempt to bring the final PAH concentration of the treated soil to a level significantly below that which could be achieved by biodegradation alone.

Pennsylvania Power and Light (PP&L), Brodhead Creek Site, Stroudsburg, Pennsylvania

The Brodhead Creek Superfund site in Stroudsburg, Pennsylvania has been selected for the demonstration of the contained recovery of oil wastes (CROW) process. The primary contaminant at the site is coal tar produced as a byproduct of a coal gasification plant. Identifiable contaminants include benzene, polynuclear aromatic hydrocarbons (PAHs), and phenols. A large amount of coal tar has migrated through the surficial aquifer and is now pooled in a depression approximately 6 meters wide and 18 meters long. The aerial extent of the pooled coal tar will be better defined during a predesign sampling effort tentatively scheduled for early December 1992.

The CROW process was selected in a record of decision (ROD) as an interim remedy to reduce the amount of free coal tar pooled at the base of the aquifer. The CROW process will use a system of injection and recovery wells to remove the coal tar. Water heated to a temperature of approximately 90 degrees Celsius will be injected at the base of the aquifer through sic to eight injection wells on all sides of the pooled coal tar. Dual completion recovery wells located in the center of the coal tar pool will be used to recover ground water and coal tar. The lower completion recovery well is designed to recover the injected water and coal tar; the upper completion recovery well is intended to maintain a copy of cooler ground water over the treatment area. The maintenance of a cool water cap over the treatment area is intended to prevent contamination from migrating into the unsaturated zone. The fluids produced from the recovery wells will be sent to an oil-water separator for treatment. Most of the outflow water from the oil-water separator will be reinjected by the CROW process, while the remainder of the water will be treated in a bioreactor and discharged to Brodhead Creek. If the water does not meet the requirements of a National Pollutant Discharge Elimination System (NPDES) permit, treatment in the bioreactor will be followed by carbon adsorption. The U.S. Environmental Protection Agency (EPA) Region 3 has set the cleanup criteria at 60 percent removal of the free coal tar measurable in monitoring wells. Remediation Technologies, Inc. (ReTech), the prime contractor supervising the remedial effort for the potentially responsible parties, has indicated that the CROW process will be operated until the amount of recovered contamination has stabilized.

The Superfund Innovative Technology Evaluation (SITE) program will monitor all phases of CROW process installation, operation, and post-operation sampling. The steps that will be undertaken to design and build the CROW process include predesign sampling, process design, construction, and operation. If the current schedule is followed, the predesign sampling will occur in December 1992, the design will be completed by May 1993, construction will be completed by the end of July 1993, and the system will be operated from August 1993 through October and possibly into December 1993. During the predesign sampling, the SITE program will collect samples of the site soil and pure coal tar. The samples will be used to refine and validate the analytical methods. The SITE program demonstration will include soil and ground-water sampling and monitoring of operational parameters. Soil samples will be collected before and after the CROW process operation to determine the reduction of subsurface contaminants. The ground water, injected water, and recovered water will be sampled to determine the amount of contamination recovered. During CROW process operation, the SITE program will monitor pumping rates' injected, recovered, and ground-water temperatures; and water levels. The data collected will be used to evaluate the effectiveness of the CROW process at the Brodhead Creek Superfund site and to determine the factors that will affect the CROW process at other sites.

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Groundwater Remediation: Extraction and Removal of TCE & Cr^{6+} at an NPL Site

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This case study focuses on the engineering analysis of a treatment process used in a National Priority Listed (NPL) site in a midwestern State within the continental United States. The primary contaminants intended to remove from the groundwater at this site are Trichloroethylene (TCE) and hexavalent chromium (Cr^{6+})

The groundwater treatment plant, for this site belonging to an aircraft repair and paint company, is designed for a flow rate of 150,000 gal./day (567 m^3/day). The cleanup period is estimated to be 30 years. The treated water is planned for industrial reuse at the same facility.

The waste characteristics of this NPL site are very common to many aerospace industries and other industrial sites. The cleanup method used at this site for TCE and Cr^{6+} removal could be used in similar other sites since it renders a high (99.99%) contaminant removal efficiency and offers an environmentally clean method with very minimal sludge/waste generation.

Based upon the result of a study, involving a complete engineering analysis of several different processes that are available for removal of organics, mainly trichloroethylene (TCE), and metals, primarily hexavalent chromium (Cr^{6+}), the following treatment train was selected for this NPL site.

- Organic Removal Process
- Metals Reduction Process
- Metals Precipitation process
- Final polishing process

The treatment processes for the groundwater treatment plant (GWTP) are summarized below:

1. The Organic Removal process consists of the Aquadetox system, developed by Dow Chemical and patented for removal of high boiling organic compounds. This process has been found to be effective in removal of most of the organic compounds, which are listed as hazardous by the U.S. Environmental Protection Agency (EPA). The stripping technology, whether an air stripper or a steam stripper, can provide 99.9999% removal efficiency. The effluent from this process is expected to have non-detectable concentration (less than 1 ppb) of the organic contaminants. The Aquadetox process is also accepted under the EPA's Superfund Innovative Technology Evaluation (SITE) program. This technology, working at over 10 locations, eliminates any carbon polishing of the effluent water. The conventional air stripping provides only about 90-95% removal of volatile organic compounds.

2. The Metals Removal Process consists of the following:

The incoming groundwater contaminated with hexavalent Chromium (Cr^{6+}) is treated by a reduction process first. This reduces the Cr^{6+} to the trivalent form, Cr^{3+}. The metal is then removed as precipitate from the groundwater.

In the first stage of treatment, the pH is lowered to 2.5 by the addition of 98% Sulfuric acid (H_2SO_4); a pH probe in the tank controls this addition. The stream is made acidic to facilitate the reduction reaction. The reducing agent to be used in the process is sodium metabisulfite ($Na_2S_2O_5$). This chemical reduces the hexavalent chromium, Cr^{6+}, to trivalent chromium, Cr^{3+}.

The automatic addition of sodium metabisulfite is controlled by an Oxidation Reduction Potential (ORP) measuring instrument. Proper reduction of chromium can be seen readily by a color change from yellow to blue in the treatment tank.

After being reduced, the stream from the first stage flows to the second stage tank for primary precipitation treatment. The pH is raised to 9.0 to precipitate the trivalent chromium as a chromium hydroxide. This is accomplished by adding a 50% sodium hydroxide solution; the amount of addition is controlled by a pH probe. Chromium is an amphoteric metal which means that it is highly soluble at both a low pH as well as at a high pH. For this reason the pH is maintained at the optimum value of 9.0. Practically, this value can not be precisely controlled due to the addition of the sodium hydroxide in large quantity. If the pH differs greatly from this value, excess trivalent chromium remains in the solution. At a pH of 9.0 the trivalent chromium and other heavy metals precipitates as metal hydroxides. The sludge generated by this process is expected to be 75% less than that generated by the Ferrous Sulfate process, which is commonly used in old metal processing/plating industries.

A secondary precipitation of these metals occurs in the pH adjustment tank, where the pH is maintained at 9.0 (for further precipitation) by adding sodium hydroxide or sulfuric acid as required. Thus if the pH goes to a value of 10.0, it is lowered to 9.0 by adding sulfuric acid. Likewise, if the pH falls to 8.0, sodium hydroxide is added to raise the pH to 9.0. This addition is controlled by a pH probe located within the tank. The precipitated metal hydroxides exists as light density particles.

The treated water is then transferred to the flash mix tank of the clarifier, using a centrifugal pump. The pumping is controlled automatically by a level monitoring probe which cycles the pump on or off. To promote flocculation, a polyelectrolyte is added to the stream.

The effluent from the precipitation process has a chromium concentration of about 20-50 parts per billion (ppb). The effluent then passes through the final polishing process to further reduce the concentration of chromium and other heavy metals to 10-15 ppb.

3. The Fine Filtration Process involves a Polymer Enhanced Cross Flow Sand Filtration.

This sand filtration system,Dynasand™ is a patented process. It has some unique features in sand filtration. It is a continuous, backwash, upflow, deep and granular media filter. The filter media is continuously cleaned by recycling the sand internally through an airlift pipe and sand washer. The regenerated sand is redistributed on top of the sand bed allowing for a continuous uninterrupted flow of filtrate and reject water.

Feed is introduced into the bottom of the filter, then flows upward through a series of riser tubes and is evenly distributed into the sand bed through the open bottom of an inlet distribution hood. The influent flows upward through the downward moving sand bed with solids being removed. The clean filtrate exits from the sand bed, overflows a weir, and is discharged from the filter. Simultaneously, the sand bed, along with the accumulated solids, is drawn downward into the suction of an airlift pipe which is positioned in the center of the filter. A small volume of compressed air is introduced into the bottom of the airlift. The sand, dirt, and water are transported upward through the pipe at a rate of about 200 gpm/ft^2. The impurities are scoured louse from the sand during this turbulent upward flow. Upon reaching the top of the airlift, the dirty slurry spills over into the central reject compartment. The sand is returned to the sand bed through the gravity washer/separator, which allows the fast settling sand to penetrate, but not the dirty liquid. The washer/separator is placed concentrically around the upper part of the airlift and consists of several stages to prevent any short circuiting. By setting the filtrate weir above the reject weir a steady stream of clean filtrate flows upward, countercurrent to the sand, through this washer section and acts as a liquid barrier that carries away the dirt and reject water. Since the sand has a higher settling velocity than the dirt particles, it is not carried out of the filter. The sand is redistributed by means of a sand distribution cone. The sand bed is continuously cleaned while both a continuous filtrate and a continuous reject stream are produced.

For an effluent of 10 ppb to 20 ppb at a flow rate of 65 to 70 gpm, a Filter with a Polyblend emulsion polymer feed system is recommended for the polishing process. This proven process has been successfully used at an AT&T plant in Mesquite, Texas and in a Groundwater treatment plant of Stauffer Chemical Co. in Martinas, California. The effluent chromium level of 10 ppb was attained by using just the sand filters at that treatment facility. A simplified flow chart of the proposed groundwater treatment process is shown on Figure 1.

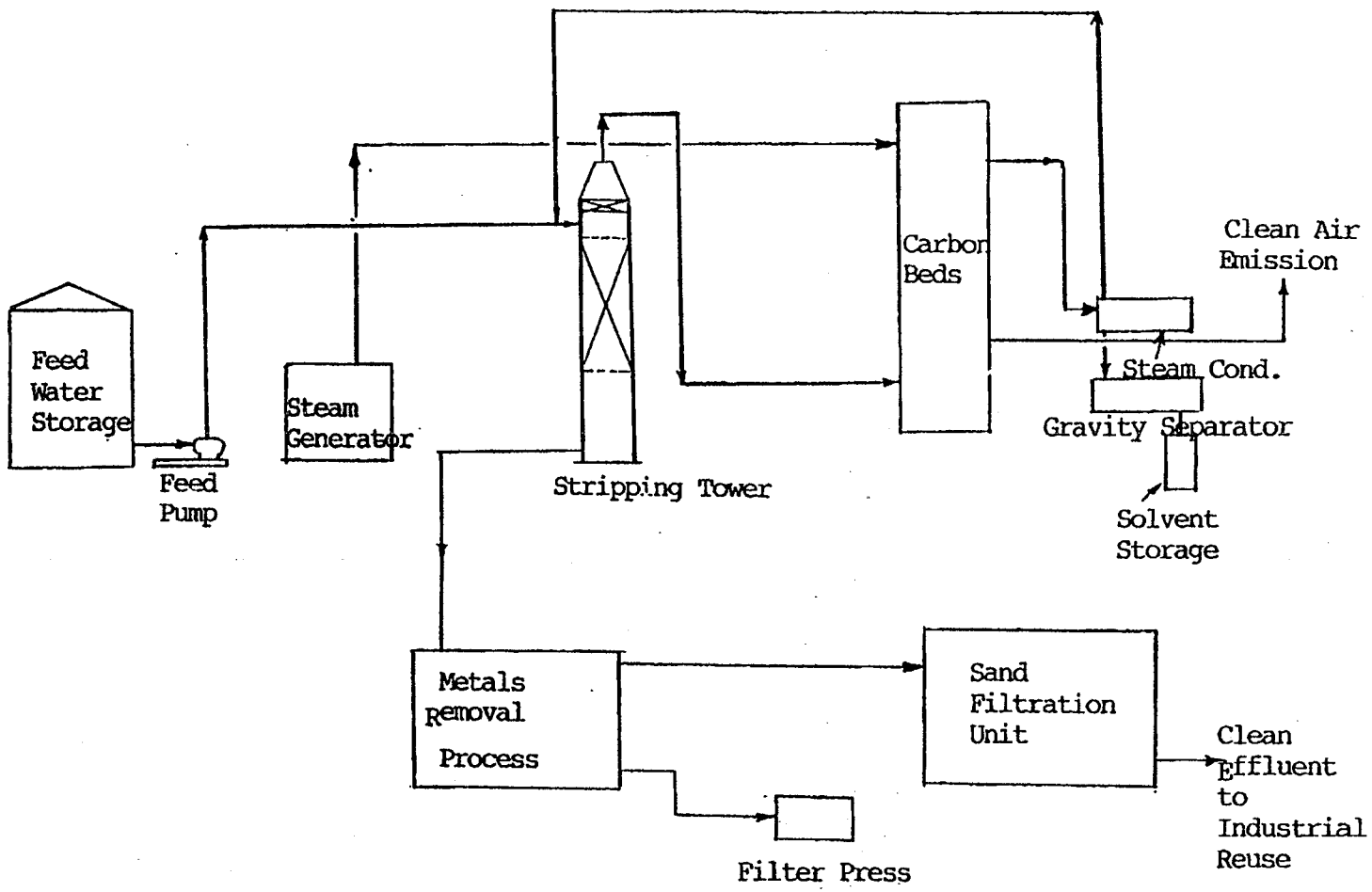

FIGURE 1 Flow chart of the proposed groundwater treatment plant

The annual operating cost of this system is very low compared to the reverse osmosis or ion exchange systems, since the Dynasand™ system gets continuously regenerated. The only operational cost involved in this process is the electric utility cost and the polymer cost. Labor cost is minimal in this operation.

The automated control mechanism routes the water through the optional polishing process if, and only if, the concentration of chromium in the effluent is over 50 ppb, or any other desired value. The polishing process involves fine filtration. The whole process is completely automated which cuts down a significant cost of this long-term cleanup operation.

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THE USE OF HORIZONTAL WELLS IN REMEDIATING AND CONTAINING A JET FUEL PLUME - PRELIMINARY FINDINGS

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ABSTRACT

A Pilot Study/Demonstration Study (PS/DS) is being performed at Williams Air Force Base in Chandler, Arizona, to demonstrate the ability of horizontal wells to remediate and contain a jet fuel plume. The jet fuel plume is floating on the water table at approximately 220 ft below ground surface. The associated dissolved plume flows east-southeast in the shallow aquifer that is approximately 25 ft thick.

One horizontal well is installed in an east-west direction with the screen located approximately 15 ft below the floating jet fuel. This well is parallel to the long axis of the plume. During the PS/DS, this well will be evaluated for the ability to capture the most contaminated section of the plume. Based on testing of the first horizontal well, a second horizontal well may be installed in a north-south direction near the downgradient edge of the dissolved plume. This well will be perpendicular to the long axis of the plume. During the PS/DS, this well will be evaluated for the ability to act as a barrier to plume migration.

A short-term pumping test has been performed on the horizontal well. Short- and long-term pumping tests have been performed on vertical extraction wells also installed at the site. Preliminary findings of these pump tests are compared and discussed.

1. INTRODUCTION

The U.S. Air Force Air Training Command is conducting a Pilot Study/Demonstration Study (PS/DS) at Williams Air Force Base in Chandler, Arizona, which is listed on the Environmental Protection Agency National Priorities List. The purpose of this PS/DS is to evaluate the ability of horizontal vs vertical extraction wells for the remediation and containment of a jet fuel plume at the liquid fuels storage area (LFSA). The PS/DS is performed under an interagency agreement between the Department of Defense and the Department of Energy that is being administered by Martin Marietta Energy Systems, Inc.'s, Hazardous Waste Remedial Actions Program (HAZWRAP). CDM Federal Programs Corporation has been contracted by HAZWRAP to conduct the PS/DS.

The LFSA covers approximately 5 acres and has been used since 1942. The fuel storage system was composed of numerous underground storage tanks and several thousand feet of 4-in.- and 6-in.-diam delivery pipes. Most of this fuel storage system has been removed. Leaking tanks and fuel lines

have resulted in a JP-4 jet fuel plume in the uppermost aquifer. This plume consists of a free product plume (650,000-1,400,000 gal) (IT Corporation 1992) and an associated dissolved contaminant plume.

Beneath the site, an unsaturated zone of intermixed clay, silt, sand, and several gravel zones and thin caliche layers extends to a depth of 220 ft below land surface (bls). These deposits are representative of channel, floodplain, terrace, and alluvial fan deposition (Laney and Hahn 1986). The shallow aquifer is approximately 25 ft thick and is composed of intermixed clay, silt, and sand. Underlying the shallow aquifer is a clay aquitard approximately 20 ft thick. Below the aquitard is a semiconfined aquifer that is several hundred feet thick and is used as an irrigation and drinking water supply.

Investigations between 1984 and 1992 resulted in the installation of 31 shallow and 5 deep monitoring wells (Fig. 1). Potentiometric data from the site indicate that groundwater flow in both aquifers is to the east-southeast. The eastern extent of the aquitard is currently unknown, although it has been identified in three downgradient compliance wells more than 1000 ft from the LFSA. Apparent product thickness measurements from wells within the free product plume vary from <0.1 ft to >10 ft. Groundwater sampling results indicate a large dissolved contaminant plume in the shallow unconfined aquifer associated with the free product plume.

2. PROJECT PURPOSE AND SCOPE

The purpose of the PS/DS is to compare the effectiveness of horizontal and vertical extraction wells in containing and remediating contaminated groundwater from the shallow unconfined aquifer. Before contracting installation of the first horizontal well, a groundwater model was used to help evaluate potential effectiveness of horizontal wells at this site. The model, which will be discussed in more detail later, indicated that horizontal wells would be an effective means of capturing the contaminant plume.

Based on the plume geometry, hydrogeological characteristics, and modeling results, it was determined that the optimum placement of the first horizontal well would have an east-west orientation with a screen 500 ft in length located approximately 15 ft below the floating jet fuel (235 ft bls). This well, parallel to the long axis of the plume, is the longest and deepest horizontal well ever installed for environmental cleanup applications. During the PS/DS, this well will be evaluated for the ability to capture the most contaminated portion of the plume. If testing of this horizontal well indicates efficient plume recovery, a second horizontal well with a screen 500 ft in length will be installed in a north-south orientation near the downgradient edge of the dissolved plume. This well will be perpendicular to the long axis of the plume. During the PS/DS, this well will be evaluated for the ability to act as a barrier to plume migration.

Two vertical extraction wells were installed near the upgradient edge of the free product plume to compare the efficiency of horizontal and vertical wells at this site . Both a 4-in.- and a 10-in.-diam extraction well were installed to evaluate the increase in efficiency with well diameter. Two additional monitoring wells were installed for use as observation wells during aquifer testing.

Upgradient of the plume, four 4-in.-diam injection wells were installed in the unsaturated zone. Groundwater will be extracted during long-term tests from the horizontal and vertical extraction wells, treated in a wastewater treatment plant, and reinjected into the shallow unconfined aquifer. This

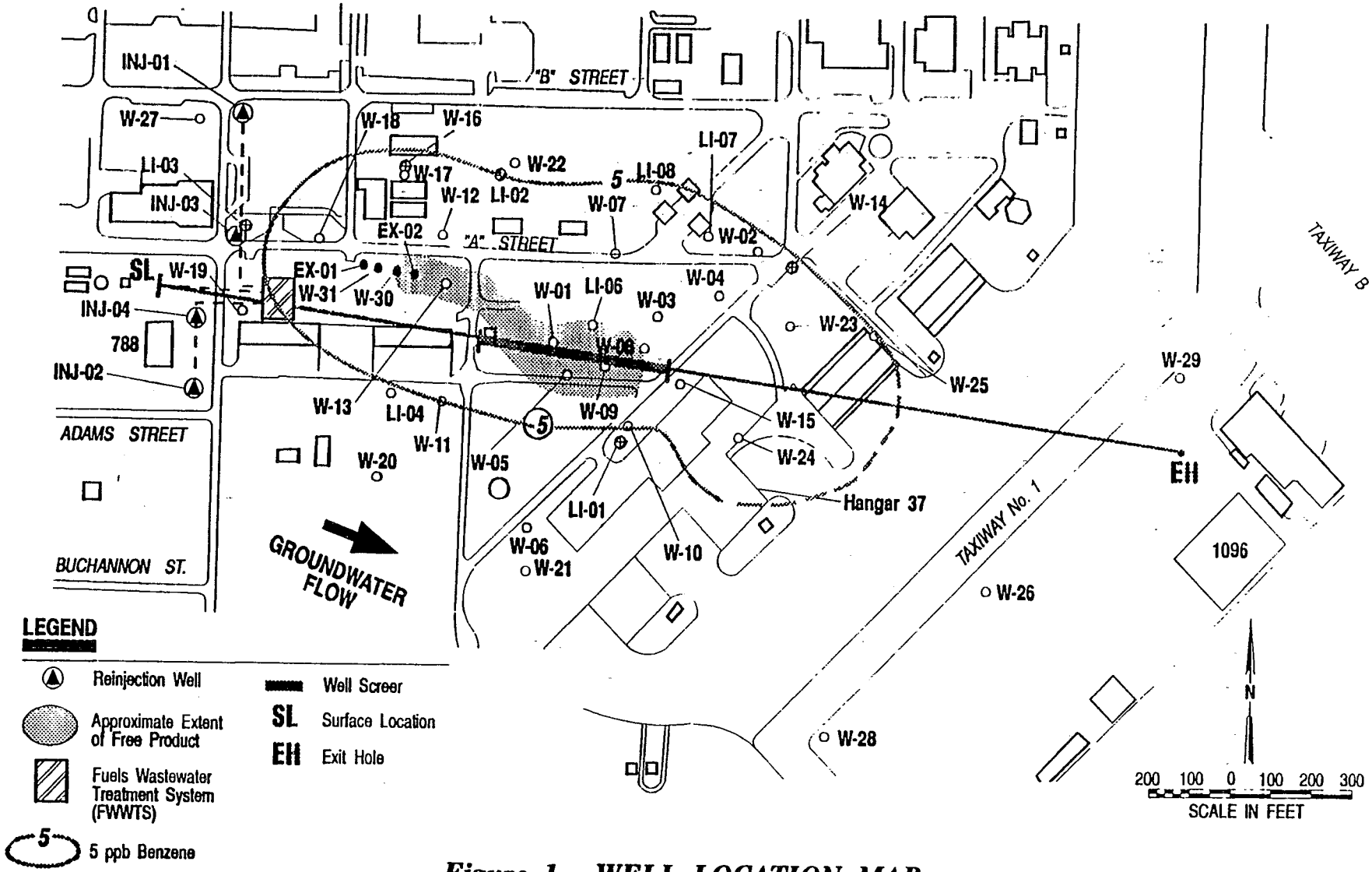

Figure 1. WELL LOCATION MAP.

should prevent dewatering of this relatively thin, low-yielding aquifer and accelerate the rate of cleanup by creating a groundwater mound upgradient of the plume.

3. PRELIMINARY MODELING

A three-dimensional model (DYNFLOW) using a horizontal finite element grid of 725 nodes and 1344 elements was used to simulate the potential effectiveness of horizontal wells at this site. Based on previous aquifer test results, a horizontal hydraulic conductivity (K_h) of 1 ft/day was used. Vertical hydraulic conductivity (K_v)/K_h was varied between 1/10 and 1/100. Specific yield was assumed at 0.20. The elevation of the horizontal wells was evaluated at 5 and 15 ft below the groundwater surface. Pumping rates were varied from 13 to 40 gpm and test duration from 10 to 360 days. Figure 2 illustrates the predicted groundwater surface after 360 days of pumping at 15 gpm from two horizontal wells with screens located 15 ft below the groundwater surface. The leading edge of the contaminant plume is engulfed within the zone of capture. Therefore, the preliminary results indicated that two horizontal wells should effectively contain the contaminant plume.

4. VERTICAL WELL INSTALLATION

The two vertical extraction wells were installed to a depth of approximately 250 ft with a mud rotary drill rig. The saturated zone was cored, and screen slot size was determined based on sieve analysis. Forty feet of 0.010-in. slotted, wire-wrapped, stainless steel screen was placed to extend 10 ft above the static water table. A carbon steel riser was installed above the screen to ground surface. The annulus was backfilled with 20/40-size quartz sand to 3 ft above the screen. A 2-ft-thick bentonite seal was installed above the sandpack. The annulus was then backfilled to ground surface with cement bentonite grout. Monitoring well construction was similar except for the use of 0.020-in. slotted screen and PVC riser material.

The four injection wells were installed to a depth of 200 ft with a mud rotary drill rig. Construction specifications were 100-180 ft of 0.020-in. slotted, inverted V-wire wrapped, stainless steel screen with stainless steel riser to the ground surface. The annulus was backfilled in the same manner as the extraction wells.

5. HORIZONTAL WELL INSTALLATION

The horizontal well was installed using river crossing technology to a depth of 235 ft. Two boreholes were abandoned because of drilling or installation difficulties before successful installation of the first horizontal well. The custom-made rig used for installation included a hydraulically operated, gear-driven feed frame trailer, a control trailer, and a mud tank/mixer trailer. The gear-driven feed frame trailer is raised at one end, and the other end is placed in a mud pit to set the entry angle. For this well, the entry angle was 20° to the ground surface.

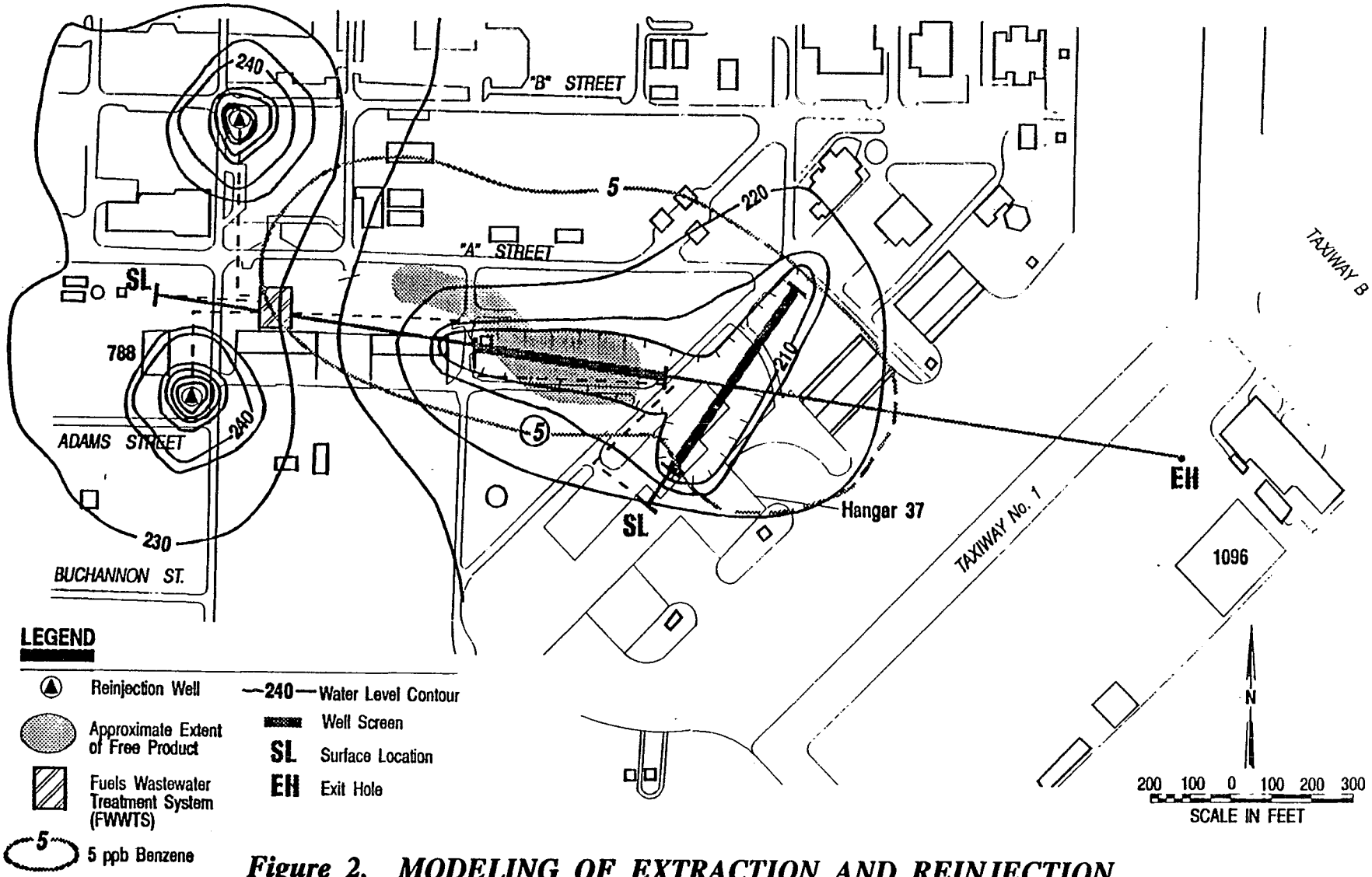

Figure 2. MODELING OF EXTRACTION AND REINJECTION.

Extraction/Reinjection Rate - 15 GPM/Well
360 Day Water Level Contours

Figure 3 illustrates the well installation technique. A pilot hole (step 1) is drilled at a 20° angle and becomes horizontal at 860 ft measured length (235 ft true vertical depth). The pilot hole is then steered horizontally for 500 ft, and the angle is then built to 16° toward an exit location 1250 ft beyond the end of the horizontal section. The pilot hole is drilled with 6-in.- diam drill string and a 9-in.-diam tricone bit. The drill string is steered using a bent subassembly and a drill bit with one jet. Increasing the borehole angle up or down, left or right, is achieved by orienting the bent subassembly in the desired direction and jetting while advancing the drill string without rotation. Drilling a straight hole without changing the angle is accomplished by rotating the drill string while jetting.

A downhole magnetic guidance system, located in the probe directly behind the drill bit, is connected to the surface by wire line and determines the real-time inclination and azimuth of the bent subassembly. Based on this information and the pipe length, trigonometry is used to determine the borehole location. Secondary confirmation of the borehole location is obtained by halting drilling operations every 30 ft (one joint length) and applying an electrical current to a wire loop on the surface, thereby creating a magnetic field of known geometry and intensity over the path of the borehole. This magnetic field is measured at the probe and modeled. The location of the probe is then determined relative to the proposed borehole path.

The downhole location equipment is a proven technology for river crossing boreholes, which are usually no deeper than 100 ft bls. Drilling of the three boreholes during this project showed that the secondary confirmation tools lost depth accuracy below 150 ft. The secondary confirmation tool azimuth readings generally remained accurate throughout the three boreholes. The primary downhole magnetic guidance system remained accurate for depth and azimuth throughout the three boreholes. A downhole gyroscopic tool was used to confirm the borehole location for the first two boreholes. This tool confirmed that the boreholes were within 2.5 ft (plus or minus) of the proposed depth.

After the pilot hole is successfully installed, a 16-in.-diam reamer bit is attached to the drill string at the exit location and pulled back to the entrance location, thereby enlarging the borehole (step 2). Drill string is shuttled from the entrance to the exit location and added behind the reamer bit so that a complete drill string remains in the borehole. After completing the first ream, an 18-in.-diam reamer bit is added at the exit location and pulled back by the same method, further enlarging the borehole (step 3). After completion of the second ream, the 16-in.-diam reamer bit is again attached to the drill string at the exit location. Immediately behind the reamer bit is a swivel assembly. Behind this swivel assembly are the well completion materials. The swivel assembly allows rotation of the drill string and reamer bit without rotation of the well completion materials. This minimizes stress on the well completion materials during installation. All well completion materials are welded together and placed on rollers on the ground surface before installation. The well materials are then pulled into place from the exit to the entrance location for well completion (steps 4 and 5).

Figure 4 illustrates well construction specifications including 500 ft of prepacked, 0.008-in. slotted, wire-wrapped, stainless steel screen with 40/60 sandpack. The inside diameter of the screen is 6.0 in. and the outside diameter is 10.75 in. The prepack sandpack is 1.7 in. thick. Epoxy-coated carbon steel riser material 11 in. in diameter and 860 ft long is installed from the screen to ground surface.

Well development was accomplished by first attaching a fire hose to the well and flushing water down the well, out the screen, and up the annulus, exiting at both the entrance and exit locations. The well was flushed for 6 hours at 150 gpm until returns cleared significantly. The exit borehole was then

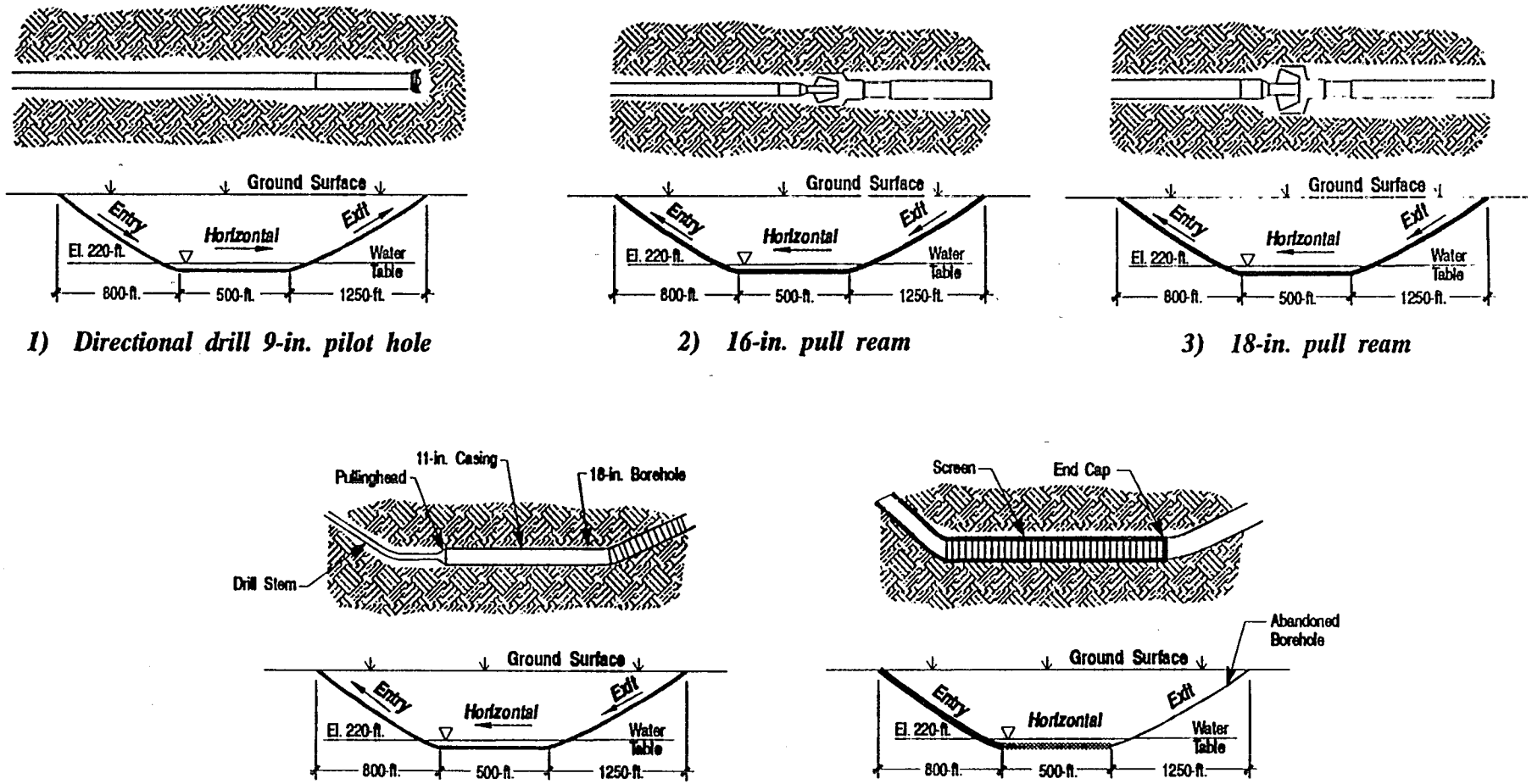

Figure 3. DRILLING AND HORIZONTAL WELL INSTALLATION PROCEDURE.
Williams Air Force Base

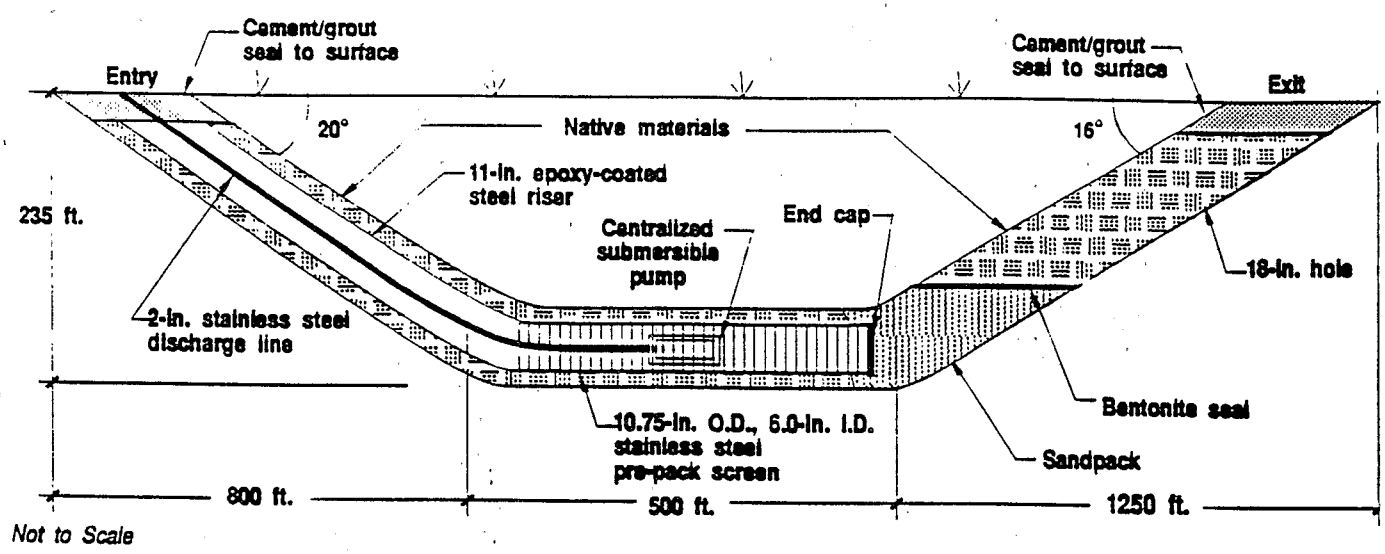

Figure 4. HORIZONTAL WELL CONSTRUCTION DIAGRAM.

plugged and a jetting tool inserted in the screened section of the well. An environmentally safe spotting fluid designed to break up mudcake on the borehole walls was pumped into the well screen at three locations. The borehole was then allowed to sit for 24 hours before another high volume flush was performed. The entrance borehole was then plugged and a pump placed in the well. Pumping was performed with the pump located in different sections of the well screen until the water became clear of suspended solids.

6. AQUIFER TESTS

Aquifer tests of the vertical and horizontal wells were performed to provide data for development of a more realistic interpretation of the aquifer underlying the site.

7. VERTICAL WELL AQUIFER TESTS

Step-drawdown and constant rate 72-hour aquifer tests were performed on the 4-in.- and 10-in.-diam vertical extraction wells, EX-01 and EX-02. Additionally, EX-02 was pumped for 21 days. Water levels were recorded using data loggers and transducers placed in monitoring wells MW-30 and MW-31 and extraction wells EX-01 and EX-02. All wells are fully penetrating and screened in the same interval.

Before conducting the first aquifer test, background water levels were monitored. Barometric pressure and precipitation measurements from the Sky Harbor Airport in Phoenix were obtained during the testing periods to evaluate their effect on water levels. Eight-hour step-drawdown tests initially were performed on the vertical extraction wells to determine the specific capacity of the wells and to choose the optimum pumping rate for the long-term tests. Constant rate pumping tests were performed on the two vertical extraction wells. After completion of each constant rate test, recovery of the water table was monitored.

8. VERTICAL WELL RESULTS

Vertical extraction well EX-01 was pumped at a constant rate of 3.8 gpm for 72 hours. Well EX-01 is 254 ft deep and screened between 212 and 252 ft bls. Before the start of pumping, the static water level was 215.4 ft bls. Transducers were placed in the pumping well (EX-01) and three observation wells (MW-31, MW-30, and EX-02) to record drawdowns. Wells MW-31, MW-30, and EX-02 are 27, 102, and 127 ft, respectively, from the pumping well, EX-01.

After 72 hours, a total of 14.6 ft of drawdown was measured in the pumping well. Drawdowns in the observation wells ranged from 0.61 ft in MW-30 to 0.42 ft in EX-02. In general the data indicate steep cones of depression surrounding the pumping well because of low transmissivity of the formation.

Distance drawdown plots indicated the largest drawdown was recorded in observation well MW-30, more than 100 ft from the pumping well. This suggests an increased hydraulic connection between EX-01 and MW-30 relative to the other observation wells. This is possible considering the site stratigraphy of interbedded sands, silts, and clays. Well MW-31 recorded the next largest drawdown and is within 27 ft of the pumping well.

Time vs drawdown plots from the pumping and observation wells resemble delayed gravity drainage as described in Fetter (1988). The corrected drawdowns in EX-01, MW-31, and MW-30 were used to determine hydraulic conductivity and specific yield values using the Neuman Method (1975) for delayed gravity drainage. Horizontal hydraulic conductivities calculated from observation well data ranged from 9.62 ft/day to 11.73 ft/day. Calculated vertical hydraulic conductivities ranged from 0.07 ft/day in MW-30 to 0.08 ft/day in MW-31. These correspond to a k_v/k_h ratio of approximately 1/140. Specific yields (S_y) ranged between 0.023 (MW-30) and 0.286 (MW-31). The time drawdown plot for MW-30 may not have reached the late curve, resulting in the lower values of S_y. Time drawdown data for EX-01 resulted in a hydraulic conductivity of 3.0 ft/day. Recovery data from EX-01 was used to calculate a hydraulic conductivity of 2.58 ft/day.

Extraction well EX-02 was pumped for 72 hours at approximately 2 gpm. Drawdown in the observation wells increased until 1100 minutes into the test. At this time, the drawdown declined steadily until the last day of the 3-day test when it began to rise in a curve similar to the initial drawdown. Total rainfall for the month before this test was three times the monthly average. The sudden drop in drawdown may be partially caused by delayed gravity drainage from low permeability clays. Because of the later anomalous data, drawdown data from MW-30 for the first 1000 minutes of the test was used to calculate a hydraulic conductivity of 1.8 ft/day.

Sustained pumping rates from the two vertical extraction wells varied considerably. Also distance drawdown plots did not decrease linearly with increased distance from the pumping well. These findings indicate heterogeneous, nonisotropic conditions. Increasing well diameter did not increase recovery. Recovery rates are a function of formation properties and well efficiency.

9. HORIZONTAL WELL AQUIFER TEST

A 3-day constant rate aquifer test was performed on the horizontal well. The pump was placed in the middle of the screened section, and a transducer was installed inside a drop pipe placed at the beginning of the horizontal section. Transducers were installed in monitoring wells LI-06, W-01, W-03, W-05, and W-08 surrounding the horizontal screened section.

During the test, hand water level and product-water interface measurements were taken to confirm transducer readings and to determine the effect that pumping has on the product-water interface.

10. HORIZONTAL WELL RESULTS

The pumping test on the horizontal well consisted of pumping the well at 9.8 gpm for 3 days. Wells within 30 ft of the horizontal well recorded drawdowns of less than 0.40 ft indicating a steep cone of depression similar to that observed in the vertical well aquifer tests. During the test, product thicknesses rose steadily in the observation wells within the free product plume. The water table decline in the cone of influence was minimal. The apparent product thickening is likely the result of removing the skimming system from these wells 48 hours before initiating the test.

The value of hydraulic conductivity from the horizontal well test data was calculated using the following analytical equation for flow to a trench (Powers 1981).

$$\frac{Q}{2X} = \frac{K(H^2 - h^2)}{2880\ L}$$

where:

Q	=	discharge (gpm)
X	=	length of trench (screen) (ft)
K	=	hydraulic conductivity (gpd/ft^2)
H	=	saturated thickness at distance L from trench (ft)
h	=	saturated thickness above screen at end pumping (ft)
L	=	distance between trench and point where H is measured (ft).

Calculated hydraulic conductivities ranged from 0.14 to 0.33 ft/day. These values are much lower than those calculated from the vertical well aquifer test data. This is not unexpected because of the adverse impact to the formation from the three attempts at well installation. Upon completion of an on-site treatment system, the well will be developed further and pumped to obtain additional data.

11. FUTURE MODELING EFFORTS

Currently the finite element numerical model (DYNFLOW) developed by CDM Federal is being adapted to include site geologic conditions as well as calculated hydraulic properties at the site. Results of aquifer tests from the horizontal well will be used for transient calibration of the model. This will enhance the model's capability to predict aquifer response to pumping in the horizontal well.

12. SUMMARY AND CONCLUSIONS

The PS/DS being performed to evaluate the ability of horizontal vs vertical extraction wells to remediate and contain a JP-4 plume will require additional data before definitive conclusions can be reached. Four-in.- and 10-in.-diam vertical extraction wells and a 6-in.-diam horizontal extraction well have been successfully installed. Only preliminary aquifer testing of the horizontal well has been performed.

Aquifer test results from vertical extraction wells show low transmissivity and vertical hydraulic conductivity and a very steep cone of depression. Therefore, a tight vertical well spacing (25-50 ft) would be required to remediate the site with vertical wells. These tests also indicate that increasing well diameter does not increase the recovery rate in this heterogeneous formation.

A short-term aquifer test performed on the horizontal well also shows a very steep cone of depression. Based on the initial results, a horizontal well may perform more effectively as a barrier than for plume recovery at this site. After further testing, a decision will be made as to whether a second horizontal well will be installed at this site.

Future testing of the horizontal well will include pumping at different locations in the horizontal well screen, long-term (30 day) and short-term tests, low and high pumping rate tests, an evaluation of whether product recovery from the skimming pumps is increased during water table depression, and pumping from two pumps simultaneously in the horizontal well.

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EVALUATION OF THERMAL EXTRACTION TECHNOLOGIES FOR TREATMENT OF SOILS CONTAMINATED WITH COAL TARS AND WOOD PRESERVATIVES AT THE PACIFIC PLACE SITE, VANCOUVER, B.C.

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INTRODUCTION

The British Columbia Ministry of Environment, in cooperation with Environment Canada's Demonstration of Site Remediation Technologies (DESRT) Program, conducted treatability studies of several treatment technologies to evaluate their effectiveness for the treatment of soil from a contaminated site.

The site is a 185 acre area of industrial land located in Vancouver, B.C. Historically, a wide variety of industrial activities operated on the site, including two manufactured gas plants, sawmills, boat building, metal plating, wood preservation, carpet cleaning, railway yards, and fuel storage. In particular, coal tars and metal oxide wastes from the coal gasification plants and wood preservatives were mixed with fill material. Contaminants detected at elevated concentrations on the site included polycyclic aromatic hydrocarbons (PAHs), cyanide, lead, sulfur, total petroleum (extractable) hydrocarbons, and chlorophenols.

The technologies evaluated included incineration, thermal extraction, bioremediation, and stabilization/solidification. This paper focuses on the testing of two innovative thermal extraction technologies: the Chemical Waste Management X*TRAX process; and the UMATAC Industrial Processes AOSTRA Taciuk Processor. This paper includes a brief description of each technology, procedures utilized in each study, results, and estimated costs for full-scale treatment.

CHARACTERISTICS OF SOILS TESTED

Soil samples were collected from the site by excavating pits to the desired depths; the targeted soils were then mixed in the excavation using the bucket of the excavator. After mixing, samples were coarsely screened and placed into shipping containers. All samples were shipped to vendors in accordance with the Canadian Transportation of Dangerous Goods Regulations and the U.S. Department of Transportation Regulations.

Four different sample types, with varying concentrations of PAHs, chlorophenols, oil and grease, and metals, were provided for testing in the thermal extraction systems. As would be expected from such a site, the fill was heterogenous and contaminant concentrations exhibited a wide variability, even between split samples. In general, all the soil samples were poorly sorted (well graded) and were characterized as consisting primarily of fine to coarse sand with approximately 17 to 34% silt and clay. Samples also contained debris such as brick fragments, metal fragments, and wood chunks. Sample moisture content ranged from 10 to 45% and averaged 25%. The pH of each sample was near neutral (6.9 to 7.2) except for Sample 1, which had a pH ranging from 4.2 to 5.0. The chemical characteristics of each of the four samples are summarized below.

Sample 1. This sample location is characterized by the presence of coal tars; the average concentration of total PAHs in Sample 1 was 3,375 mg/kg. Oil and grease concentrations ranged from 29,000 to 200,000 mg/kg with average concentrations of 112,000 mg/kg. Total cyanide concentrations in Sample 1 were between 2,900 and 5,000 mg/kg. Sample 1 also was notably high in total sulfur (ranging from 1 to 17 percent).

Sample 2. Total PAHs in this sample ranged from 42 to 348 mg/kg (averaging 117 mg/kg). Oil and grease concentrations ranged from 4,200 to 15,600 mg/kg. Lead concentrations were between 116 and 5,600 mg/kg in this sample. Zinc was also high, averaging 2,347 mg/kg.

Sample 3. This sample was collected from an area historically used as a dip tank for wood treating. Pentachlorophenol concentrations ranged from 9 to 309 mg/kg (averaging 136 mg/kg) and tetrachlorophenol ranged from 125 to 500 mg/kg (averaging 242 mg/kg). PAHs were also detected in this sample, averaging 260 mg/kg total PAHs. Oil and grease ranged from 8,300 to 23,200 mg/kg.

Sample 4. Sample 4 was characterized by high concentrations of lead, ranging from 8,000 to 12,500 mg/kg. Total PAHs averaged 151 mg/kg; oil and grease concentrations averaged 700 mg/kg.

TREATABILITY STUDY PROCESS

The vendors were required to perform detailed chemical and physical analyses of the soil samples using specified analytical protocols, prior to treatment and at the end of the treatment period. In addition, detailed analysis of treatment by-products or residuals was also required.

The major objectives of the treatability studies were to:

- Determine or validate technology effectiveness.
- Develop pricing data for full-scale operation.
- Evaluate the likelihood of delisting treated waste under B.C. procedures.
- Demonstrate compliance with emissions and effluent standards.
- Provide information potentially useful for other contaminated sites.

Cleanup goals were established for the treatability study program in order to evaluate technology performance. The "British Columbia Standards for Managing Contamination at the Pacific Place Site", developed by the British Columbia Ministry of Environment, formed the basis for the target clean-up levels for organic contaminants. The clean-up goals are included in Tables 1 and 2.

A brief description of each thermal extraction technology, the study procedures used in testing, the testing results and estimated costs are discussed in the following sections.

X*TRAX

Technology Description

The X*TRAX system, developed by Chemical Waste Management, Inc., is a low temperature thermal separation process that vaporizes or steam strips organic compounds from soils or sludges. It consists of an externally fired rotary dryer and gas treatment system. A simplified flow diagram of the X*TRAX system is provided in Figure 1.

Soils or sludges are fed into a rotary dryer and heated. Treated solid residues exit the dryer and are collected in a hopper. Nitrogen is used as a carrier gas for the volatilized organics which are transported from the rotary dryer to a gas treatment system.

The gas treatment system includes a spray tower/scrubber, primary and secondary shell-and-tube heat exchangers for condensing the gases. In the full-scale X*TRAX system, most of the nitrogen gas is recycled, except for about 10 percent that is vented to the atmosphere. The bench-scale system is equipped with two activated carbon filters for treating residual organics in the gas stream.

Liquids and particulates (and less volatile organic compounds) from the spray tower are passed through a gravity phase separator and are then filtered to separate out solids. Condensed liquids from the heat exchangers are composited, filtered, and phase separated for further treatment as necessary.

Review of the flow diagram indicates that the X*TRAX system produces several treatment residuals:

- Treated solids from the dryer
- Phase separator water (this is continuously recycled to the spray tower)
- Phase separator filtrate (particulates and some organics)
- Phase separator oil
- Filtrate from condensate
- Condensed water
- Condensed oil (not always produced in lab-scale tests)
- Emissions

The full-scale X*TRAX system is a transportable unit capable of treating up to 125 tons per day of soil with a moisture content of 20%. CWM also operates a pilot-scale unit that is mobile and can treat about 5 tons per day of material containing 30% moisture.

Testing Program

Bench-scale treatability testing was conducted using a laboratory-scale X*TRAX unit which uses the same components as the full-scale X*TRAX system. Samples 1, 2, and 3 were individually tested at two operating temperatures: 482°C and 371°C. In all cases, residence time was 85 minutes. Prior to processing, the samples were screened through a 1/4 inch sieve and then homogenized. The feed was sampled once each hour, beginning and ending at steady state conditions. The feed samples were composited for each temperature condition and later submitted for laboratory analyses. An average of about 7 kilograms of each soil sample was fed to the system. Feed rate ranged from 8 to 13 grams per minute, depending on the sample type.

Treated solids and condensates were collected and weighed every 15 minutes. Solids were composited for each steady state condition and then were subsampled for analytical testing. The condensates and phase separator liquid were filtered through 25 micron filter paper. The filtered condensate was poured into a separatory funnel from which samples for analysis were taken. The filter cakes and phase separator water products were subjected to chemical and physical analyses.

Because of the small scale, no organic liquid phase products were generated in these studies, nor were emissions collected and analyzed.

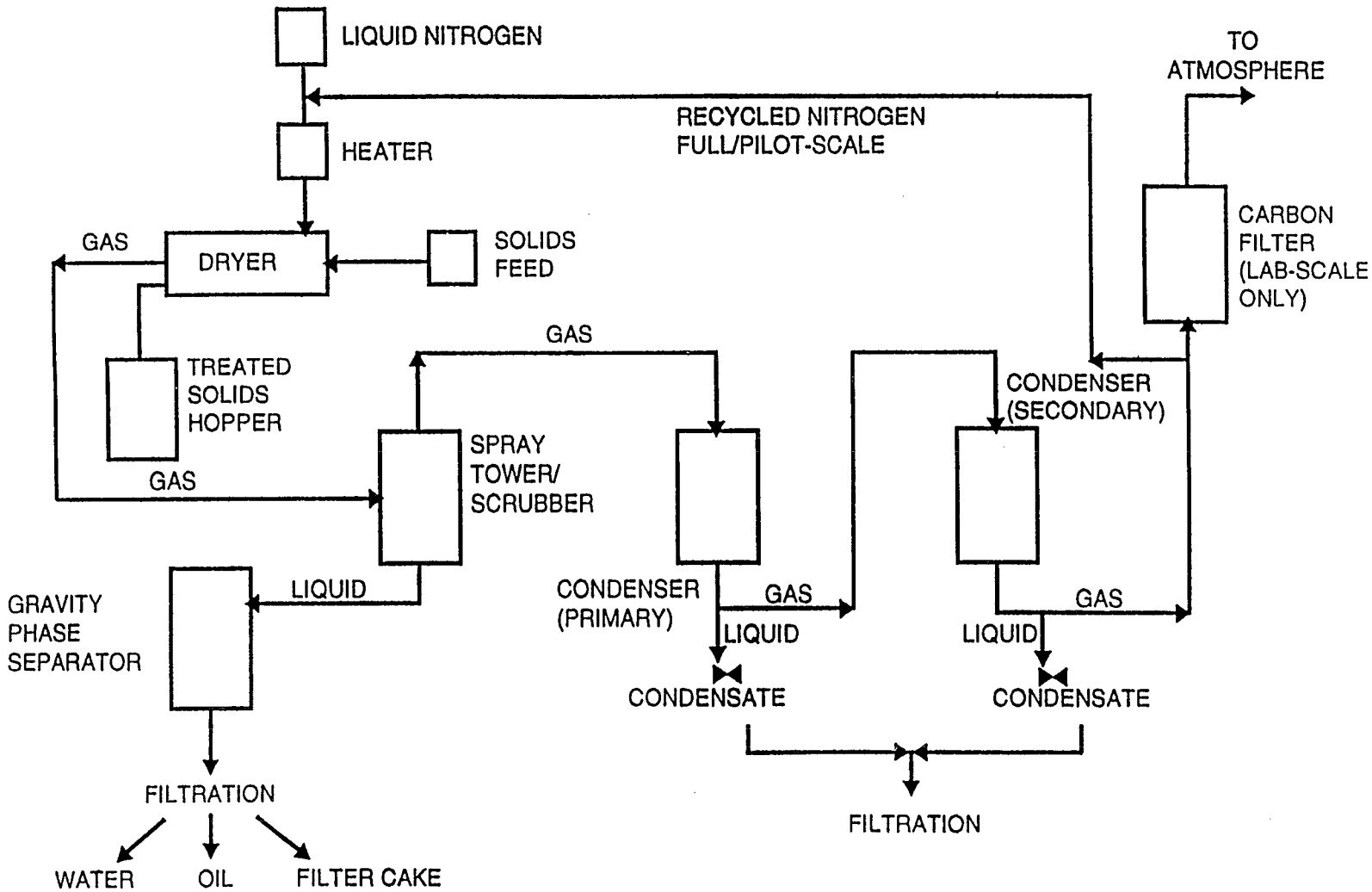
Results

The analytical results indicate that the X*TRAX process was effective at removing organic compounds from contaminated soils and meeting the treatment goals for the treatability study. Table 1 provides a summary of results for the 482°C operating condition.

In Sample 1, the highly contaminated sample, total PAHs (16) were reduced by 99.93 percent at the 482°C operating condition. The concentrations of PAHs (as well as other organic constituents) in the treated soil were well below the established treatment goals. Similar PAH and other organic compound removal efficiencies were achieved in Samples 2 and 3.

Pentachlorophenol was reduced by an average of approximately 98 percent, and 2,3,4,6-tetrachlorophenol by an average of approximately 92 percent for all three samples tested.

Figure 1. X*TRAX Flow Diagram



Source: Modified from "Pacific Place Project Treatability Technical Study for British Columbia Hazardous Waste Management Corporation", Chemical Waste Management of Canada, Inc.

Concentrations of chlorophenols in some of the treated soils appeared to be slightly above the treatment goals.

The vendor reported that concentrations of dioxins and furans in the Sample 1 feed soil (3.7 ppt TCDD equivalency) decreased after processing through the X*TRAX system (to 1.6 ppt TCDD equivalency).

Total metals concentrations in the samples did not change significantly as a result of the X*TRAX treatment process, nor did the solubility of the metals appear to be affected by treatment, based on extraction testing. Total cyanide in the treated soils from Sample 1 was reduced from 2,500 mg/kg to 6 mg/kg in the lower temperature run and to less than 0.5 mg/kg in the 482°C run.

Organics concentrations in the condensed water and phase separator water produced during the treatability study were generally very low or insignificant except for oil and grease and total phenolics. Oil and grease concentrations ranged from less than 5 to 24 ppm. Total phenolics were detected at high levels in both condensed and phase separator water (54 and 58 ppm, respectively) from Sample 3 soils and in condensed water from Sample 1 soils (5.51 ppm). These concentrations exceed the B.C. effluent standard for phenols.

There were insufficient products to allow for the analysis of liquid-phase organics. Analysis of emissions during the treatability study was not performed due to the small scale of the equipment.

Examination of the analytical testing performed on treatment residuals from this study shows that a significant proportion of the PAHs from all sample types and chlorophenols in Sample Type 3 were removed in the spray tower and were deposited on the phase separator filter cake. A small amount of the total PAHs and chlorophenols were also removed from the piping between the dryer exit and the spray tower ("carryover holdup"). Some of the cyanide was also removed on the phase separator filter cake and from the piping between the rotary dryer and the spray tower.

Estimated Treatment Costs

The vendor estimated a unit cost for soils treatment and disposal of condensed liquids and filtrates at about $600(US) per ton. The cost assumed treatment of about 27,000 tons of soil, and included mobilization, labor, health and safety, sampling and analysis, and ambient air monitoring.

Discussion

Based on the data provided in the treatability study report, the X*TRAX process appears to be an effective technology for removing organic contaminants from the tested soils. However, several treatment residuals are produced that require proper management/disposal (i.e., filtrates, condensed oil, condensed water, phase separation water).

During full-scale operation of the X*TRAX, condensed water and phase separator water produced during the treatment are typically applied to the treated soil to control dusting. As noted above, the concentrations of some organic contaminants in the two wastewater streams were of concern, making the use of the water for dust control a questionable practice. However, CWM reports that in full-scale treatment the water is tested first to ensure that the quality of the water is acceptable (for disposal of the treated soil) before it is applied to the treated soil.

The treatability study could not provide data on condensed organic-phase liquids, and full-scale data pertaining to this waste stream were not available at the time of the testing program. However, if free-phase organic liquids were produced during full-scale operation, it is likely that they would require incineration at an approved hazardous waste incinerator.

TABLE 1. Selected Organic Contaminant Concentrations, X*TRAX Treatability Study

Contaminant	Sample 1		Sample Type 2		Sample Type 3		Treatment Goals
	Run Feed (ppm)	482 °C Treated Soil (ppm)	Run Feed (ppm)	482° C Treated Soil (ppm)	Run Feed (ppm)	482° C Treated Soil (ppm)	(Pacific Place Level B Standards (ppm)
PAHs							
Benzo(a)anthracene	<0.014	0.18	3.2	<0.014	12		1
Chrysene	65	0.20	3.5	<0.001	11.0	<0.001	1
Benzo(b)fluoranthene	60	<0.001	4.3	<0.001	9.1	<0.001	1
Benzo(k)fluoranthene	27	0.050	5.1	<0.0004	6.8	<0.004	1
Benzo(g,h,i)perylene	190	<0.0047	<0.0047	<0.0047	8.9	<0.0047	1
Pyrene	220	0.35	4.4	<0.0025	36.0	<0.0025	10
Benzo(a)pyrene	400	<0.010	9.5	<0.010	18.0	<0.010	1
Indeno(1,2,3-cd)pyrene	61	0.033	3.7	<0.001	6.8	<0.001	1
Acenaphthene	<0.005	<0.005	<0.005	<0.005	<0.008	<0.005	10
Acenapthylene	45	<0.008	<0.005	<0.008	<0.008	<0.008	10
Anthracene	100	0.057	8.8	<0.0007	5.3	<0.0007	10
Fluoranthene	530	0.68	6.3	<0.0007	43.0	<0.0007	10
Fluorene	110	<0.0006	1.8	<0.0006	4.3	<0.0006	10
Napthalene	1,300	0.41	<0.005	<0.005	<0.005	<0.005	5
Phenanthrene	320	0.29	3.5	<0.005	27.0	0.18	5
Total PAHs	3,428	2.25	54.1	0	192.6	0.18	20
Chlorophenols							
2,4,6-Trichlorophenol	<0.42	<0.42	<0.07	<0.07	<0.07	<0.07	0.5
2,4,5-Trichlorophenol	<0.66	<0.66	1.6	<0.11	<0.11	<0.11	0.5
2,3,4,6-Tetrachlorophenol	<0.66	<0.66	2.4	0.58	<0.30	<0.11	0.5
Pentachlorophenol	<1.8	<1.8	9.4	<0.30	<0.035	<0.3	0.5

AOSTRA TACIUK PROCESSOR

Technology Description

The AOSTRA Taciuk Processor (ATP) is owned and operated by UMATAC Industrial Processes in Calgary, Alberta (the technology is also known as the SoilTech ATP Plant in the U.S.). The ATP is a thermal extraction technology that separates organics from solids by pyrolysis and distillation. A flow diagram of the ATP is provided in Figure 2. For the treatability study testing, UMATAC was a subcontractor to Newalta Corporation of Calgary.

The processor consists of a rotary kiln with a preheat zone, operating at about 260°C; a reaction zone, operating at between 317°C and 649°C; and a combustion zone, operating at 538°C to 815°C. Water vapor and the more volatile organics are extracted in the preheat zone. Oils and heavier organics are removed in the reaction zone. Both the preheat and the reaction zones are maintained in anaerobic conditions to prevent oxidation of the organics. The combustion zone burns coke from thermal cracking that forms on the solids in the reaction zone. Oxygen is added to the system in the combustion zone.

The flue gas from the combustion zone is passed through a baghouse and a wet scrubber. Carbon absorption is sometimes added for final gas scrubbing in full-scale treatment. Treated solids are discharged from the kiln as tailings. The steam and organics produced in the preheat zone and the organics separated out in the reaction zone are withdrawn under vacuum and are condensed in separate vapor trains. The condensed water generally requires treatment before disposal. The oily waste must either be incinerated or used as fuel for the processor.

As can be determined from examination of the process flow diagram, this treatment process produces several treatment by-products:

- Preheat Zone

  Vapor stream: water, oil, gas (recycled to combustion unit)
  Solids stream: heated, dried solids (to reaction zone)

- Reaction Zone

  Vapor stream: cyclone solids, bottom oils (removed at 150°C - 210°C), heavy oils (removed at 100°C - 150°C), light oils (removed in heat exchanger), sour water, off gases (flared or recycled to combustion zone)

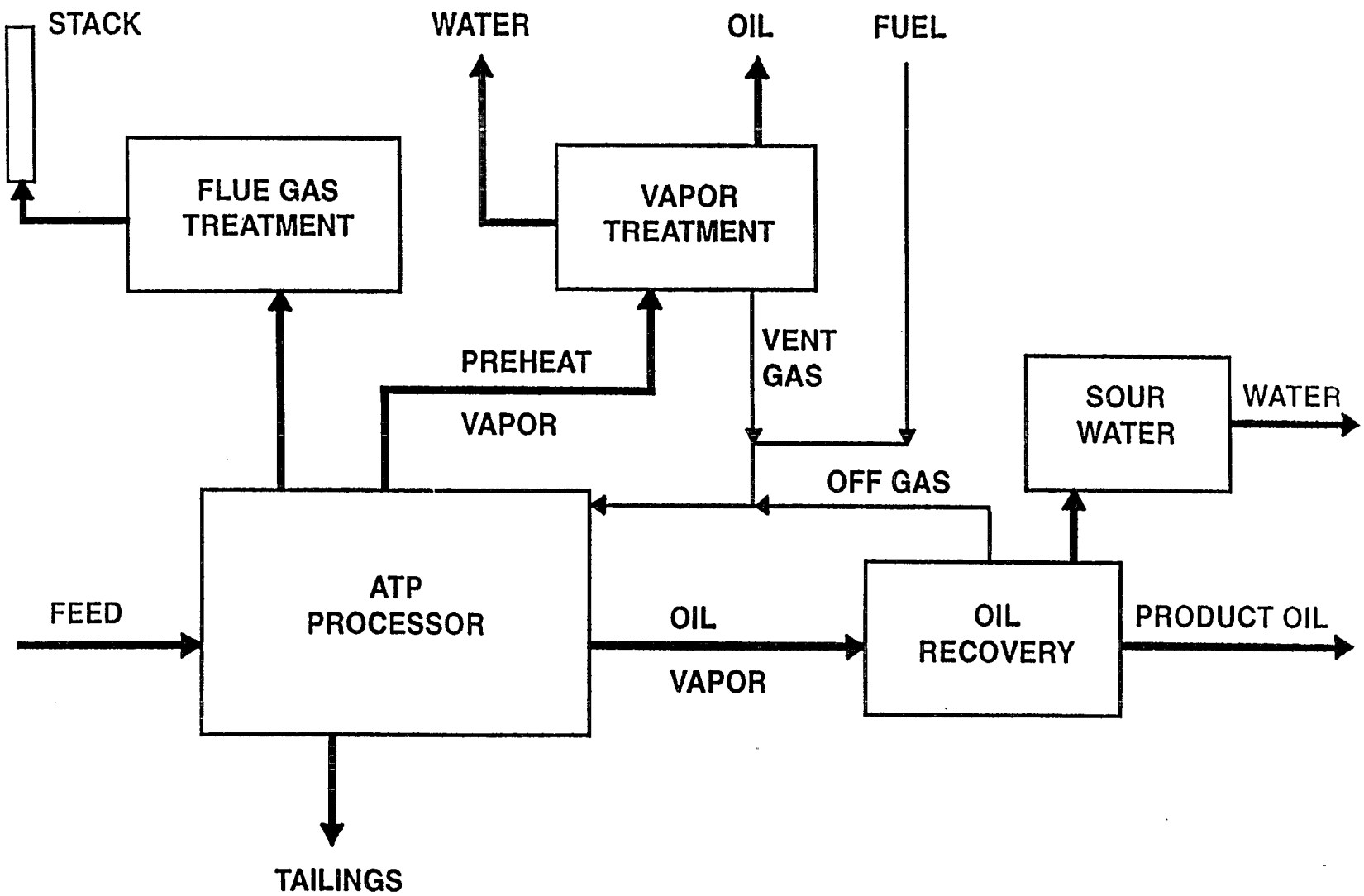
  Solids stream: coked solids (to combustion zone)

- Combustion Zone

  Flue gas stream: cyclone fines, baghouse fines, scrubber water, scrubber solids, cleaned gas

  Solids stream: treated tailings

Figure 2. Aostra Taciuk Process (ATP) Flow Diagram



Source: "Treatability Study Report, Pacific Place Soils Remediation Project", Newalta Corporation, June 30, 1992.

Testing Program

Both bench- and pilot-scale studies were conducted using the ATP. In addition, a bench-scale wastewater treatment study was performed to evaluate the effectiveness of a combination of standard treatment technologies for treating preheat water and sour water. Only the pilot-scale study is presented here.

Based on the success of the batch-scale testing program, pilot-scale testing in UMATAC's 5 tonne per hour prototype unit was undertaken. A total of four tests were performed using the 5 tonne per hour ATP. Samples 1 and 3 were processed separately and a blend of Samples 1, 2, and 4 and a blend of Samples 2 and 4 were also tested. Because of the high sulfur content in Sample 1 and the concern that the sulfur dioxide emissions would be exceeded, UMATAC added sand in a four-to-one ratio to the sample material before processing. The vendor also added sand to the third and fourth test runs to reduce moisture content.

Each test lasted between 3.4 and 4.4 hours; feed rates ranged from 2.7 to 4.1 tonnes per hour, depending on the sample type. Exit temperatures in the reaction zone averaged 526°C. Exit temperatures in the combustion zone averaged 648°C.

During each test run, samples of the feed and samples of the treated tailings (treated soils, baghouse ash, and cyclone ash) were collected every 30 minutes. Composite samples of each of these were submitted for analytical testing. Condensates, both water samples and oil samples, were also collected every 30 minutes and analyzed from each run.

Monitoring of stack emissions was also performed during three test runs to demonstrate compliance with emissions standards and for calculating destruction and removal efficiencies (DRE) and mass balances.

Results

Comparisons of the concentrations of selected organic compounds in the feed material and the treated soils and ash are provided in Table 2.

In general, the ATP achieved nearly 100 percent removal of organic contaminants from the soil samples. The concentrations of PAHs in the tailings were all less than detection limits (practical quantitation limits of 0.33 - 0.53 ppm). It should be noted that concentrations of organics in the feed were low due to dilution from the addition of sand before processing. For example, after dilution with sand, the concentration of total PAHs in the Sample 1 run averaged about 46 mg/kg. In the run combining Sample Types 1, 2, and 4, total PAH concentrations averaged 309 mg/kg. These concentrations are considerably lower than those found in undiluted soil samples.

Analyses of dioxins and furans were performed for the second run (Sample 3 soils). Concentrations in the feed, treated soils, and ash streams were all less than 1 ppm. The data provided by the vendor is suspect, however, due to poor surrogate recoveries reported by the vendor's laboratory.

Useful information about reduction of chlorophenolic compounds was not generated in this testing program because the concentrations of chlorophenols in the soils received by UMATAC were non-detectable (6.6 ppm detection limit).

Some volatile organic compounds were detected at high levels (as high as 300 ppm) in baghouse ash, most notably toluene and xylene. No explanation of these levels was offered by the vendor.

Cyanide was reduced to less than detection limits in the treated soils containing soil from Sample 1. Generally, low concentrations of cyanide were detected in cyclone dust and baghouse ash.

TABLE 2. Selected Organic Contaminant Concentrations, ATP Treatability Study

Contaminant	Sample 1 + Sand				Sample 3				Sample 1, 2, 4 + Sand				Treatment Goals
	Feed Soil (ppm)	Treated Soil (ppm)	Cyclone Dust (ppm)	Baghouse Ash (ppm)	Feed Soil (ppm)	Treated Soil (ppm)	Cyclone Dust (ppm)	Baghouse Ash (ppm)	Feed Soil (ppm)	Treated Soil (ppm)	Cyclone Dust (ppm)	Baghouse Ash (ppm)	Pacific Place Level B Standards (ppm)
TEH[1]	145	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	150
Oil & Grease	118	26	22	13	1180	21	65	74	159	<5	7	9	1000
Phenols	<0.01	<0.01	<0.01	0.53	0.13	0.01	0.02	0.05	0.05	<0.01	<0.01	<0.01	1.0
Total Chlorophenols[2]	ND	ND	ND	ND	ND	<	ND	ND	ND	ND	ND	ND	1.0
Dioxins/Furans[3]	NT	NT	NT	NT	0.566	0.005	0.553	0.596	NT	NT	NT	NT	NA
Total PAHs [4]	46.2	ND	<	3.3	2.17	ND	<	16.5	309.2	<	<	3.2	20
BTEX [5]	ND	ND	ND	ND	ND	ND	30	133	<	ND	ND	130	5.0, 30, 50, 50

Notes:
(1) Total Extractable Hydrocarbons (Modified EPA Method 8015), average of duplicate columns. Detection limit in ash streams ranged from 9 to 48 ppm.
(2) Detection limit for pentachlorophenol in treated soils and ash was 1.65 ppm.
(3) Data suspect due to poor surrogate recoveries.
(4) Detection limits for PAHs ranged from 0.33 to 0.462 mg/kg.
(5) Detection limits for BTEX ranged from 20 to 70 mg/kg.
< = Below detection limit
NT = not tested
ND = not detected
Data from: "Treatability Study Report, Pacific Place Soils Remediation Project," Newalta Corporation, June 30, 1992.

In general, the concentrations of metals were reduced somewhat in the treated soils from what was reported in the feed, and were higher in the cyclone dust and baghouse ash (particularly arsenic, copper, lead, tin, and zinc).

The testing program produced about 2.5 tons of oil (1.6 tons of which was from make-up oil for the hydrocarbon vapor stripper). In general, the oils contained very low levels of inorganics (except for calcium and sulfur) and low levels of benzene, toluene, ethylbenzene, and xylene (BTEX). The vendor did not analyze the oils for PAHs or chlorophenols. However, data from the third party laboratory analyses of the oils, indicated significant concentrations of PAHs in the oils, as would be expected. Dioxins and furans were also present in significant concentrations (ranging from 0.5 to 130 ppb TCDD toxicity equivalence) in the bottoms oil from processing Samples 1 and 3 (oil from the blended run was not analyzed for dioxins or furans). This is based on data from the third party laboratory. The data from the vendor's laboratory, which also reported high levels of TCDD, are suspect due to poor surrogate recoveries.

Stack Emissions

During the testing programs, sulfur dioxide limits were exceeded in both tests using Sample 1 material. This, according to UMATAC, was due to the scrubber on the prototype equipment which can only achieve 50 to 60 percent sulfur dioxide removal.

Particulate limits were exceeded in the second and third test runs (emissions were not monitored in the fourth test). According to the vendor, this was due to damaged bags in the baghouse that were not discovered until testing was completed.

Total oxides of nitrogen exceeded the emissions criteria for NO2 in one test run. Since NO_2 was not directly measured, the vendor has stated that it is possible that the NO_2 limit was not exceeded. Carbon monoxide limits were also exceeded. This was explained by the vendor as attributable to low combustion efficiencies attained during the testing program.

All metals discharges were well below emissions standards. Dioxins and furans were not measured in emissions samples as planned, because of insufficient sample volume.

The vendor calculated DREs for PAHs using both the B.C. Special Waste Regulation method, and Alberta Environment's method (which takes into account more of the waste streams). Using the B.C method for calculation, the vendor reported DREs ranging from 98.41 to 100.00%. DREs of 99.99% were not achieved for anthracene, fluoranthene, naphthalene, phenanthrene, and pyrene in one or more test runs.

In general, all of the water products from the processor (preheat, sour, and scrubber water) were found to be contaminated with various compounds that would require treatment before discharge. Contaminants present in significant concentrations in one or more of the water samples included oil and grease, phenols, ammonia, hexavalent chromium, aluminum, lead, manganese, and cyanide. Naphthalenes were detected in the sour water and preheat water in the parts per billion range. The scrubber water also proved to contain several contaminants in excess of effluent limits including oil and grease, aluminum, arsenic, zinc, manganese, total suspended solids, cyanide, and ammonia.

Estimated Treatment Costs

The vendor estimated a unit cost for soils treatment and disposal of condensed liquids and filtrates at about $200 (US) per ton. The cost assumed treatment of about 27,000 tons of soil, and included mobilization and demobilization, materials preparation, labor, health and safety, sampling and analysis, quality assurance/quality control, site preparation, and closure.

Discussion

In general, the ATP demonstrated that it was effective at removing organic compounds and cyanide from the contaminated soils and at meeting the treatability study goals. However, it is not certain how the pilot-scale processor would have performed had the feed soils not been diluted with sand and the concentrations of contaminants been higher in the feed.

Emissions standards for metals were met in the study. However, meeting stack emissions for conventional parameters (SO_2, CO, NO_2, and particulates) proved problematic for the ATP in this treatability study. The vendor has concluded that this is due to the use of old equipment that was not properly functioning. It is expected that some of these problems could be corrected by improvements in the system (for example, by using properly functioning baghouse filters and a more efficient scrubber). However, sulfur levels in Sample 1, if they are as high as those found in the study soils, may require dilution of the soils and/or reduced throughput to meet SO2 emissions standards, thus increasing treatment costs. Carbon monoxide emissions are indicative of poor combustion efficiency. The vendor has indicated that CO emissions could be controlled by adding an afterburner to the unit. However, it is uncertain whether such a modification will be effective, and it may increase treatment costs.

DRE calculations were based on measurements of PAHs in the soils and the stack emissions. Due to the variability of contaminant concentrations in the feed soils, the DREs may be somewhat uncertain. However, the vendor's DRE calculations show that the DRE performance standard of 99.99% was not met for several of the PAH compounds. This may be partly due to the low concentrations of PAHs in the feed, which make it more difficult to meet DREs.

Based on data from both the vendor's laboratory and the third party laboratory analyses of oils, significant concentrations of dioxins and furans were found in the oils. Since only very low levels of dioxins and furans were detected in feed samples (from this and other studies), this may mean that the ATP is creating dioxins. However, a mass balance has not been calculated to verify this hypothesis. No information was obtained for evaluating the concentrations of these compounds in stack emissions.

SUMMARY AND CONCLUSIONS

Bench-scale testing of the Chemical Waste Management X*TRAX process and the AOSTRA Taciuk Processor were performed using soils contaminated with PAHs, chlorophenols, lead, cyanide, and varying levels of oil and grease. Pilot-scale studies were also performed using the ATP. Based on the results of the treatability studies, both of these technologies were effective at removing organic contaminants from the treatability study soils. Organics in the treated soils ranged from non-detectable levels to the low parts per billion range and were virtually all less than the treatment goals.

Stack emissions in the ATP were acceptable for metals but were unacceptable for several constituents (SO_2, CO, NO_2, and particulates). The use of equipment in poor repair, limited the extent to which the emissions results from the testing program could be evaluated and used to predict performance in full-scale operation.

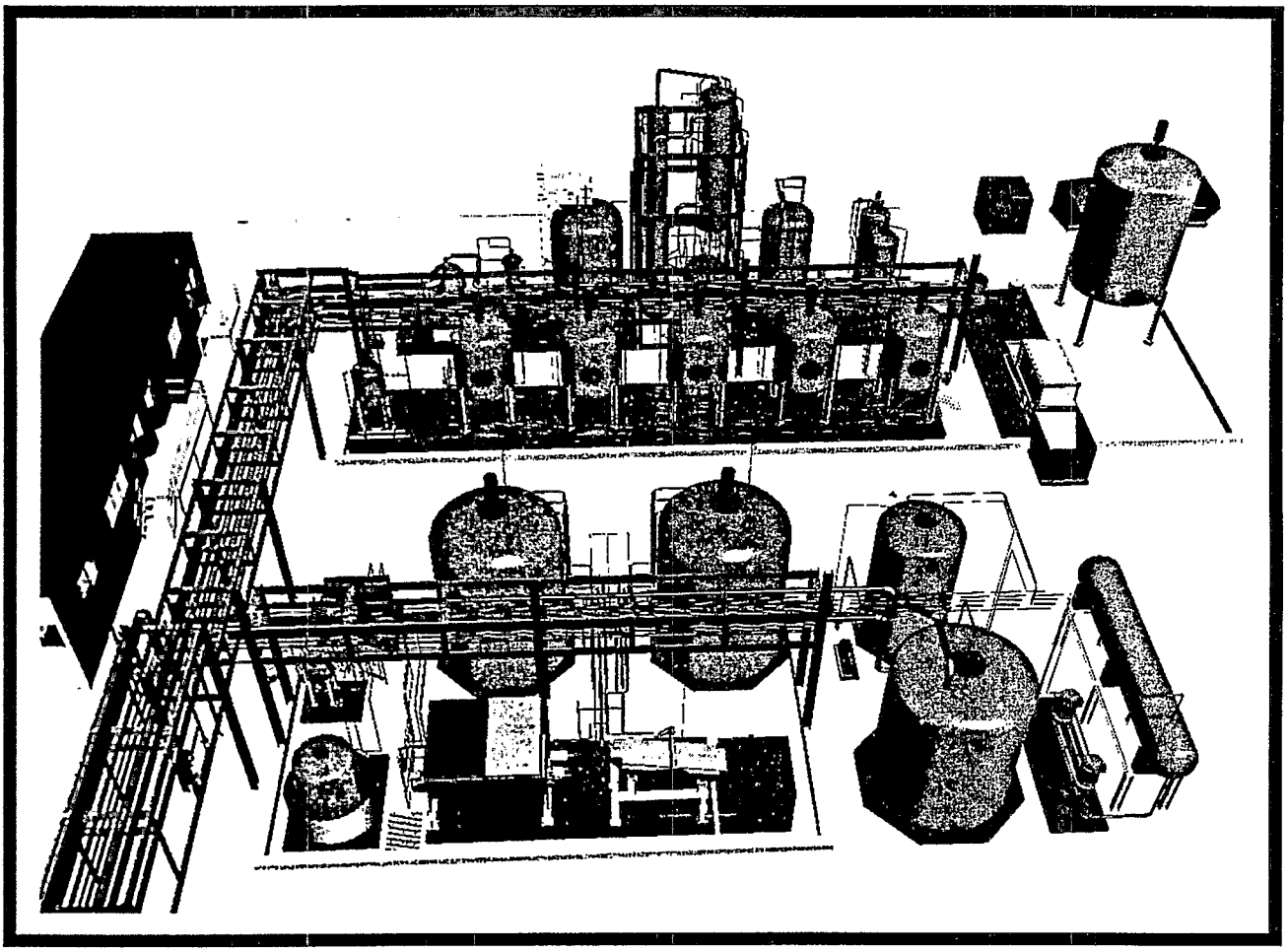
Emissions in the X*TRAX system were not measured in the study, due to the small quantity of soils processed. Therefore, additional information from full- or pilot-scale operation of the unit would be needed to assess compliance with any applicable emissions standards.

Of concern in thermal extraction systems is the potential for the production of dioxins and furans when precursors (particularly chlorophenols) are present. In the ATP test results, concentrations of these compounds in feed soils and treated soils and ash were insignificant. However, significant concentrations of dioxins and furans were observed in the condensed oils. In the X*TRAX system, dioxin and furan concentrations in the feed and treated soil were insignificant and well below regulatory levels. No dioxin testing was performed on the condensate phases or the off-gases because these treatment residuals were not produced in sufficient quantities for analytical testing. Therefore, the question of whether dioxin and furan generation may occur in the X*TRAX system was not answered in this treatability study.

In conclusion, based on the results of these treatability studies, both the X*TRAX and the ATP systems appear promising for the treatment of soils contaminated with manufactured gas plant wastes and wood preservatives. However, additional research or data on full-scale operation of these systems is needed to address the potential production of dioxins and furans, before either technology is selected for treatment of soils containing precursors.

CF Systems
Solvent Extraction Technology
For Site Remediation

A Post "Site Demonstration Update"



CF SYSTEMS' SOLVENT EXTRACTION TECHNOLOGY FOR SITE REMEDIATION A POST "SITE DEMONSTRATION UPDATE"

INTRODUCTION

In September 1988, CF Systems' Solvent Extraction Technology, on a pilot-scale, was tested and evaluated under EPA's Superfund Innovative Technology Evaluation (SITE) Program. The final Applications Analysis Report (EPA/540/A5-90/002) was issued in August 1990. This current paper contains a synopsis of that demonstration, an update on recent developments of the technology, and a review of the commercial scale application of the technology.

CF Systems' proprietary Solvent Extraction Technology uses a liquefied gas, such as propane, butane or carbon dioxide, as the solvent to extract organics from solids, sludges and wastewaters. The solvent, containing extracted organics, is separated from the treated product and the solvent is recovered by distillation in the Solvent Recovery System, condensed and recycled to the extraction system. The extracted organics are discharged from the system and typically sent either to a disposal or recycling facility.

The unique physical properties of a liquefied gas, such as low viscosity, density and surface tension, result in a solvent which has a significantly higher rate of extraction in comparison to conventional solvents. Additionally, these enhanced physical properties accelerate the rate of settling of the soil/solvent mixture following extraction which broadens the applicability of the process to include the treatment of fine clays and silty sediments. Due to high volatility, liquefied gas solvents are easily and economically recovered from the treated waste matrix by distillation. This minimizes the potential for solvent residues in the treated soils and aqueous streams as well as in the extracted organics.

Materials that can be successfully and economically extracted include:

- Petroleum-derived hydrocarbons
- Chlorinated hydrocarbons, including PCBs, dioxins, and pesticides
- Phenols, alcohols, and organic acids

Areas of applications of this Technology include:

- Remediation of contaminated sludges, soils, sediment, and fill at Superfund, production and disposal sites thus:
  - eliminating the need for off-site disposal
  - meeting mandated clean-up standards
  - recovering or separating organics for recycle or disposal
- Integration with refining, petrochemical, and industrial processes to:
  - minimize or eliminate hazardous waste production
  - minimize treatment costs
  - recover product or by-product for recycle or resale
- Removal of organic contaminants from wastewater streams to:
  - meet regulatory standards for wastewater discharge
  - recover product for recycle
  - minimize treatment and disposal costs

- On-site treatment of hazardous wastes at refineries or petrochemical units to:
  - meet existing and projected standards for land disposal
  - minimize waste volumes and disposal costs
  - minimize liabilities of transportation and disposal of hazardous waste

CF Systems is a subsidiary of Morrison Knudsen Corporation, a $2 billion diversified services company with primary emphasis in the engineering, construction, and environmental sectors. CF Systems supplies engineered solvent extraction systems and remediation services to the refining, process, and environmental industries. Several commercial-scale systems employing the proprietary technology have been built and the technology has been specified for the remediation of a Superfund sites.

CF Systems successfully completed its first commercial Best Demonstrated Available Technology (BDAT) treatment operation at the Star Enterprise Refinery in Port Arthur, Texas. The propane-based solvent extraction unit processed listed refinery wastes (F and K) and produced treated solids that met land-disposal treatment levels. The unit was operated continuously from March, 1991 to March, 1992 and had an on-line availability in excess of 90%.

The first commercial wastewater treatment unit was put into service in October, 1991 at the Clean Harbors waste treatment facility located in Baltimore, Maryland. This unit is a CO_2-based extraction unit designed to treat large volumes of wastewater containing hydrocarbon contaminants.

CF Systems has been selected by the Texas Water Commission (TWC) and the EPA as the sole-source supplier of a solvent extraction system for remediation of the United Creosoting Superfund site in Conroe, Texas. This unit will employ a batch process to treat non-pumpable solids containing poly aromatic hydrocarbons (PAHs) and dioxins. The unit capacity will be in excess of 200 tons per day (TPD).

SITE DEMONSTRATION PROGRAM

The SITE program demonstration of the CF Systems solvent extraction technology was conducted to obtain specific operating and cost information that could be used to evaluate the potential applicability of the technology to Superfund sites. The demonstration was conducted concurrently with dredging studies managed by the U.S. Army Corps of Engineers at the New Bedford Harbor Superfund site in Massachusetts.

Contaminated sediments were treated by CF Systems' Mobil Demonstration Unit (MDU), which had a rating of 20 barrels per day of sludge feed, on a once through basis. The MDU used a liquefied propane and butane solvent mixture to extract organics from contaminated sediments. During the tests, treated sediments were recycled through the unit to simulate the design and operation of a full-scale, four-stage unit. Recent MDU operation has employed a batch processing technology, similar to that now proposed for full-scale remediation.

The MDU was tested on sediments obtained from New Bedford Harbor, Massachusetts which contained PCB concentrations of 350 and 2,575 parts per million (ppm). Table 2.1 summarizes the feed and treated solids PCB concentrations for two of the tests.

The objectives of the SITE testing included an evaluation of:

(1) the unit's performance,
(2) system operation,
(3) health and safety considerations,

(4) equipment and system materials handling problems,
(5) projected system economics.

The conclusions drawn from the test results are given in Table 2.2, with an evaluation of the findings versus current developments in table 2.3. The primary conclusions were:

Polychlorinated biphenyl (PCB) extraction efficiencies of 90 percent were achieved for New Bedford Harbor sediments containing PCBs ranging from 350 to 2,575 ppm. Concentrations of PCBs in the clean sediment were as low as 8 ppm.

Some operating problems occurred during the SITE tests; such as, intermittent retention of solids in system hardware and foaming in the treated sediment collection tanks.

Operation of the MDU at New Bedford did not present any threats to the health and safety of the operators or local community.

The projected cost of applying the technology to a full-scale cleanup at New Bedford Harbor ranged from $148 to $447 per ton. The predicted onstream factor for the full-scale commercial unit is the variable that introduces the greatest uncertainty to the cost estimates.

Table 2.1
Summary of "Site Test Data"

Stage Number	Test 2 PCB Conc. (ppm)	Cumulative PCB Removal %	Test 4 PCB Conc. (ppm)	Cumulative PCB Removal %
Feed	350		2575	
Stage 1	77	78	1000	61
Stage 2	52	85	990	62
Stage 3	20	94	670	74
Stage 4	66	81	325	87
Stage 5	59	83	240	91
Stage 6	41	88	200	92
Stage 7	36	90		
Stage 8	29	92		
Stage 9	8	98		
Stage 10	40	89		

	Table 2.2 New Bedford Harbor SITE Demonstration Findings
Performance Test Objective	**Findings**
Removal Efficiency	The technology can separate organics from harbor sediments, sludges, and soils. PCB extraction efficiencies greater than 90 percents were achieved for New Bedford Harbor sediments and treatment levels as low as 8 ppm PCBs were attained.
Foaming	Foaming of treated sediments occurred.
Flow Control	Solvent flow fluctuated widely and caused the solvent to feed ratio to fall below specifications.
Solids Retention	Solids were retained in process hardware.
Extract Quality	Solids were observed in organic extracts.
Health & Safety	No significant releases of pollutants to the atmosphere or surrounding area soils occurred. Results of the demonstrations tests show that the CF Systems technology is capable of operating without risk to personnel or the surrounding community.
On-Stream Factor	For the purposes of the economic evaluation an 85 % availability was assumed. This level of availability was considered optimistic in the Applications report.
Propane Loses	Propane losses were not quantified in the evaluation; however, they were reported to be significant.
PreTreatment /PostTreatment	Pretreatment (removal of coarse solids) was required to maintain feed sediment particle sizes below 1/8 inch. Post-treatment such as thermal destruction of the concentrated extract may be necessary.
Remediation Costs	The Applications Analysis Report estimated total treatment costs for New Bedford Harbor (Pile to Pile) to be $450/ton for Hot Spots and $150/ton for the Base Case. These were considered to be optimistic in view of the required availability to achieve these costs.

Table 2.3
Historical Performance Comparison SITE Program to Present Day

Test Objective Performance/ Design Criteria	New Bedford Demonstration	Laboratory Pilot Plant Operation	Commercial System Operation	Future System Criteria
Removal Efficiency	Test 2: 92 % PCB Test 4: 97.5% PCB	PCB 99.9 % PAH 99 % VOA 99.9 %	Port Arthur PAH 99% + VOA 99.9 % +	PCB 99% + PAH 99% + VOA 99.9 %
Foaming	Caused Poor Performance	Eliminated	Eliminated	Eliminated
Flow Control	Caused Poor Performance	Eliminated	Eliminated - System Design	Eliminated - System Design
Solids Retention	Cross Contamination	Operational Issue	Eliminated - System Design	Eliminated - System Design
Extract Quality	Disposal Costs	Eliminated	Eliminated: 1% in Extract	Eliminated: 1% in Extract
Health & Safety	No Problem - Design Criteria	Procedures - Design	Procedures - Design	Procedures - Design
On-Stream Factor	85% Estimate	90% Estimate	1 Year Factor: 92 %	90 % Design
Propane Loses	10% Of Feed	1% Of Feed	1 Year Factor: 1% Of Feed	Design: 1% Of Feed
Pretreatment / Post-Treatment	Sieving <1/8 " Extract Disposal	1/4 " Max.	1/4 " Max.	1/4 " Max.
Remediation Costs	$150-$450/Ton	$150-$450/Ton		Projected: $100-$350/Ton

BENCH AND PILOT SCALE WORK

CF Systems has been operating a bench-scale testing facility since 1980 and its experience in performing laboratory-based feasibility studies for both commercial clients and governmental agencies is considerable. The composition of samples sent to CF Systems for testing has ranged from dry soils/sludges to sediments and wastewaters. These samples have originated from a variety of sources including, Superfund and RCRA Closure sites, ongoing waste streams generated from industrial operations, and planned remediation sites. The results obtained from these bench-scale extractions have been used to develop a broad experimental data base for the extraction of organics from hazardous wastes using a variety of liquefied gases as extractive solvents. These data are the foundation for the different solvent extraction units CF Systems has designed and built. Typical bench-scale data is given in Table 3.1.

The MDU, used for the New Bedford Harbor study, has been modified to allow for operation in a Batch treatment mode for non-pumpable wastes and sludges. This, and other changes in the system design and operation, has resulted in significant enhancement of the technology for remediation service.

The following is an outline of some of the studies carried out at bench scale and pilot scale.

Massachusetts Superfund Site

CF Systems was contracted to perform a bench scale treatability study to determine the feasibility of using liquefied propane as a solvent to remediate PCB-contaminated soils from a Superfund site in Massachusetts. This study was done as part of the remedial design phase of work at this Superfund site, and was performed at CF Systems testing facility under a TSCA R&D permit granted from EPA Region I.

The results from this study (Table 3.2), indicate that the composite sample (i.e., 697 ppm PCBs) was reduced to 0.36 ppm after six stages of extraction. The second "hot spot" sample, which contained 13,800 ppm PCBs in the feed, was reduced to 1.5 ppm after six stages of extraction. The percent reduction of PCBs from these two soil samples was calculated to be 99.95% and 99.99% respectively, and are an indication of the high PCB removal rates that can be achieved using liquid propane as a solvent.

Star Enterprises Refinery, Port Arthur, Texas.

The pilot-scale Mobile Demonstration Unit (MDU) had its initial start-up at Star Enterprise's Port Arthur refinery in September, 1987. Waste materials processed through the unit included contaminated soils from a clay pit, ditch skimmer sludge, and tank bottoms. The resulting treated solids product streams were analyzed by Star and the concentration of individual components, including PAHs and volatiles, were found to be well below the regulatory levels established for the treated solids.

PCB-contaminated NPL site in Augusta, Maine

This bench-scale treatability study was carried out to determine the feasibility of using CF Systems' solvent extraction process to treat five soil and sediment samples collected from a PCB-contaminated Superfund site in Augusta, Maine. A variety of soil types (i.e., clay, fill, and sediment) were processed and it was demonstrated that liquefied propane extraction was capable of reducing the PCB levels to below 1 ppm. The overall PCB removal efficiency for this study exceeded 99%, with PCB concentrations in the treated solid as low as 30 ppb. Results from this

bench-scale study resulted in a contract for CF Systems to conduct a Pilot Scale Remedial Design Treatability Study at the site.

PCB-contaminated Naval Station site in Adak, Alaska.

The purpose of this bench-scale treatability study was to determine the feasibility of using CF Systems' solvent extraction process for the remediation of PCB-contaminated soils at a Superfund site in Alaska. Samples were collected from the site and tested. The results of this study indicated that solvent extraction utilizing liquid propane as the extractive solvent was an effective treatment process for the remediation of PCB-contaminated soils. Analytical results showed that an overall PCB reduction of 99% was achieved in the study.

Waterways Experiment Station, Vicksburg, Mississippi.

In April of 1989, CF Systems conducted a pilot-scale technology demonstration for the EPA at the Waterways Experimental Station in Vicksburg, Mississippi. CF Systems utilized its Mobile Demonstration Unit (MDU) for this study. The purpose of this demonstration was to develop treatment standards for the KO48-KO52 listed refinery wastes, and CF Systems' solvent extraction process was in fact the only solvent extraction technology to be field-tested for that purpose. The results of this treatability study were used by the EPA to develop BDAT treatment standards for five listed refinery wastes.

United Creosoting Superfund Site, Conroe, Texas

CF Systems conducted a pilot-scale treatability study for EPA Region VI and the Texas Water Commission at the United Creosoting Superfund site in Conroe, Texas. The objective of this treatability study was to evaluate the effectiveness of CF Systems' solvent extraction process for the remediation of soils containing creosote-derived organic contaminants, such as PAHs, PCPs, and Dioxins. Treatment data from this field demonstration showed that the overall concentration of PAHs were reduced by 95.7% in the two soil samples, and subsequent full-scale treatment data indicates that PAH reductions of >99% are possible through the optimization of extraction operating conditions. Based on the results of this pilot-scale study, CF Systems' critical fluid solvent extraction process was selected for full-scale remediation at the United Creosoting Superfund site.

TABLE 3.1
SELECTED CF SYSTEMS TREATABILITY STUDIES

			Concentration (PPM)		
Client	**Site**	**PCOC's**	**Feed**	**After Treatment**	**Removal Efficiency**
Texas Water Commission	United Creosoting Superfund Site	PAHs PCPs Dioxins	2324.0 33.9 312.0	51.7 5.59 14.8	97.7% 83.5% 95.3%
Metcalf & Eddy	Pine St. Canal Superfund Site	PAHs	240.	16.	93.4%
Occidental Chemical	No. Tonawanda	Dioxins	23. ppb	0.6 ppb	97.4%
Central Maine Power	O'Connor Superfund Site	PCBs	113.	3.4	97.0%
U.S. Navy	Adak Naval Air Station	PCBs TPHs	305. 7850.	2.2 34.	99.3% 99.6%
NY Dept. of Envir Conservation	Booth Oil Site	PCBs TPHs	12.4 40.3	<0.24 0.24	>98.% 99.4%
Metcalf & Eddy	Norwood Superfund site	PCBs Dioxins	13,800. 7.068 ppb	1.4 0.09924 ppb	>99.9% >99.9%
Kerr McGee	Wood Treating Site, OK	PAHs PCPs	In progress	In progress	

Table 3.2 PCB Contaminated Superfund Site Solvent Extraction Results				
Sample	Composite Sample (ppm)	Cumulative % Removal	Hot Spot Sample (ppm)	Cumulative % Removal
PCB in Feed	697.0		13800	
PCB After Extraction Stage No.				
1	14.0	97.99	178	98.71
2	1.4	99.80	26.8	99.81
3	2.9	99.58	10.3	99.93
4	0.2	99.97	5.3	99.96
5	0.07	99.99	2.6	99.98
6	0.3	99.96	1.4	99.99

COMMERCIAL-SCALE PROCESS

CF Systems' proprietary Solvent Extraction soil treatment process involves the use of liquefied gases, such as propane, as the solvent to extract and separate organic contaminants from soils and sludges. The unique physical properties of a liquefied gas, such as low viscosity, density, and surface tension, result in a solvent with significantly higher rates of extraction in comparison to conventional solvents. Additionally, the enhanced physical properties accelerate the rate of gravity settling of the soil/solvent mixture following extraction which broadens the applicability of the process to include the treatment of fine clays and silty sediments. Due to high volatility, liquefied gas solvents are easily recovered from the waste matrix which minimizes the potential for solvent residues in the treated soils.

CF Systems has successfully completed the first commercial on-site BDAT treatment operation at the Star Enterprise Refinery in Port Arthur, Texas. The propane-based solvent extraction unit processed listed refinery K- and F-wastes and produced treated solids that met land-ban requirements. The unit operated continuously from March 1991 to March 1992, with an on-line availability in excess of 90%. Following fixation for heavy metals, the treated solids were disposed of in a Class I landfill. During operation, 100% of the feed material was treated to meet the land-ban specifications. Multiple feeds, including API separator solids, slop oil emulsion solids, slop oils, and contaminated soils were treated. Typical

treatment results for a refinery waste are given in Table 4.1.

The first commercial wastewater treatment unit was put into service in October 1991, at the Clean Harbors waste treatment facility in Baltimore, Maryland. This unit is a CO_2-based extraction unit designed to treat large volumes of wastewater containing hydrocarbon contaminates. Recovered hydrocarbons will be disposed of in an incinerator while treated wastewater will be discharged to the local POTW.

CF Systems has been selected by the Texas Water Commission (TWC) and the EPA as the sole-source supplier of a solvent extraction system for remediation of the United Creosoting Superfund site in Conroe, Texas. This unit will employ a batch process to treat non-pumpable solids containing poly aromatic hydrocarbons (PAH's) and dioxins. Unit capacity will be in excess of 200 tons per day.

Process Description

The CF Systems solvent extraction process for remediation of organic-contaminated soils and sediments is comprised of the following systems:

- A Feed Delivery System
- An Extraction/Gravity Settling System
- A Treated Solids Filtration System
- A Solvent Recovery System
- A Vent Gas Recovery System

Feed Delivery

Soil delivered to the process battery limits is screened to less than 1/4 inch to remove oversized material. Oversize materials are segregated and reprocessed to an acceptable size through the use of mechanical size reduction equipment. Oversized material can also be washed to remove attached "fines" and surface contamination. The screened soil is sent to the extractor(s) via an enclosed conveyor/screw auger system. In most cases, the process does not require other forms of soil pretreatment, such as dewatering or the addition of chemical reagents.

Extraction System

The extraction system is comprised of one or more agitated extraction vessels where contaminated soil is contacted with liquefied propane. The number of extraction vessels and the size of the vessels and agitators determine the rate of throughput and the degree of organics removal. Exact configuration of the extraction system is determined during the bench test phase of the project.

Contaminated soil is fed to the extractors where it is contacted with liquid solvent pumped from the Solvent Recovery System. Following the extraction step, the agitators are stopped and settling of the soil from the solvent occurs. Settling of soil from the solvent occurs rapidly in the extraction vessel due to the enhanced physical properties of the solvents. Following settling, the solvent/organics phase is drained to the Solvent Recovery System where the solvent is recovered.

The extraction-settling-draining process is repeated in the extraction vessel until the extraction is complete. The final step involves injecting water into the extraction vessel in order to displace residual liquid propane, which is insoluble in water, and is displaced from the top of the extractor. This final water displacement step in the extractor vessel forms a treated soil/water slurry that is fed to a belt filter press operation.

Filtration System

This system includes the soil/water slurry day tank, belt filter press, and all required drums and pumps for routine filter press operation. Treated filter cake from the

filter press has high compressive strength, and is suitable for land disposal. Treated filter cake also has the appropriate moisture content for the addition of solidification/stabilization reagents for the fixation of metals, if required.

Solvent Recovery System

This system contains an extract surge vessel, the main solvent recovery still, a solvent condenser and a solvent recycle pump. The solvent/organics mixture (extract) flows from the extract surge drum to the main solvent recovery still, where the solvent is vaporized using steam, hot oil or the heat from a vapor recompression cycle.

Solvent vapor from the still is condensed and flows to the solvent storage drum. The solvent recycle pump takes a gravity suction from this drum and pumps liquid solvent, on demand, to the extraction system.

From the main solvent recovery still reboiler, organic-rich extract flows to a low pressure organics recovery drum, where residual solvent is removed from the extracted organics and sent to the Vent Gas Recovery System. Recovered extracted organics are sent to storage and disposal.

Vent Gas Recovery System

A low pressure compressor recovers low pressure solvent vapor from the organics recovery drum, recovered organics storage and from low pressure vents from the treated soils system. The compressed recovered solvent is returned to the main still for recycling.

CF Systems' Solvent Extraction: Benefits

The primary benefit of using CF Systems' solvent extraction process at large scale organic-contaminated sites is low treatment costs. The low operating (i.e., utility) requirements for this process results in treatment costs in the range of $100 to $350 per ton at sites containing greater than 10,000 cubic yards of soil.

The process has been commercially proven at Star Enterprises where it operated for over one year, 24 hours a day, seven days per week, with an on-line availability exceeding 90%.

The systems is totally enclosed, with no process vents or emissions, thereby reducing the level of complexity associated with obtaining required permits.

No chemical additives or reagents are required for this process, and the organics are extracted and recovered unchanged and unreacted. For most applications, the pretreatment requirements are minimal, consisting of size reduction to less than 1 inch particle size diameter.

The process is operated at ambient or near-ambient conditions, thereby eliminating the potential for the formation of toxic compounds and their subsequent release to the environment.

Table 4.1

TYPICAL TREATED SOLIDS - REFINERY WASTE

Compound	Typical Feed (mg/kg)	Product (mg/kg)	Percent Removal	BDAT (mg/kg)
Volatiles				
Benzene	65	<1.0	>98	14
Ethylbenzene	130	<1.0	>99	14
Toluene	250	<1.0	>99.4	14
Xylene	480	1.5	99.7	22
Semi-Volatiles (PAH)				
Naphthalene	350	1.8	99.5	42
Phenanthrene	450	<1.0	99.8	34
2-Methyl Phenol	10	ND	N/A	6.2
Anthracene	37	<1.0	>97	28
Benzo(A)-Anthracene	5	ND	N/A	20
Pyrene	35	<1.0	>97	36
Chrysene	19	ND	N/A	15
Benzo(A)-Pyrene	5	ND	N/A	12
Phenol	10	<1.8	>90	3.6
4-Methylphenol	10	ND	N/A	6.2
Bis(2-E.H.) Phthalate	10	ND	N/A	7.3
Di-n-Butyl Phthalate	ND	ND	N/A	3.6

COMMERCIALIZATION OF INNOVATIVE TECHNOLOGIES - CHALLENGES AND SOLUTIONS

(A Technology Vendor's Perspective)

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COMMERCIALIZATION OF INNOVATIVE TECHNOLOGIES-CHALLENGES AND SOLUTIONS

A Technology Vendor's Perspective

INTRODUCTION

Commercializing innovative technologies for the remediation of hazardous waste is a task fraught with obstacles and challenges. Experience in the field indicates that many of the obstacles and challenges can be overcome when the industry, including owners, regulators and purveyors of innovative technologies, work together. However, should the various parties continue to operate from their own isolated spheres without considering the others' needs, goals and constraints, then the use of innovative technologies will be stifled and new cost-effective solutions will not be applied to the hazardous waste problems of today and the future.

Even with more harmonious institutional relations, the current mind-set of the federally driven "command and control" regulatory program for cleaning up contaminated sites thwarts the commercial development and application of innovative technologies. That mind-set is the false assumption that complex sites with complex wastes can be adequately understood based on "studies" that justify a selected design of a total site remediation system that will work. Consequently, hazardous waste generators are being asked to sign on up-front for implementation of a "total solution" with imperfect knowledge, unproven technology and astronomical costs. These risk-posing factors flow downhill from site owners to remediation contractors and vendors in the form of contracts, hence, the deterrent to owners, contractors and vendors to invest in the development and use of innovative waste treatment technologies.

This paper discusses several key obstacles which emerge from this mind-set that must be overcome to foster innovative technologies in the market place. Solutions to

overcoming these obstacles are also presented. These obstacles and solutions are based on real-life experiences of bringing, or attempting to bring, innovative technologies to the commercial level in the hazardous waste industry of today.

With a co-operative spirit, a more workable approach to remediating sites and a few changes in the contractual methods of handling these endeavors, innovative technologies can be developed and commercialized to achieve more cost effective solutions to our hazardous waste problems.

OBSTACLES AND APPROACHES TO SOLUTIONS

Predicting Performance (or Lack Thereof)

Comprehensive long-term performance of innovative technologies cannot be predicted with any degree of certainty for the complex waste and subsurface conditions that exist at hazardous waste sites. Yet innovative technologies often may represent the most cost-effective method of cleaning all or portions of the site. However, in today's regulatory approach, agencies are asked to chose and owners are asked to accept a technology based on site investigatory information and to guarantee that the technology will work to clean the site to often unrealistically low levels of concentration. Without the certain predictability, the innovative technologies often do not make the first cut. Even if the technology is selected, the purveyors of the technology cannot predict long-term performance to the unrealistic low levels for the ill-defined complex conditions based on the limited investigatory site information. They therefore do not bid the work, or have to add such high contingencies that the technology does look financially attractive. Only if they are allowed to apply their technologies in a step-wise sequential remediation approach with near-term realistic goals can they successfully apply and commercialize their technologies.

Reducing Microscopic Regulation

The current ad-hoc system for determining residual waste stream performance standards during construction impedes innovation. The characteristics and volumes of residual wastes generated by the application of treatment technologies during the construction phase are not predictable at bench-scale or even pilot-scale testing because of the varying site conditions and waste characteristics encountered as site remediation proceeds. Yet, engineering designs attempt to define in absolute terms the performance standards and emission rates that must be met during construction.

When remediation is undertaken under the Superfund program where Potentially Responsible Parties (PRP) have assumed the lead role, residual waste stream performance standards and rates are typically incorporated into Remedial Action Plans which themselves are considered a part of Consent Decrees and Records of Decision. Therefore, any change in performance standards resulting from site conditions during full-scale remediation may require agreement of all the parties to the decree including the EPA, Department of Justice, State and PRPs. When Superfund projects are financed by the Fund and construction administered by the U.S. Army Corps of Engineers (COE) under an agreement with EPA, contractors and technology vendors are faced with convincing the COE. For historic, cultural reasons, the COE tends to treat remediation projects as standard civil engineering public works project where engineering designs tend to be viewed as sacrosanct.

Within this ad hoc decision framework, risks and uncertainties abound. Vendors are expected to warrant that they can meet these prescribed emissions performance standards and limitations. Failure to meet them usually results in shutdowns and protracted negotiations. Enforcement actions and penalties are a possibility.

The market responds to these risks and uncertainties in the only way it can, by increasing contingencies and bid prices, taking the chance the problem will not arise and fighting it out with the owners and regulators (the change order route) if it does, or declining to bid the technology. None of these alternatives is a good option financially or in terms of developing and maintaining good vendor <u>and</u> technology reputation in the industry.

A decision protocol is needed that will allow performance standards to be established based on full-scale proof-of-process testing on site wastes that will assure the technology will operate to its best capability <u>and</u> assure that the off-site public is protected and the on-site condition does not worsen. Such a decision protocol should

allow technologies to be operated uninterrupted from proof-of-process through to completion, provided that the off-site public is protected.

Risk Sharing

To realize savings through the use of cost-effective, innovative technologies, the regulators, the owners of the site and the vendors of the technologies must share the risk as well as the benefits. Each of these entities needs to understand that it cannot regulate, contract and/or receive payments as would when more developed, mature technologies are used. The risk sharing and the rewards must be fair and equitable to all concerned. Regulators must accept the premise that as long as the short-term treatment activities do not pose an unacceptable risk to the off-site public or worsen the on-site condition, the technology should be allowed to operate.

Institutional Attitudes and Mechanisms

In our industry today there is a tendency to think that the key to any problem, in this case the commercialization of innovative technologies, has at its core an "engineering solution." In reality, the problems are institutional and, once resolved, the engineering component, that which most of us are trained to concoct, can be brought to the table.

The main barriers to commercialization of innovative technologies are, at their core, institutional problems. In summary, they include: regulator's "command-and-control" and enforcement mentality; regulators, owners and contract administrators penchant to view the use of innovative technologies as no different than standard civil engineering projects; tendency to pass on risk to remediation contractors and technology vendors; and, a mind-set "letting the perfect be the enemy of the good" in terms of designing solutions to complex hazardous waste sites.

Canonie Environmental Services Corp. (Canonie) has had the most success in commercializing technologies where the risks have been shared and the institutional mechanisms for the project have been well developed and mutually understood by the parties involved. Case studies discussed herein include such projects as the McKin Superfund site where the Low Temperature Thermal Aeration (LTTA®) Technology was originally developed and commercialized; the Gould Superfund site where the patented Waste Battery Treatment System is being commercialized; and the San Jose Superfund site where the Accelerated Vacuum Extraction Process was developed and applied on a commercial scale.

Canonie also has commercialized innovative technologies on projects where the risk sharing and the institutional mechanisms were less than desired and the results have not been satisfactory. Even when the technology was technically successful, the financial burden on the vendor and the schedule of performance have been so adversely effected that participation on future projects of the type become very unattractive and commercialization of the technology is severely curtailed. Such was the case on the Wide Beach Superfund Site and the Waukegan Harbor Superfund Site where the SoilTech Anaerobic Thermal Processor (ATP) Technology was applied in two different modes for the first commercial applications of this technology.

COMMERCIALIZATION EXPERIENCES - CASE STUDIES

Case Study #1 - McKin Superfund Site

The Mckin Superfund site provides a good example of how innovative technologies can be applied at a commercial level while still being developed, if the parties are cooperative and the risks are shared. This project was done during the early days of the Superfund program when such innovation and risk sharing were common. Low Temperature Thermal Aeration (LTTA®) was the innovative technology developed and used in the successful cleanup. At that time, no commercial thermal aeration systems existed.

The McKin Superfund site was formerly a liquid waste storage, treatment and disposal facility for volatile organic solvents, chemicals and heavy oils. As a result of improper operation, the soils and ground water were impacted by VOCs and oils. The site was also subject to a high degree of public exposure because it was within 300 feet of several residences. This site was ranked No. 32 on the National Priorities list at the time of the Record of Decision (ROD) in 1985.

The ROD had called for the soils to be excavated and disked on the surface to remove the VOCs prior to being backfilled. However, the VOC concentrations were to be kept below a certain level at the site boundary. Disking to remove VOCs would certainly have caused exceedances at the boundary and would have taken an unacceptably long time to complete.

Canonie, while working with one of the main PRPs, realized that ex-situ processing was the only way to accomplish the intent of the ROD without causing unacceptable emissions. However, to design, build and permit a system would have caused the project to go far beyond the specified completion date, resulting in substantial costs, and still would not result in a proven commercial-level treatment technology.

Canonie was aware of an existing asphalt aggregate dryer that had an air permit to work in the area of the McKin Site. A technical review indicated that the heat and mixing action in the dryer would vaporize the organics in the soil and clean the soil to meet the specified criteria. The vapors could not, however, be released into the air. Therefore, to capture the vapors and assure that the provisions of the dryer air permit were not violated, Canonie engineered an extensive and innovative air treatment train using primarily existing air treatment components

from other projects or commercially available, including vapor phase carbon and slurry scrubber. This combination of existing and engineered systems was the initial formulation of the patented Canonie LTTA® system.

At the time the LTTA® treatment train was proposed to the owners and the agencies on the McKin project, there was no guarantee that the system would clean the soils, would not violate emission standards at the site boundary or would not cause microscopic emission excursions of the internal components of the system. Yet the system offered the owners the potential for substantial cost savings and the ability to meet the project schedule. All that was needed was an agreement to share some of the risk of applying the system at full production level and a cooperative spirit in entering the project.

No threat to the residents living near the site could be tolerated, and they had to be part of the overall plan. Consequently, a door-to-door campaign was implemented to discuss what was to occur, what precautions were going to be taken and what the risks and rewards (i.e., the cleanup of the site) would be. The public supported the total program.

The system was mobilized and test runs were conducted. The system was adjusted to improve performance. Full production was implemented under the monitoring of emissions and treated soils by the regulatory agencies which was conducted at the boundaries of the site and not at the microscopic emission points at, or internal to, the equipment. Equipment performance criteria for less innovative types of technology were not imposed on the unit (i.e., the agencies did not try to apply incineration performance criteria merely because this was a new type of thermal device). The owners, in cooperation with the equipment developer/vendor, monitored the costs.

The project was the first NPL site cleanup to be successfully completed in EPA Region I. The remediation was used by the EPA as an example of success of the Superfund program. The owner received a clean site at less than the original estimated cost and the contractor was adequately reimbursed for his efforts. Most important, the public was the all-around winner.

Case Study #1 (Continued) - McKin Superfund Site

Case Study #2 - Wide Beach Superfund Site

The application of the innovative SoilTech ATP Technology to remediate PCB-contaminated soils at the Wide Beach Superfund Site represents an case wherein technical success can be achieved in spite of non-cooperative behavior on the part of some of the parties, provided, however, that the developer/vendor is willing to take a large portion of the financial and performance risk.

The Wide Beach Superfund site was a residential area on the shores of Lake Erie near Buffalo, New York, where PCB-contaminated oils had been used for dust suppression on community roads. The PCBs existed throughout the roadways as well as in driveways and lawns. The ROD called for the PCB-contaminated soils to be excavated and treated with a dehalogenation process, a new and developing technology. The original estimated quantity to be treated was nearly 20,000 tons. The project was managed by the COE as the Contracts Manager for the EPA.

Even though dehalogenation had never been accomplished at a commercial level anywhere in the world, the COE wrote a standard performance specification and solicited unit-price hard bids for the work. The successful bidder for the treatment portion of the contract was a technology developer/vendor of a batch process for dehalogenation which had been doing some test work on the site. The technology was, however, not developed much beyond the bench-scale, or at most the pilot-scale level, and application of this process to full-scale remediation was speculative at best. The technology developer was supported in the bidding and contracting efforts by the prime contractor, who was responsible for the excavation and other miscellaneous work.

When the prime contractor began to realize the excessive risks he had assumed, he began to seek alternate solutions. He discovered that Canonie, through its subsidiary company, SoilTech, had a technology developed to commercial level that would desorb the PCBs from the soil. The addition of the dehalogenation capability looked feasible, but was not proven. Desorption was a developing innovative technology already, and adding the dehalogenation process made matters even more innovative and speculative.

Since the contractual and bidding mechanism for this project was not geared toward risk sharing and application of innovative approaches, the prime contractor could only apply the SoilTech ATP Technology with dehalogenation systems added by submitting a Value Engineering Proposal with fixed unit prices. SoilTech was asked to supply these prices and to take all the risk that

performance would be successful. There was no mechanism for nor willingness by the COE to allow any risk sharing or to allow adjustments for changing site conditions, equipment performance on this innovative application, or other adjustments typically required to respond to the needs of applications of innovative technologies at the commercial level on a first-time basis. The COE's attitude was (and continues to be) that the developer and vendor should take all the performance and financial risk.

On the Wide Beach project, Canonie and SoilTech elected to take the risk. Canonie/SoilTech had to agree that no compensation would be received for the mobilization and testing if the processing was not successful in this first-time commercial level application. This was a gamble of over $1 million, not something a small company with a new innovative technology would be likely, or able, to take.

The gamble proved to be a technical winner. The SoilTech ATP Unit successfully removed and dechlorinated the PCBs in the soil and provided soils with non-detectable levels of PCBs after treatment. The gamble, however, turned out to be a financial disaster due to the rigid contractual position of the COE and its inability and unwillingness to share in any of the risk.

As with most Superfund work, the site characterization was valid to define the extent of the contamination, but was inadequate in defining the parameters necessary to apply and adequately price the application of the treatment technology, especially an innovative treatment technology.

When excavation began, it was discovered that the majority of the soils to be treated were very clayey in nature, more so than expected from the site characterization. Even though the equipment had to be adjusted significantly and the production rate had to be slowed (with attendant cost impacts) to accomplish the technical success (not an unusual occurrence when applying innovative technology at the commercial level for the first time), the COE would not consider an adjustment in the quoted unit price. The developer/vender of the technology (Canonie/ SoilTech) was told to keep working regardless of the costs and difficulty.

Case Study #2 (Continued) - Wide Beach Superfund Site

The project continued, and the quantities of treatment doubled; again, not an unusual occurrence at a CERCLA site. The innovative application of the SoilTech ATP Technology with dechlorination capabilities continued to perform well and cleaned over 42,000 tons of soils to non-detectable levels. This was the first commercial application at this scale world-wide and was hailed by EPA and the scientific community as a major success. (The technology received a national award in the Association of Bay Area Governments for the best innovative technology.) However, the COE has denied all claims and continues to administer the contract as if the work were standard ordinary construction work.

Case Study #2 (Continued) - Wide Beach Superfund Site

Case Study #3 - Gould Battery Superfund Site

The Gould Battery Superfund site in Portland, Oregon, is another example of how innovative treatment technology can be developed and applied through joint cooperation among the owners, the regulators and the technology vendors. This project is a first-of-a-kind and has significant potential for the remediation of similar sites nation-wide.

Automobile batteries were recycled at the site over a period of 32 years. Lead, copper and other metals were extracted from the batteries by crushing, separation and smelting methods. The waste materials, principally battery casings and furnace products (matte, slag, etc.) were used as fill material both on and around the property. The site was placed on the NPL in 1983 and a Remedial Investigation/Feasibility Study (RI/FS) was completed in 1988. The ROD issued in 1988 specified excavation, treatment and recycling of fill material as the preferred remediation method. Specifically, the selected remedy contemplated recycling plastics, hard rubber (ebonite), metallic lead and lead oxide/lead sulfate products from the process. The feasibility study, however, failed to demonstrate that the requirements of the ROD could be achieved with any known treatment, technology, including processes then being used commercially for automobile battery recycling.

At this point in the project, the owner and the EPA entered into a Consent Decree to conduct predesign studies to collect information on the treatment, recycling, and health and safety aspects of the project. Canonie was retained to perform this work, which resulted in the successful development of innovative technology for the treatment of the wastes on the Gould Superfund site.

In electing to pursue the predesign studies route, the EPA avoided the pitfall of specifying a remediation approach which could not be met with existing technology and which would have resulted in a costly failure for both the regulators and the owners. Realizing there was no precedent for remediating abandoned battery wrecking sites, Canonie sought to develop a treatment approach which would minimize the risk associated with technology innovation. Canonie accomplished this by characterizing the site from a treatment rather than contamination standpoint. Existing unit processes, used previously in the mining industry, were selected for the conceptual process flowsheet, but configured in such a way as to meet the site regulatory requirements for the remediation. The process developed by Canonie not only produced the required recyclable products, but addressed water treatment and off-site disposal issues by reducing

or eliminating toxic chemicals from the process. Public health exposures to dust and air borne lead emissions were mitigated by developing and incorporating a wetting agent/dust control system which is totally compatible with the process.

This approach resulted in a significant reduction of the remediation cost over projections made during the RI/FS phase. Most importantly, the treatment technology was developed through the stages of bench-scale, pilot-scale and on-site demonstration.

In the Gould project the risks were shared in some proportion by the participants. The owner paid for the technology development, but may receive revenue from its application on other sites. The EPA took the risk that a process and/or approach could be developed to meet the requirements of the ROD. The technology developer (Canonie) took the risk that the remediation project could be completed at a cost substantially below the amount projected in the RI/FS. By performing the work on a target value basis, Canonie had the incentive to complete the project at even lower costs if possible.

The confidence built among the participants during the predesign studies phase was sufficient to persuade the owners to negotiate the remediation contract with Canonie on a sole-source basis. This relationship continues to strengthen during the construction phrase of the project through the participation of the owners, regulators, and the contractor in resolving problems as the remediation progresses.

Case Study #3 (Continued) - Gould Battery Superfund Site

Case Study #4 - Waukegan Harbor Superfund Site

The SoilTech ATP Technology applied at the Waukegan Harbor Superfund site represents an example of a technical success for an innovative technology, but where the variable nature of the site conditions and where micro-monitoring of the equipment operation by the agencies caused unwarranted financial burden on the developer/vendor of the technology.

The sediments of the Waukegan Harbor and an adjacent stream were heavily impacted with PCBs with concentrations in excess of 20,000 parts per million (ppm). This site ranked No. 86 on the National Priorities List. Remediation alternatives were limited because the harbor was located adjacent to a public beach and was used for both recreational and commercial boating activities.

The selected remedy was to excavate or dredge the contaminated soils, then remove 97 percent of the PCBs and dispose of the resultant soils in an on-site vault. Innovative technologies were required to remove the PCBs from the soils since, at the time of the ROD, incineration was the only method used for treatment of PCB contaminated soils. Solvent extraction and thermal desorption were considered. The SoilTech ATP Technology thermal desorber was selected. Even though SoilTech had not been applied commercially and, in fact, a commercial transportable unit did not exist, the technology was well advanced with operating pilot units of similar size to the planned transportable unit.

Canonie agreed to a lump-sum contract to perform the excavation and dredging and to treat the estimated 19,000 tons of material by thermal desorption using the SoilTech ATP Technology. On the basis of this contract, the transportable unit was manufactured at a cost of more than $5 million, to be immediately sent to the Waukegan site to process the soils.

A provision was included in the work plan at the insistence of the agencies that stack emissions had to meet "six-nines" Destruction Removal Efficiency (DRE) for PCBs, a requirement that was not applicable to this technology (but one the agencies felt comfortable with) because the SoilTech ATP Unit did not destroy PCBs and the emissions volume was orders of magnitude below that of an incinerator. However, the agencies were adamant and the developer/vender of the technology had little choice but to accept this stipulation in the work plan if the project was going to progress. There were some indications from bench-scale

work that this could be achieved and, if it was close, the developer/vender assumed that the agencies would be reasonable, given the difference between this technology and the incineration technology for which the criterion was established.

Within the first few days of excavation at the site, unanticipated PAH-contaminated soils were discovered and the whole project was stopped so the agencies could determine what to do. The resultant delays lasted for well over two years. Meanwhile, the technology developer/vendor was sitting with a $5 million piece of equipment having to pay debt service with no income. Notification of delays were given to the owner and delay claims are being discussed, but this did not help the technology developer with the difficult financial conditions caused by the delay. Eventually, when the extent of the delay was finally clear, SoilTech was able to find another interim project, but not without unanticipated costs and interruptions in the overall commercialization plan for the technology. Without strong financial backing, this initial perturbation could have resulted in the end of this technology's commercialization.

Eventually the Waukegan project was once again under way. The SoilTech ATP Unit was mobilized to the site, test work was done and production level processing began. The soil types and water content were ideal for the unit and production progressed at rates near the name plate capacity. The soils clean-up criterion was near 500 ppm PCB. The cleaned soils had levels of less than 4 ppm maximum and often were non-detectable. The project was going to be a technical, schedule and financial success, when the agencies again brought the whole process to a halt for failure of the ATP Unit to demonstrate the requisite DRE of 99.9999 percent after repeated tests (the ATP was demonstrating 99.9996 percent DRE).

Risk assessments conducted by EPA indicated that the health risk at the boundary of the site was less that 10^{-9}, a level two orders of magnitude below requirements cited in the Site Health and Safety Plan. The owner's experts determined that the amount of natural volatization of PCBs from stockpiled waste awaiting processing in the ATP would exceed the mass of emissions that would result from completing the project with a demonstrated DRE of 99.9996 percent. The site's citizens advisory committee was appraised of the situation and voted to recommend completion of the SoilTech portion of the project since, at the time of shutdown, more than 50 percent of the contaminated material had been treated.

Faced with these arguments, EPA allowed the project to restart and proceed to completion. However, it choose the lengthy administrative remedy of modifying the Consent Decree to relax the emissions standard to 99.999 percent DRE. This required agreement on the part of the owner, the State of Michigan and the Department of Justice.

The decision to relax the emissions standard was a difficult one for the EPA Region as this Region has a commendable track record of successful pollution control by imposing strict "technology-based" standards and, in the 1970s established the knowledge base within EPA that allowed EPA to promulgate nationally enforceable Best Available Technology Economically Achievable effluent guidelines for industrial discharges under the National Pollutant Discharge Elimination System (NPDES) program in the early 1980s. However, the administrative remedy of modifying the Consent Decree proved to be more complicated and time consuming than anticipated.

During the negotiation process, however, the equipment and labor were sitting idle. Frantic efforts were underway by the on-site crews supported by technical staff in an attempt to make the equipment meet the criterion so operations could continue. Carbon beds were added, dehalogenation agents were tried and other near-research-level attempts were incorporated. None of these efforts improved the performance of the unit to clean the soils, added to public health or environmental protection or in any way helped the remediation of the project.

Finally, approximately two months after the processing was halted and before the criterion change process could be culminated, the developer demonstrated a DRE of 99.99999 percent, accomplished in cooperation with the Region and EPA's Risk Reduction Laboratory in Cincinnati, Ohio, by additions and adjustments to the equipment and plugging a hole in the carbon bed that had remained undetected during previous attempts at improving air emission controls.

The cost to the developer/vender was, however, over $500,000, the remediation of the site gained nothing, and the developer/vendor missed a window of opportunity for another project.

Case Study #4 (Continued) - Waukegan Harbor Superfund Site

Case Study #5 - San Jose Superfund Site

The development and application of a commercial-level Accelerated Vacuum Extraction System at the San Jose Superfund Site is a good example of the way an innovative technology can be effectively commercialized by risk sharing among all parties involved.

The San Jose Superfund site resulted from leakage of an underground tank containing waste solvents. The solvents reached the underlying drinking water aquifers and caused significant concern. The remediation was accomplished in a classic example of the Sequential Risk Mitigation approach advocated by Canonie including pump and treat, source removal, containment with a slurry wall and contaminated soils remediation. The use of the Accelerated Vacuum Extraction System was part of the on-site soils remediation.

At the time of the soils remediation requirement, the owner of the property had accomplished much of the remediation through the sequential application of several different innovative technologies and approaches. The remaining contamination was concentrated in the vadose zone of the on-site soils. The site was sufficiently remediated that prospective buyers were interested in the property. However, the property could not be sold with the soils contamination remaining at levels above those considered acceptable to the agencies.

Canonie assessed the situation and presented two options to the owner.

1. *Regular Vacuum Extraction using many wells pumped at low rates with small pumps. This was the system most were using at the time to accomplish soils aeration. The capital cost was low; however, the time to remediation could be long and somewhat unpredictable, and the operation and maintenance costs could be high.*

2. *Accelerated Vacuum Extraction consisting of an innovative system designed by Canonie to accomplish acceptable levels in the soils in a time frame consistent with the impending sale and development of the property. The capital costs were higher, but if the system performed as predicted, the overall costs would be lower due to the lower operation and maintenance costs. The system was, however, unproven at commercial levels.*

Canonie worked with the agencies to establish turn-off criteria for both systems based on realistic anticipation of the performance of the respective technologies. The accelerated system was more difficult to discuss since the agencies had not seen such a system perform.

The owner elected to go with the accelerated system and worked with Canonie on its development and application. The owner shared in the financial risk and in the risk that the system might not perform as predicted. The agencies shared in the risk by not imposing unrealistic operating performance criteria and agreeing to reasonable shut-off criteria.

The system was built and installed. The performance was near that projected. The chemicals were removed from the ground on a schedule almost identical to that predicted. The site was remediated and ready for sale at the time indicated.

The cooperation of all parties for this application of an innovative technology was excellent. The developer was not financially burdened nor did he receive windfall profits. The owner received remediation at a lower overall cost than with a more conventional system. Since the owner also paid for the equipment, it was available to do another project for the owner at no additional capital. The agencies were able to show a site remediated in a timely manner. The project was a success to all concerned because of the cooperative risk sharing of all parties involved.

Case Study #5 (Continued) - San Jose Superfund Site

PROPOSAL TO EPA

Canonie's experience at commercializing innovative hazardous waste treatment technologies as depicted above represents considerable technical success, but not always financial success. Ultimately, the viability and credibility of the hazardous waste remediation industry (including regulators and regulated alike) will depend upon two interrelated issues, financial success of those whom we rely upon to develop and commercialize technologies and a regulatory approach which will foster cleanup of hazardous waste sites quicker, cheaper and in a manner that will minimize risks and liability for generators and site owners.

In response to this need, Canonie has made an unsolicited written proposal to EPA entitled, "Accelerating Superfund from the Remediation Contractors' Perspective." The precepts of this proposal as they relate to commercialization of innovative technologies are:

1. The selection of hazardous waste treatment technologies should be made on the basis of reducing risk on a sequential basis by tackling the parts of the problem that pose the greatest overall risk to the public first. In doing this, a site should be viewed in a holistic sense and the arbitrary distinction made by the current regulatory structure of "operable units" be eliminated.

2. Hazardous waste treatment technologies should be selected only according to a realistic expectation that they can remediate a waste to a certain level of clean-up.

3. Once selected, the technology should be allowed to operate without microscopic regulation, provided the off-site public is protected and the on-site conditions do not worsen.

4. The marketplace will foster the development of innovative technologies whose performance capability continues to improve simply because of the desire of site owners and contractors to limit liability and risks.

The following summarizes Canonie's recommendations to EPA.

Sequential Risk Mitigation

Sequential Risk Mitigation as depicted on Figures 1 and 2 is a comprehensive and structured approach to investigating, engineering and remediating complex hazardous waste sites utilizing the "observational approach" to construction. Selection of remedial actions and technologies is made in a sequential fashion (see example shown in Figure 3) according to five levels of probable range of risk or status of contamination that are estimated for the site (described in Figure 2).

Employing a repetitive approach of "investigate," "select," "implement," and "observe," sites are remediated in a sequential fashion without much of the ritual (and attendant "transaction" costs) of the RI/FS and remedial design phases of the current Superfund program (or their RCRA equivalents). Knowledge obtained by observing the effects of previous levels of remediation activity serves as the basis to select the next remedial actions and technologies appropriate to the next desired level of cleanup.

The role of risk assessment in the Sequential Risk Mitigation model is significantly different than that currently promulgated by EPA. We recommend that traditional risk assessment methodologies to determine long term cleanup goals be deferred until the site reaches Level IV. Canonie's proposed use of risk assessment is much more truncated as it is designed for a different purpose, to determine the probable "range of risk" that a site represents or would represent without intervention. This "range of

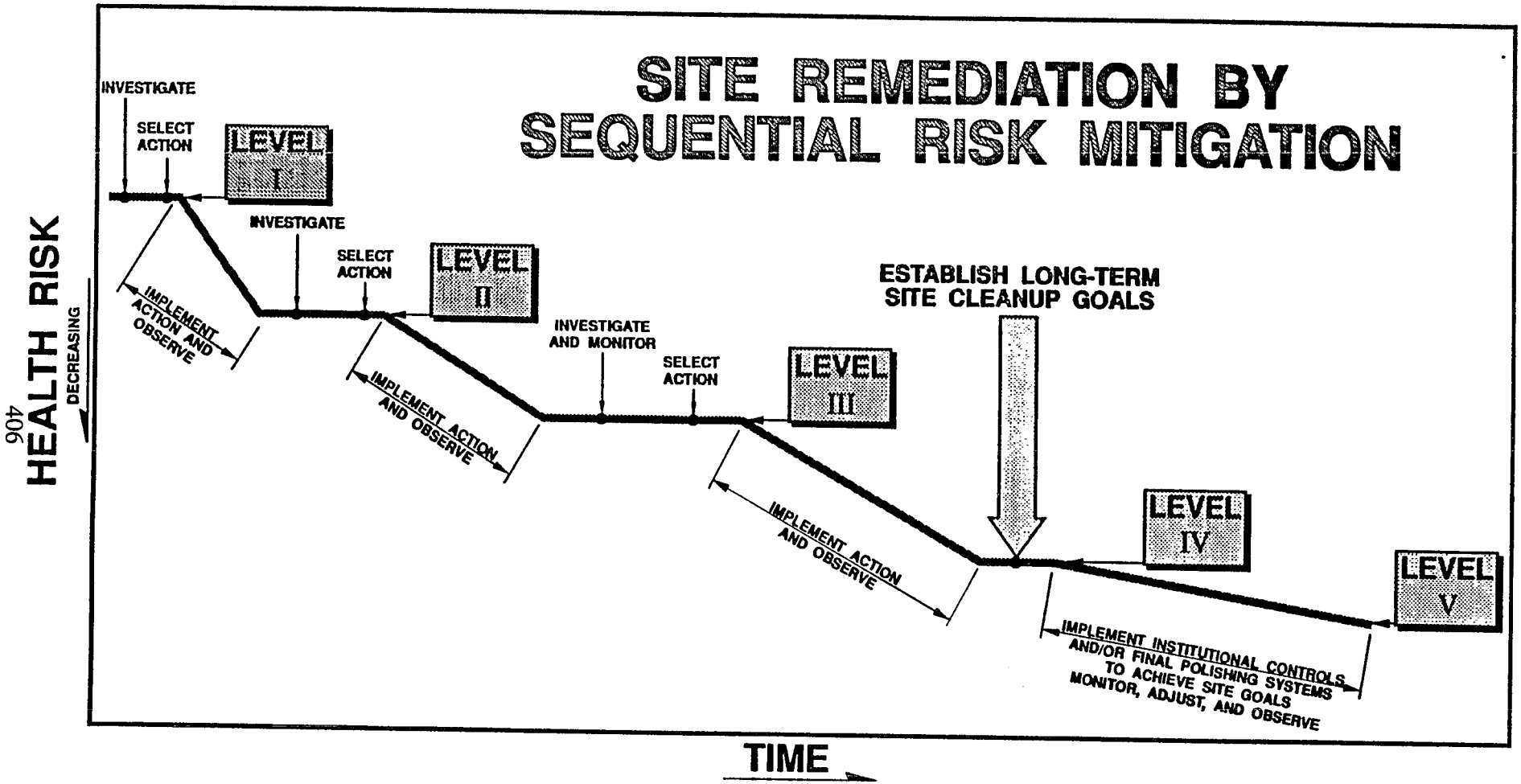
SITE REMEDIATION BY
SEQUENTIAL RISK MITIGATION
HEALTH RISK
DECREASING
TIME
INVESTIGATE
SELECT ACTION
LEVEL I
IMPLEMENT ACTION AND OBSERVE
INVESTIGATE
SELECT ACTION
LEVEL II
IMPLEMENT ACTION AND OBSERVE
INVESTIGATE AND MONITOR
SELECT ACTION
LEVEL III
IMPLEMENT ACTION AND OBSERVE
ESTABLISH LONG-TERM SITE CLEANUP GOALS
LEVEL IV
LEVEL V
IMPLEMENT INSTITUTIONAL CONTROLS AND/OR FINAL POLISHING SYSTEMS TO ACHIEVE SITE GOALS
MONITOR, ADJUST, AND OBSERVE

FIGURE 1

SITE REMEDIATION BY SEQUENTIAL RISK MITIGATION

LEVEL	HEALTH RISK RANGES	DESCRIPTION
I	IMMINENT DANGER to 10^{-4}	SERIOUS SITUATION THREATENING PUBLIC HEALTH AND ENVIRONMENT
II	10^{-2} to 10^{-4}	HOT SPOTS, EXPOSED FREE PHASE CHEMICALS, DNAPLs/LNAPLs IN DRINKING WATER AQUIFER WITH CLEARLY DEFINABLE PATHWAYS AND/OR RAPID MOVEMENT OF CHEMICALS
III	10^{-4} to 10^{-5}	SUBSURFACE BURIED CHEMICALS OF MEDIUM CONCENTRATIONS, DISSOLVED CONSTITUENTS IN GROUND WATER WITH SLOW MOVING OR ILL DEFINED PATHWAYS
IV	10^{-5} to 10^{-6}	CHEMICALS OF LOW CONCENTRATIONS, IN SOILS AND GROUND WATER AT SIGNIFICANT DEPTHS BELOW GROUND SURFACE, POORLY DEFINED PATHWAYS
V	$< 10^{-6}$	MINUTE CONCENTRATIONS IN SOIL AND GROUND WATER WITH NO REALISTIC OR AT MOST REMOTELY POSSIBLE PATHWAYS

FIGURE 2

LEVEL III – DESIGNED AND/OR STRATEGIC ACTION REQUIRED TOWARD LEVEL IV

CONTAMINANT

REMEDIAL ACTIONS	A						B						C						D						E					
	HYDROCARBONS (GASOLINE, DIESEL FUEL OIL, etc)						VOLATILE ORGANICS (SUCH AS SOLVENTS TCE, AND TCA)						SEMIVOLATILE ORGANICS (SUCH AS CHLOROBENZENES, PHENANTHRENES, AND PHTHALATES)						CREOSOTE						PCB					
	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b
SOILS AND SOLIDS																														
1. EXCAVATE LARGER AREAS OF LOW CONCENTRATION MATERIALS AND:																														
A. TREAT ON-SITE BY:																														
STABILIZATION	–	–	–	◐	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	●	–	–	–	–	–	◐	–	–
HIGH CAPACITY MOBILE THERMAL DESORPTION	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–
HIGH CAPACITY MOBILE INCINERATION SYSTEMS	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–
HIGH CAPACITY SOIL WASHING	–	–	–	◐	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–
HIGH CAPACITY BIOREACTIONS	–	–	–	○	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	○	–	–
PRODUCTION LEVEL INNOVATIVE TECHNOLOGICAL SYSTEMS	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–
B. TRANSPORT OFF-SITE TO:																														
LANDFILL	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	◐	–	–
INCINERATION	–	–	–	○	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–
RECYCLE/TREATMENT CENTER	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	◐	–	–	–	–	–	○	–	–
2. IN-SITU TREAT BY:																														
SURFACE DILUTING BY MIXING	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	○	–	–
VACUUM EXTRACTION	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	◐	–	–	–	–	–	○	–	–	–	–	–	–	–	–
BIOREMEDIATION	–	–	–	●	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	●	–	–	–	–	–	○	–	–
STABILIZATION	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	●	–	–	–	–	–	◐	–	–
PRODUCTION LEVEL INNOVATIVE TECHNOLOGICAL SYSTEMS	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–

REMEDIAL ACTIONS	F						G						H						I						J					
	CHLORINATED PESTICIDES (SUCH AS DDT, DIELDRIN, AND KEPONE)						NONCHLORINATED PESTICIDES (SUCH AS PARATHION, GLUTARALDEHYDE, AND GLYCISSATE)						METALS						RADIOACTIVES (RADIUM, PLUTONIUM, URANIUM, etc)						COAL TAR					
	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b	1	2	3a	3b	4a	4b
SOILS AND SOLIDS																														
1. EXCAVATE LARGER AREAS OF LOW CONCENTRATION MATERIALS AND:																														
A. TREAT ON-SITE BY:																														
STABILIZATION	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	–	–	–
HIGH CAPACITY MOBILE THERMAL DESORPTION	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	●	–	–
HIGH CAPACITY MOBILE INCINERATION SYSTEMS	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	◐	–	–
HIGH CAPACITY SOIL WASHING	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	○	–	–
HIGH CAPACITY BIOREACTIONS	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	–	–	–	–	–	–	◐	–	–
PRODUCTION LEVEL INNOVATIVE TECHNOLOGICAL SYSTEMS	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–
B. TRANSPORT OFF-SITE TO:																														
LANDFILL	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	○	–	–
INCINERATION	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	◐	–	–
RECYCLE/TREATMENT CENTER	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	◐	–	–	–	–	–	–	–	–	–	–	–	◐	–	–
2. IN-SITU TREAT BY:																														
SURFACE DILUTING BY MIXING	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	–	–	–	–	–	–	●	–	–
VACUUM EXTRACTION	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
BIOREMEDIATION	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
STABILIZATION	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	●	–	–	–	–	–	●	–	–	–	–	–	●	–	–
PRODUCTION LEVEL INNOVATIVE TECHNOLOGICAL SYSTEMS	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–	–	–	–	◐	–	–

LEGEND:

CONTAMINANT CONDITIONS:

- 1 OPEN AND EXPOSED AT SURFACE
- 2 DRUMMED OR CONTAINED
- 3a SUBSURFACE IN SOIL – FREE PHASE
- 3b SUBSURFACE IN SOIL – PARTIALLY SATURATED
- 4a SUBSURFACE IN GROUND WATER – FREE PHASE IN DRINKING WATER AQUIFER
- 4b SUBSURFACE IN GROUND WATER – DISSOLVED PHASE IN UNUSED AQUIFER

APPLICABILITY OF TECHNOLOGY:

- ● VERY APPLICABLE
- ◐ APPLICABLE UNDER CERTAIN CIRCUMSTANCES
- ○ NOT VERY APPLICABLE BUT SHOULD BE CONSIDERED
- – NOT APPLICABLE

METHOD FOR INITIAL SCREENING OF REMEDIAL ACTIONS/TECHNOLOGIES FOR VARIOUS CONTAMINANTS AND SITE CONDITIONS – LEVEL III TO LEVEL IV

PREPARED FOR

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

FIGURE 3

risk" serves only as a bench-mark to determine the appropriate remediation strategy and to measure progress as the site passes through various phases (levels) of remediation.

Because sites are approached holistically, and interim goals for remediation are the subject of remedial actions (not 100 percent solutions based on studies of operable units), innovative approaches will be fostered.

Emissions Control During Construction

To address the central question of health protection during the operation of on-site technologies, each site should be viewed as an "envirosphere" as depicted on Figure 4. This figure shows various sources of emissions that can be predicted to occur at the site during the remediation phase. EPA would establish a "Boundary Condition" for the contaminants of concern, based on an acceptable level of the temporary risk involved. The "Boundary Condition concept" is illustrated in Figure 5.

The site owner and/or remediation contractor would develop a "Site Emissions Control Plan" (SECP). Methodologies for estimating and modeling emissions would be EPA-approved.

Project construction would be allowed to proceed without interruption, provided site boundary conditions are not exceeded. Treatment technologies could be operated in a flexible manner.

In addition to the boundary conditions monitored for health protection during construction activities, the policy framework would adopt a "technology-based" component which would assure that the selected separation/treatment remediation technologies perform to their maximum efficiency under site conditions. The

ENVIROSPHERE

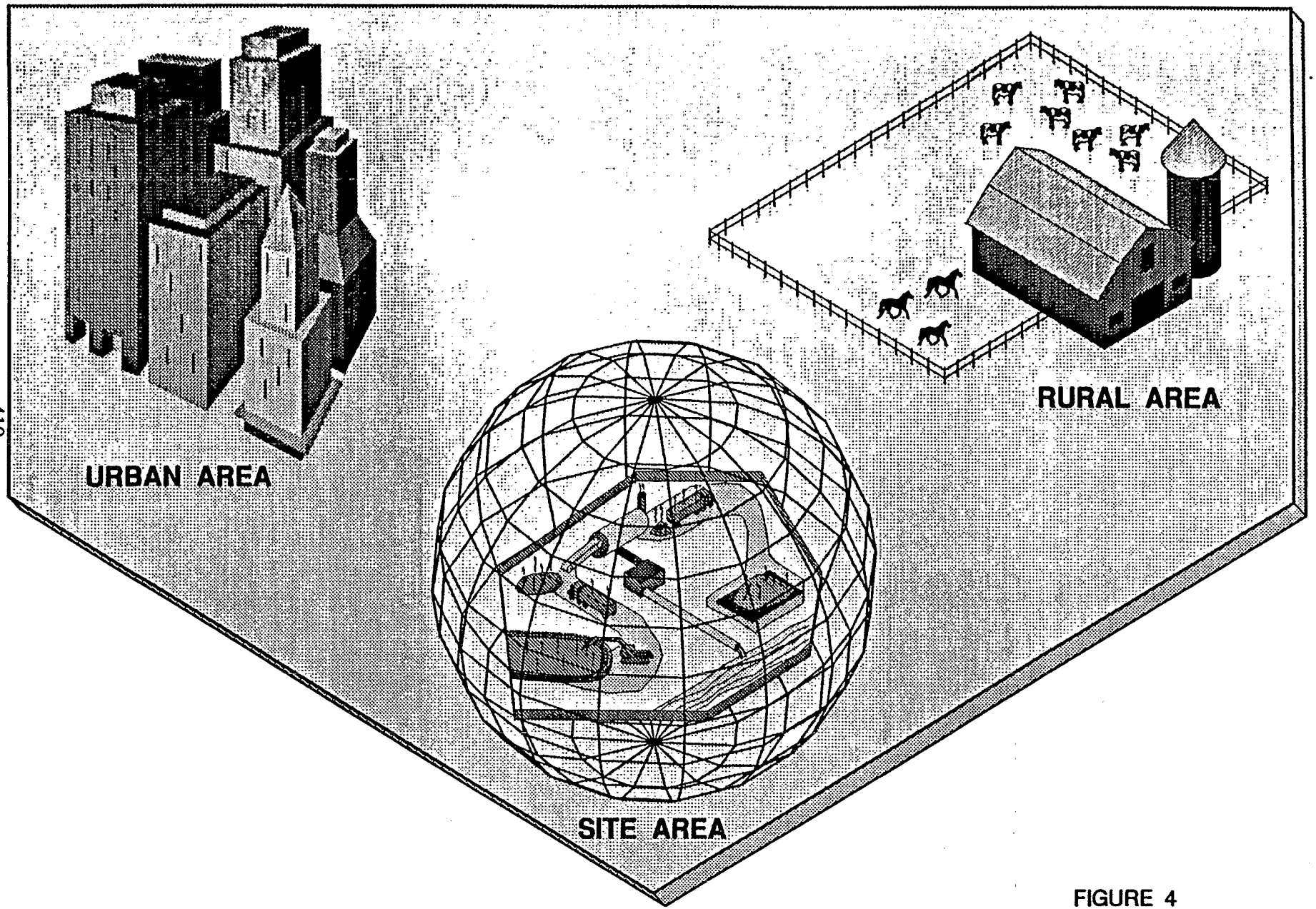

FIGURE 4

SITE BOUNDARY

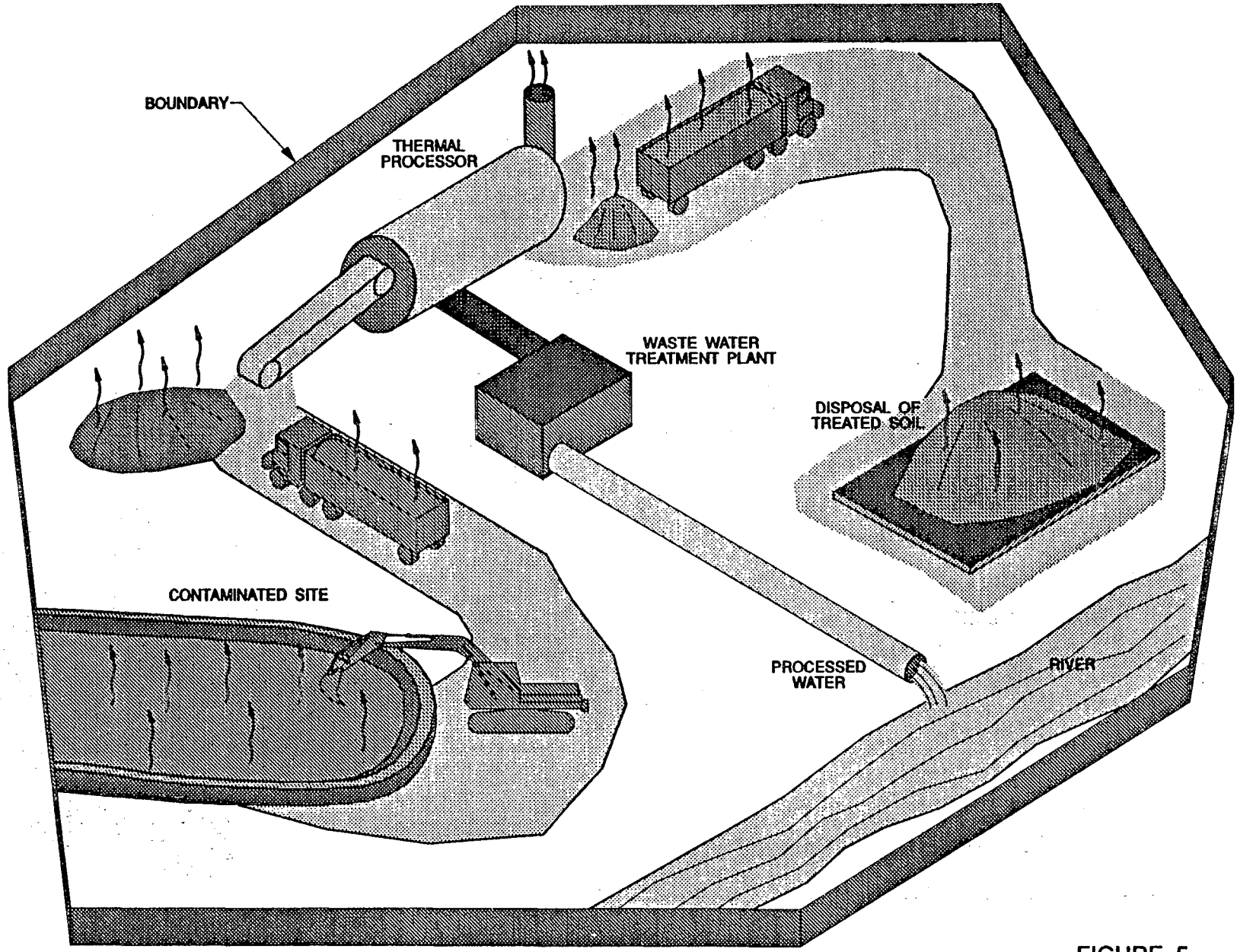

FIGURE 5

determination of "Best Technical Performance" would be made during the "proof-of-process" phase based upon a "Proof-of-Process Plan" prepared by the owner/contractor during the RD phase.

Together, the Boundary Condition and Best Technical Performance components form a policy framework for establishing emissions performance standards which can be characterized as the "Best Technical Performance That is Health Protective."

We view the combining of both health- and technology-based considerations as critical to address concerns of the public regarding health protectiveness. The EPA is also assured that the primary treatment/separation technologies achieve a greater degree of emissions control efficiency than would otherwise be allowed on the basis of human health. If the proof-of-process phase is extended to determine the best technical performance on the contaminated medium as well as residual air emissions, remediation to levels below the action limit established in the ROD represents a factor of safety against future liability.

Summary

In summary, the following rules should apply to the selection and operation of innovative technologies and approaches toward more cost-effective site remediation:

Selection of Technologies for Remediation

1. Investigation of sites should be limited to gathering that only information needed to select an RA to reduce the health risk from one level to the next.

2. An RA technology should be selected based on the health risk level of the site and the ability of that technology to reduce the health risk by at least one level.

3. Observation should be made during the implementation of an RA to allow realistic, pertinent, cost-effective selection of an RA to take the site to the next lower level of health risk.

Operation Constraints

1. A health- and risk-based boundary condition, which is determined by the EPA, should be established for the site.

2. Exceedance of the boundary condition would result in the shut-down of operation of the separation/treatment technology.

3. On-site proof-of-process testing should be the basis for determining the best technical performance of the technology on site wastes. Operating parameters and emissions limits will be established at this time to assure the technology will perform to its capability, even when the resulting emissions are more protective than allowed under the health-based boundary condition.

4. Continuous operation of the separation/treatment technology should be allowed, provided proof-of-process testing demonstrates that boundary conditions are not exceeded.

5. In the event that emissions limits or specified operating conditions are exceeded following proof-of-process testing, but the boundary conditions are not exceeded, the owner/contractor should be provided a reasonable

response time to return the operation of the technology to a state of compliance without interrupting the operation. The EPA-approved SECP would define contingency actions and time frames.

6. EPA should not take enforcement action against the owner for failure to meet emissions limits or operating conditions provided that the failure did not arise from knowing endangerment or willful misconduct.

CONTRACTUAL MECHANISMS TO SHARE RISK

Contractual methods of risk sharing are imperative and feasible for application of innovative technologies. The totally successful projects discussed above utilized such types of contracting methods.

Unlike standard well-defined construction projects, lump sum or fixed unit prices are often not good contracting methods for applying innovative technologies. Such contracts assign financial risk to the innovative technology contractor. Many such contractors cannot define the magnitude of that financial risk and consequently cannot bid the work or must add such levels of contingency that their technology looks unattractive.

Contract methods more suited to innovative technologies include target-valve-incentive, daily-rate-cost reimbursement or time-and-materials cost reimbursement contracts with not-to-exceed limits. These contract types give incentives to the contractors to make their technology perform, yet limit their financial exposure. Contractors should not, however, be given "blank checks." Checks and balances are required. A technology can receive a bad reputation and not be selected on future jobs if significant cost overruns occur on cost-reimbursable type contracts. This can be as detrimental to the technology's future as significant financial distress to the innovative technology contractor on fixed price contracts.

Cooperation in developing an appropriate contract should be part of this plan, but all parties must be good business people. A "win-win" situation can be established whereby technical success is coupled with financial success for both the contractor and the owner.

CONCLUSION

Cost-effective development and commercialization of innovative waste treatment technologies to remediate hazardous wastes can be fostered by a more cooperative spirit on the part of regulators, owners and vendors with each making a concerted effort to understand the goals and constraints of the other and a willingness to share the risk, and a change in mind-set in planning, designing and physically cleaning up contaminated sites. The regulatory decision process needs to be redefined to allow innovative technologies to be selected on the basis of a realistic expectation of performance to a specified level of cleanup. Sequential Risk Mitigation incorporates the observational approach to construction wherein remedial actions are selected to address the most serious health risk first, with subsequent levels of cleanup defined on the basis of observations and experience obtained in the previous stages of construction.

Once construction is under way, the contractors and vendors must be allowed to modify operations to adjust to changing site and waste conditions encountered without microscopic regulation, interruption of operations of the technology and without fear of enforcement provided that the adjacent public health is protected.

Canonie's proposals for "Sequential Risk Mitigation" and the decision model for residual waste emissions control during construction can be implemented within the current Superfund statutory and policy framework. If adopted, transactional costs will be reduced and the 80/20 rule applied - eighty percent of the problem solved at twenty percent of the cost.

Without a comprehensive revamping of the regulatory approach along the lines suggested herein and in Canonie's report to EPA entitled "Accelerating Superfund from the Remediation Contractors Perspective," more cost-effective innovative technologies will not be developed and applied on a wide scale.

PREPRINT EXTENDED ABSTRACT
PRESENTED AT THE U.S. EPA FOURTH FORUM
ON INNOVATIVE HAZARDOUS WASTE TREATMENT TECHNOLOGIES:
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SAN FRANCISCO, CALIFORNIA, NOVEMBER 17-19, 1992

BIOREMEDIATION OF CHROMIUM (VI) CONTAMINATED SOLID RESIDUES USING SULFATE REDUCING BACTERIA

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Cr(VI)-containing residues are of concern when present in the environment. Chromate [hexavalent chromium, Cr(VI)] is a strong oxidant and has toxic potential. Dissolved Cr(VI) has a propensity to pass through mammalian cell membranes and, due to its water solubility, also has the potential for groundwater migration. This material often arises from the chromium roasting process, where chromium in iron-containing ore is oxidized to chromates to enable separation of the water-soluble chromates from insoluble ferric oxide. The residues from the aforementioned process contain Cr(VI) usually in a highly alkaline environment arising from the presence of rather high levels of lime (CaO), which is used in large quantities in the chromium ore roasting process. For example, water in contact with solid waste arising from lime extraction of roasted chromium bearing ores possess a pH of between 10 and 11. An extreme pH necessitates pH adjustment prior to microbiological treatment, but this often leads to saline conditions that are not conducive to bacterial proliferation.

The naturally occurring reduction of Cr(VI) to Cr(III) by hydrogen sulfide produced by sedimentary sulfate reducing bacteria has been noted by R. H. Smillie, et al. (1). However, until recently it was believed that sulfate-reducing bacteria were considered to be unsuitable for treating chromium-containing industrial waste waters because of the inherent toxicity of chromium to microorganisms.

We previously described a bioremediation system (2,3), based upon the generation of H_2S by sulfate reducing bacteria, to effectively reduce Cr(VI) present in saline aqueous fractions to the low toxicity, low solubility state, Cr(III). We have now extended this approach to include bioremediation of solid residues in contact with a liquid aqueous fraction, especially when salinity is high. We feel the use of a sulfide intermediate to effect bioremediation is superior to direct bacterial reduction for a number of reasons, especially that H_2S may "seek out" Cr(VI) by diffusing to microenvironments poorly accessible or inhospitable to microorganisms or their nutrients. For lime-containing waste the process involves the addition of a suitable acid, such as HCl, to effect a pH between 6.0 and 9.5, followed by treatment with an acclimated, anaerobic sulfate reducing bacterial inoculum. For example, 5.1 g tailings containing 950 ppm Cr(VI) and 16,000 ppm total Cr were loosely packed into a 0.7 X 17 cm glass column and then treated (down-flow) with 1.5 mL 1 M HCl, then water, then the inoculum. A black layer (indicative of metal sulfides) 1 cm thick formed at the surface while below an off white precipitate [indicative of $Cr(OH)_3$] was dispersed. Treatment continued until <0.006 ppm Cr(VI) was detectable in the effluent. In another experiment untreated solid residue exhibited 103 ppm TCLP extractable Cr(VI).

After bioremediation this value dropped to <0.0002.

We have field-tested a similar approach on a 2,000 gal/wk scale. In this particular instance the pH of the groundwater was in the neutral range so that no pH adjustment of the groundwater was necessary *in situ*. The heart of the bioremediation system was a 1,000 gal fermenter. In it was fermented a solution of sodium sulfate, ammonium sulfate, super phosphate and molasses dissolved in estuarine (brackish) water. The function of the fermenter was to effect an acidogenic phase of the fermentation in a reactor where the pH could be readily controlled. In it the molasses carbon source was fermented, and the initial production of anaerobic, sulfate reducing bacteria and H_2S-containing fermented broth occurred. The balance of the metabolic process occurred in situ. During the acidogenic stage of the fermentation the pH of the broth dropped due to the formation of VFAs (volatile fatty acids). The pH was maintained at about 8 through the addition of soda ash (sodium carbonate). Each batch of fermentation fluid was deemed to be ready for injection when the pH of the broth ceased to change.

The fermented broth and bacteria were applied to two experimental plots, a percolation site, which was designed for remediation of the Vadose zone through flooding of that zone, and an injection site, designed for remediation of the water saturated zone. The percolation site consisted of an open-bottomed box fitted with a lid and a Calgon H_2S scrubber that effected retention of fermentation broth over a specified area. It is one half of a percolation and leachate recirculation option that is a potential system for contaminated soil and groundwater remediation. The injection site consisted of a single injection well. Both sites were surrounded by a number of piezometer (pipes) for groundwater monitoring.

We found that the bioremediation of Cr(VI) on site was successful within certain limitations. Possibly the most critical factor in success is the geology of the site. Where remediation was most complete, the conductivity properties of the soil or residue were consistent with the presence of high conductivity and, therefore, preferential paths of flow. Where there was lack of maintenance of anaerobic conditions of Vadose zone areas due to rapid draining of fermented broth there was less than optimal reduction of Cr(VI).

We have performed cost estimates for the main raw materials used for the bioremediation of lime-laden sites. By titration of existing surface residue we determined that it would require about 4.3 mEquiv/g to attain a pH of 8. For a site containing 1,000,000 tons of residue this translates to 3.9×10^9 equivalents, and the same number of moles of the monoprotic acid HCl. This is equivalent to 16,700 tons pure HCl or 46,400 tons of 22° Bé (12 M HCl) material. At \$68/ton this is $\$3.2 \times 10^6$. Waste acid is often available for a considerably lower price.

The concentration of Cr(VI) is typically 3.5 g/kg, wet weight. Again, for a site containing 1,000,000 tons of residue this translates to 6.1×10^7mol of Cr(VI). The stoichiometry of the reduction of Cr(VI) [as $CrO_4^=$] to Cr(III) [as $Cr(OH)_3$] is as follows:

$$2CrO_4^= + 3H_2S + 2H_2O \text{ ---> } 3S + 2Cr(OH)_3 + 4OH^-$$

thus requiring 9.2×10^7 mol H_2S. Since H_2S is generated from $SO_4^=$ on a one to one molar basis, an equivalent number of moles $SO_4^=$ is needed. At \$90/ton this is $\$1.3 \times 10^6$ plus shipping. A portion of this cost is defrayed by the use of sulfate naturally present in sea or

estuarine water.

The cost of the carbon source is quite variable. Waste molasses is possibly obtainable at nearly shipping costs. Items such as "sugar water" are available free in the Industrial Waste Exchange Program. When these are not available, corn syrup, 43 Bé, is available for $11.22/100 lbs. Although one mole of glucose is required for the production of three moles sulfide, taking into account metabolic needs there is a requirement for 3.8×10^7 mol glucose. At $0.20/lb this comes to $\$3 \times 10^6$. Capital costs at well as ongoing pumping and analytical needs would be an additional factor.

(1) Smillie, R.H., Hunter, K. and Loutit, M., "Reduction of Chromium (VI) by Bacterially Produced Hydrogen Sulfide in a Marine Environment," *Water Research*, 15, 1351 (1981).

(2) DeFilippi, L. J. and Lupton, F. S., *Proceedings of R&D92 National Research & Development Conference on the Control of Hazardous Materials, San Francisco CA*, pp. 138-141, February 4-6, 1992.

(3) Lupton, F. S., DeFilippi, L. J., and Goodman, J. R., *U.S. Patent* 5,062,956 (1991).

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