Demonstration of Remedial Action Technologies for Contaminated Land and Groundwater

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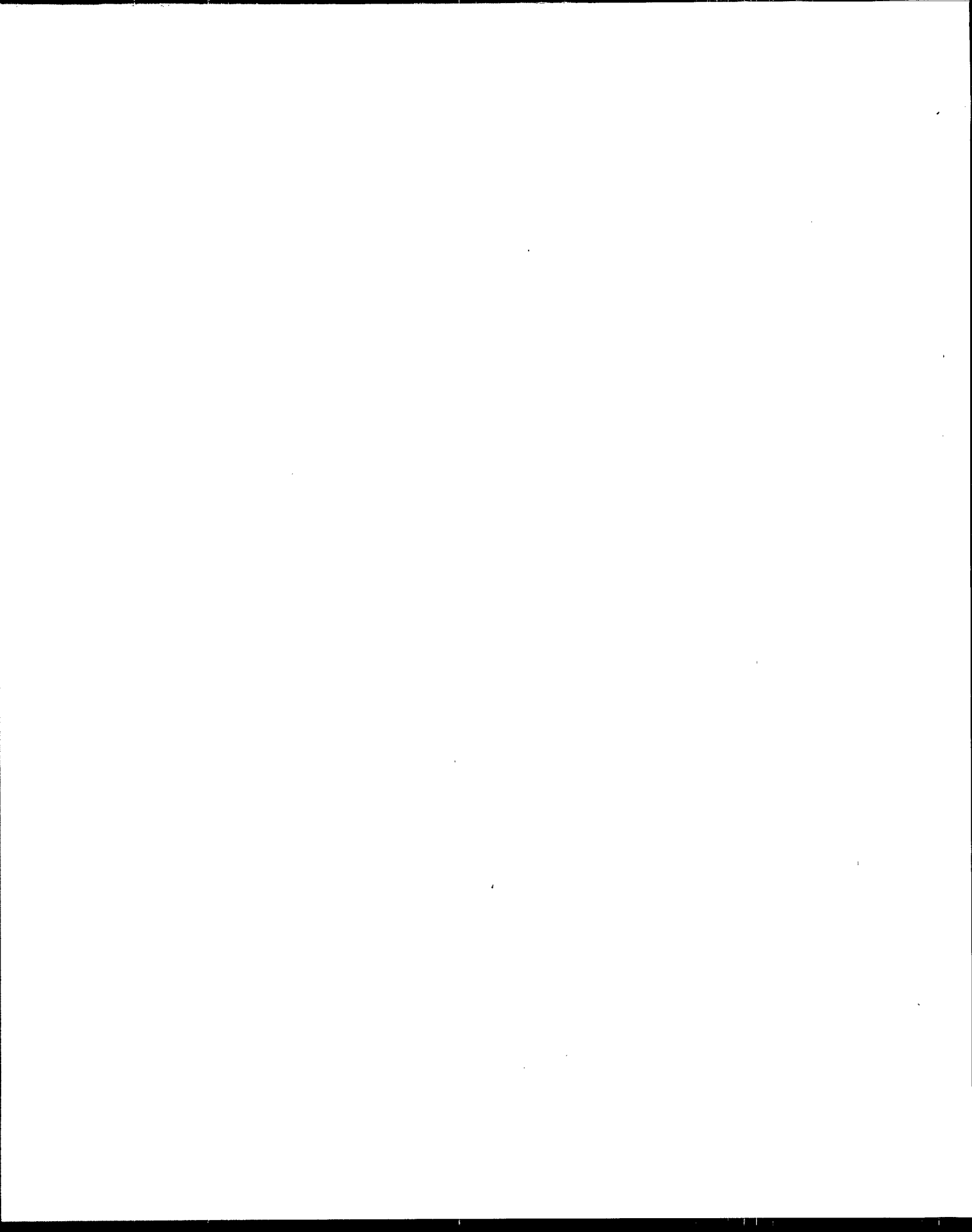
NATO/CCMS

FINAL REPORT

Volume 1

Demonstration of Remedial Action Technologies for Contaminated Land and Groundwater

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1986 – 1991

Abstract

This publication reports on the results of the NATO/CCMS Pilot Study "Demonstration of Remedial Action Technologies for Contaminated Land and Ground Water" which was conducted from 1986 through 1991. The Pilot Study was designed to identify and evaluate innovative, emerging and alternative remediation technologies and to transfer technical performance and economic information on them to potential users.

Twenty-nine remediation technology projects were examined which treat, recycle, separate or concentrate contaminants in soil, sludges, and ground water. The emphasis was on *in situ* and on-site technologies; however, in some cases, e.g., thermal treatment, fixed facilities off-site were also examined. Technologies included are: thermal, stabilization/solidification, soil vapor extraction, physical/chemical extraction, pump and treat ground water, chemical treatment of contaminated soils, and microbial treatment.

This report serves as a reference and guide to the potential application of technologies to various types of contamination; it is not a design manual. Unique to this study is the examination and reporting of "failures" as well as successes.

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Introduction

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1.1 Background

Ground water and soil contamination are among the most complex and challenging environmental problems faced by most countries today. This challenge results from a number of significant factors, such as the complex geochemical, physical and biological nature of contaminated subsurface soils and ground water; limited knowledge regarding the behavior and interaction of pollutants within these environmental matrices; and the sheer magnitude of the contamination. These factors, in turn, limit the application and effectiveness of conventional waste treatment technologies and result in high remediation costs.

As a result, there is an ongoing need for more reliable, cost-effective cleanup technologies to address these problems and many governmental and private organizations, in many countries, have committed resources to the development, test and evaluation, and demonstration of technologies to meet this need. The ongoing challenge to these organizations is how to maximize the value of these technology advancements and effectively transfer the information to people responsible for making decisions and implementing remedial actions.

Consequently, a NATO Committee on the Challenges of Modern Society (NATO/CCMS) Pilot Study was conducted from 1986 through 1991 for the purpose of identifying and evaluating innovative, emerging, and alternative remediation technologies, and transferring technical performance and economic information on them to potential users. A specific and important objective of the Study was to identify "lessons learned" from the technology demonstrations, including not only the successes but also those which illustrated technology failures or limitations. The latter type of information is rarely presented in conferences and/or discussed in the technical literature but is very important for making informed decisions that involve critical time and monetary requirements. It is also useful for defining priorities in research and development programs.

1.2 Structure of the Study

The Pilot Study Group examined a total of 29 different remediation technology projects conducted by non-NATO sponsored organizations, within member countries, over the five year course of the Study. These technologies treat, recycle, separate or concentrate contaminants in soil, sludges and ground water matrices. In some cases, such as for thermal treatment, fixed facilities off-site were studied, although the emphasis was on *in situ* and on-site biological, chemical/physical and thermal waste treatment technologies. The study did not include barrier walls or technologies in which containment was a primary technique.

1.2.1 Categories of the Technologies Examined

For the purposes of this Study, three categories of technologies in various stages of development were examined with respect to their possible use in the cleanup of polluted sites. They are:

- *Alternative technologies*: A technology that is fully proven in routine use for end-of-pipe treatment; however, performance and cost data is not readily available.

- *Innovative technologies*: A technology at the pilot or field scale for which performance or cost information is not complete, thereby impeding its use for remediation. In general, innovative technology requires field testing to prove its effectiveness before it is considered proven and available for use in remediation.

- *Emerging technologies*: A technology at a stage where successful bench testing has been conducted and pilot-scale evaluation is now required to determine its potential for use in remediation (James and Sanning 1989).

The 29 technology projects covering these categories served as a primary source for the discussion and results presented in this report. However, this project-specific information was supplemented by data from other sources, such as Fellows of the NATO/CCMS, guest expert speakers at the international meetings of the Pilot Study, and the collective experiences and knowledge of the writers. As such, the information provided in the following chapters represents a synthesis of all this information, not a compilation of the details of each project. In this way, the report serves as a reference to the relative state-of-the-technologies discussed. It is not intended to be a manual on technology applications but as a guide to the potential application of technologies to various types of contamination.

1.2.3 How the Technology Information is Presented

Chapters 2 through 8 present the results of the Pilot Study by technology area. They include the following technologies:

- Chapter 2: *Thermal Technologies*. This chapter discusses the type and use of thermal technologies in various projects examined under the NATO/CCMS Pilot Study, both fixed facilities and transportable incineration systems. Thermal processes are technologies designed to break down hazardous waste through either combustion or pyrolysis by exposure of the waste material to high temperature in a controlled environment.

- Chapter 3: *Stabilization/Solidification Technologies*. In this chapter, a general description is

given of cement based stabilization-solidification techniques. Stabilization-solidification (S/S) refers to techniques that aim at preventing migration of contaminated material into the environment by forming a solid mass.

- Chapter 4: *Soil Vapor Extraction Technologies*. Soil vapor extraction (SVE), also known as *in situ* venting (ISV), is a process that uses air to remove volatile organic compounds (VOC's) and some semivolatile organic compounds (SVOC's) from the vadose (unsaturated) zone.

- Chapter 5: *Physical Chemical Extraction Technologies*. A wide range of processes can fit within this broad category of technology. Under this Pilot Study the following processes were chosen and are discussed in this chapter: *ex situ* extraction of organic and inorganic contaminants; *in situ* jet cutting followed by oxidation of organic contaminants; *in situ* acid extraction of heavy metals; and *in situ* electro-reclamation of heavy metals.

- Chapter 6: *Pump and Treat Ground Water*. This chapter discusses the extraction of contaminated ground water from the subsurface, followed by treatment of the water at the surface to remove the pollutants. Treatment can be by means of physical/chemical/biological technologies.

- Chapter 7: *Chemical Treatment of Contaminated Soils: APEG*. This chapter discusses the chemical dehalogenation of contaminated soils using an alkaline metal hydroxide with polyethylene glycol (APEG). Processes of this type are applicable to soils and soil-like materials (after excavation) contaminated with either aromatic or aliphatic chlorinated organic compounds, although the latter require more rigorous treament conditions. It is of particular interest for the treament of soils contaminated with polychlorinated biphenyls (PCB's).

- Chapter 8: *Microbial Treatment Technologies*. A large number of organic contaminants can be degraded by microorganisms. This technology is discussed in terms of the basic biological soil remediation techniques of *in situ* biodegradation, landfarming and composting, and bioreactors.

Each of the technology chapters is organized in the following manner:

- *Introduction*: A description of the technology, including basic principles of the process and where it potentially can be applied.

- *Case Studies Chosen*: A summary of each of the projects evaluated, including why the project was chosen for evaluation. Available details on each project are presented in Volume 2.

■ *Background of the Case Study Sites as a Group*: A synthesis of pertinent information from the projects that will help readers understand the range of the technology's application in these studies. This includes the type, concentration and sources of contamination, type of soil/ground water matrices containing the contamination, and the main lessons learned, if any, in the application of the technology.

■ *Performance Results*: An assessment of the results from the case studies, including whether project objectives were met, whether the technology processes as a whole showed a common effectiveness, and lessons learned, if any, in contaminated site preparation and operational testing.

■ *Residuals and Emissions*: A discussion of multimedia residuals and emissions, if any, associated with the technology processes that need attention when evaluating the potential application of these processes to contaminated sites.

■ *Factors and Limitations to Consider for Determining the Application of the Technology*: A summary of important factors limiting the application of the technology processes including whether they are *in situ* or above ground techniques; type of soils, contaminants and contaminant concentrations they can potentially treat; level of cleanup they may be limited to; requirements for treatability/pilot studies; availability; etc.

■ *Costs*: An overview of major capital, operating and maintenance cost factors that need to be considered by remediation planners; typical costs and/or costs specific to case studies are given in some chapters.

■ *Future Status of Case Study Processes and Technology as a Whole*: A summary of the state of the technology and its expected role in future site remediations.

The process of selecting technologies for cleaning up a complex hazardous waste site is a difficult, but necessary process, and one in which countries use a variety of approaches suitable for their needs. Therefore, in addition to the technology discussions, a separate chapter on *Selecting Remedies at a Complex Hazardous Waste Site* is included (Chapter 9) to describe the remedy selection process used by the United States Environmental Protection Agency (U.S. EPA) and to examine remedial selection problems of mutual concern for many countries.

1.2.4 Summary of Conclusions

One of the major accomplishments of this Pilot Study is that it demonstrated the need to exchange technical and economic information on contaminated land and ground water remediation technologies. It resulted in an extensive set of conclusions regarding specific technologies, remediation in general, technology transfer and research needs. The conclusions are based on the technology case studies examined during the Study, as well as on expert speaker presentations and special studies carried out by the Fellows of the Pilot Study.

The conclusions reached from this Study reveal both the strengths and weaknesses of current technologies as well as what efforts are needed to increase the effectiveness of remediation tools and their application. The conclusions are summarized in Table 1-1 and fully discussed in Chapter 10 on *Conclusions and Recommendations*. Chapter 10 also provides the recommendations made by the Study members to the NATO/CCMS Council for future actions by that organization.

Insert Table 1-1

1.3 Contributions by CCMS Fellows

The Pilot Study was significantly aided by the NATO/CCMS Fellowship program. There were twelve NATO Fellows associated with this Pilot Study. Nine Fellows conducted associated studies and submitted project reports to the Pilot Study under guidance of the Pilot Study Directors. Three Fellows contributed to the preparation of the Final Report. The Fellows represented private, university and governmental organizations in Germany, Italy, The Netherlands, Turkey, the United Kingdom, and the United States. Their activities covered the range of technologies evaluated under the Pilot Study, including the development and evaluation of biological treatment technologies; chemical destruction techniques; ground water behavior; and the removal of toxic metals from soil and ground water. Many of their reports have been and are planned to be published in professional journals.

1.4 Contents of Volume 2

Volume 2 of this report contains appendices covering the following information:

■ Statements by the countries involved in this Pilot Study discussing their regulations and other overview topics (Appendix 1-A)

■ NATO/CCMS guest speakers' presentations (Appendix 1-B)

■ Final reports by the NATO/CCMS Fellows (Appendix 1-C)

■ Summaries and detailed information, when available, on specific case studies of projects ex-

Table 1-1. Conclusions for NATO/CCMS final report; demonstration of remedial action technologies for contaminated land and ground water.

This table presents a summary of the conclusions arising from the Pilot Study. They are first presented by specific technology areas represented by the chapters in this report; these are followed by general conclusions on remediation, technology transfer and research needs. These conclusions are based on the technology demonstration case studies as well as expert speaker presentations and special studies carried out by Fellows of the Pilot Study. The numbering corresponds to paragraph numbers in Chapter 10.

10.2	**Specific Technology Area Conclusions**
10.2.1	**Chapter 2:** *Thermal Technologies*
10.2.1.1	Existing high temperature incineration (on- and off-site) successfully destroys organic contamination; however, not all nations allow its use for chlorinated compounds.
10.2.1.2	Low temperature thermal desorption is a successful technology for treating volatile and semivolatile wastes.
10.2.2	**Chapter 3:** *Stabilization/Solidification (S/S) Technologies*
10.2.2.1	S/S has been proven for the immobilization of most inorganics.
10.2.2.2	Long term effectiveness data is not available.
10.2.2.3	Scientifically based S/S leaching tests would provide a more easily comparable data base than is available today.
10.2.3	**Chapter 4:** *Soil Vapor Extraction (SVE) Technologies*
10.2.3.1	SVE is a viable technology for unsaturated zone remediation of volatile and semivolatile contaminates.
10.2.3.2	Off-gases can be treated by conventional technologies.
10.2.4	**Chapter 5:** *Physical/Chemical Extraction Technologies*
10.2.4.1	Conventional extractive techniques have limited *in situ* applications.
10.2.4.2	Above ground extraction methods are powerful techniques.
10.2.4.3	Electroreclamation deserves to be extensively investigated.
10.2.5	**Chapter 6:** *Pump and Treat Ground Water*
10.2.5.1	Pump and treat is a limited technology for remediating aquifers.
10.2.5.2	Air stripping and activated carbon, as illustrated in this case study (i.e., Ville Mercier), were only partially effective treatment processes.
10.2.5.3	An ultraviolet radiation/oxidation process (Ultrox) was effective in reducing the concentration of volatile organics in ground water to acceptable levels.
10.2.5.4	A precipitation process involving the use of lime and sodium sulfide was effective in reducing the concentrations of zinc and cadmium to acceptable levels.
10.2.6	**Chapter 7:** *Chemical Treatment of Contaminated Soils: APEG Treatment*
10.2.6.1	The long term stability and behavior of the products of partial dechlorination in APEG processes require investigation.
10.2.6.2	The combination of thermal pyrolysis and APEG treatment applied at Wide Beach, New York, USA, was successful in reducing PCB concentrations to below target cleanup levels.
10.2.7	**Chapter 8:** *Microbial Treatment Technologies*
10.2.7.1	Bioremediation process scale-up from laboratory to the field is difficult.
10.2.7.2	There is a need for both data on oxygen behavior in the subsurface and improved methods of providing oxygen for *in situ* bioremediation.
10.2.7.3	There is a need for further research on bioavailability and achievable concentrations.
10.2.7.4	Soil inoculation has not been proven to enhance *in situ* bioremediation.
10.2.7.5	Permeability is a key factor in applying *in situ* bioremediation.
10.2.8	**Chapter 9:** *Selecting Remedies at a Complex Hazardous Waste Site*
10.2.8.1	Remediation should strive to be a complete solution.
10.2.8.2	Treatability studies must be conducted as early as possible for effective remedy selection, and technologies should be judged by their overall performance.
10.2.9	**Appendix:** *In Situ Vitrification*
10.2.9.1	Vitrification is a promising technique for treating mixed organic and inorganic wastes.

Table 1-1. (Continued)

10.3	**General Conclusions**
10.3.1	*Remediation*
10.3.1.1	Energy efficiency practices influence plant design and, therefore, processing costs in different countries.
10.3.1.2	Treatment and permanent solutions are preferred.
10.3.1.3	Integrated technology treatment systems are needed for site remediation.
10.3.1.4	Field treatability/pilot studies should be conducted for each technology under consideration, under the range of potentially applicable site field conditions.
10.3.1.5	Technology scale problems need to be addressed in design and testing.
10.3.1.6	A mass balance approach to remediation is desirable.
10.3.1.7	Technology remedies that transfer contaminants from one media to another should be avoided, if possible.
10.3.1.8	All remediations require proper operation and management.
10.3.1.9	Long term monitoring of permanent remediation may be necessary to ensure that cleanup goals are met.
10.3.1.10	Basic records should be preserved.
10.3.2	*Technology Transfer*
10.3.2.1	Uniform data collection is needed.
10.3.2.2	Independent technology evaluations are needed for effective technology transfer.
10.3.2.3	The NATO/CCMS network is an important source of information.
10.3.3	*Research*
10.3.3.1	There is a continuing need for development of new technologies and use of common research protocols.
10.3.3.2	Scientific understanding of processes is essential in order to ensure against formation of harmful end products.
10.3.3.3	Standardization of analytical methods is needed.
10.3.3.4	Techniques are needed to remove contamination beneath urban structures without significance disturbance to ongoing activities.

REFERENCES

James, S.C. and Sanning, D.E. Summary of the NATO/CCMS conference - The demonstration of remedial action technologies for contaminated land and ground water. In: Journal of the Air and Waste Management Association, Vol. 39, No. 9, September 1989, p. 1179.

Thermal Technologies

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ABSTRACT

Based on the site and waste characteristics of a site, thermal treatment may be most efficient. Thermal processes are technologies/systems designed to break down hazardous waste through either combustion or pyrolysis by exposure of the waste material to high temperature in a controlled environment. Thermal processes can, in a matter of seconds, destroy waste materials that might otherwise not be able to be destroyed by natural or other treatment processes.

This chapter on thermal technologies discusses the type and use of thermal technologies and various projects examined under the NATO/CCMS Pilot Study, both fixed facilities and transportable incineration systems. In the United States, the majority of fixed facilities are dedicated to the treatment of hazardous wastes generated and sent to a facility for treatment. Transportable systems are primarily used for the cleanup of uncontrolled sites (Superfund sites). While the United States intends to treat waste on site, many countries transport the contaminated material to the hazardous waste treatment facility.

2.1 Introduction

Hazardous waste thermal technologies have been selected and implemented for remediation at many contaminated sites. This technology can be used for the treatment of contaminated liquids, sludges, soils, debris, and air streams. The most common incineration technology used is rotary kiln. Other types of incineration are infrared incineration, liquid injection, hearth, fluidized beds, circulating beds, pyrolysis processes, plasma systems, and various kinds of indirect heating systems. Incineration is a proven means of destruction for many organic wastes and should be considered as a possible treatment for the cleanup of most toxic waste sites.

An incineration system includes a number of subsystems including the following:

- Waste pretreatment
  - Waste screening
  - Size reduction (grinding)
  - Waste mixing
- Waste feed
  - Belt conveyers
  - Augers
  - Apron feeders
  - Hoppers
  - Chutes
  - Pumps (for liquids, sludges, oils)
  - Screw conveyers
  - Ram feeders
- Combustion unit
  - Rotary kiln or secondary combustion chamber
  - Liquid injection
  - Fluidized bed or circulating bed
  - Infrared
  - Thermal desorption
- Heat recovery (optional - not normally applicable to on-site, transportable incineration systems)
- Air pollution control equipment to treat
  - Products of incomplete combustion

- Minimized in combustion chamber and after-burner
- Afterburners can significantly reduce the toxicity of the exhaust gas from an incinerator
  - Particulate emissions
    - Venturi scrubber
    - Wet electrostatic precipitator
    - Electrostatic precipitator
    - Quench systems
    - Fabric filter
  - Acid gases
    - Packed towers
    - Spray towers
    - Spray dryers
- Residue handling and disposal
  - Ash
    - Solidification
    - Use as fill material on-site, or dispose of it off-site
    - Scrubber water used to cool ash
  - Liquids
    - Neutralization
    - Filtration
    - Precipitation (metals)
    - Clarification
    - Carbon adsorption or air stripping (for small amounts of organics which are sometimes recovered in scrubber water)
    - Discharge to a municipal wastewater treatment system after successful pretreatment using one or more of the above options.

Tables 2-1 and 2-2 list the number and capacities of various hazardous waste incineration systems in the United States and hazardous waste incineration facilities in Europe. Table 2-3 lists specific site data from all U.S. projects.

Rotary kiln incinerators are slightly inclined (3 percent), refractory-lined, rotating cylinders. Their primary use is the combustion of organic solids and sludges and other contaminated waste such as product, contaminated soils, and liquids with a high heating value. Rotary kiln incineration involves the controlled combustion of organic waste under net

Table 2-1. Numbers and types of hazardous waste incineration facilities in the United States.

Technology	Number of units
Rotary kiln	42
Fluidized bed	15
Liquid injection	95
Hearth	32

Table 2-2. Hazardous waste incineration facilities in Europe.

Company	Location	Capacity (metric tons/yr)
INDAVER	Belgium, Antwerp	50,000
Kommunekemi	Denmark, Nyborg	50,000
SARP	France, Bassens	20,000
SARP	France, Limay	50,000
TREDI	France, Salaise	40,000
SIDIBEX	France, Sandouville	35,000
TREDI	France, St. Vulbas	6,000
GSB	Germany, Ebenhausen	100,000
ABR	Germany, Herten	30,000
ZSM	Germany, Schwabach	30,000
HIM	Germany, Wiesbaden	45,000
Broerius	The Netherlands, Barneveld	25,000
Boskalis Esdex	The Netherlands, Ijmuiden	4,000
ATM	The Netherlands, Moerdijk	60,000
AVR-Chemi	The Netherlands, Rotterdam	40,000
Ecotechniek II	The Netherlands, Rotterdam	80,000
NBM	The Netherlands, Schiedam	60,000
Ecotechniek I	The Netherlands, Utrecht	55,000
Cleanaway	UK, Brentwood	40,000
Rechem	UK, Pontypool	13,000

oxidizing conditions (the final oxygen concentration is greater than zero).

Wastes and auxiliary fuel are injected into the high end of the kiln and passed through the combustion zone as the kiln slowly rotates. Rotation of the combustion chamber creates turbulence and improves the degree of combustion. Retention time in the kiln can vary from several minutes to an hour or more. Wastes are substantially oxidized to gases and ash within the combustion zone. Ash is removed at the lower end of the kiln. Flue gases are passed through a secondary combustion chamber and then through air pollution control units for particulate and acid gas removal.

The typical hazardous waste kiln is a cylinder with an outside diameter of 3 to 4 meters, an inside diameter of 2.5 to 3 meters, and a length of 11 to 13 meters. Typically, 5 tonnes of material will be charged into the unit. Actual loads will be determined by the

Table 2-3. Site data from U.S. hazardous waste incinerator projects.

Vendor	Site Name	Site Location	Source of Contamination	Project Status	Site Size (tonnes)
AET	Valdez	Valdez, Alaska	Crude oil spill	Finished	
Canonie	Ottati & Goss	Kingston, New Hampshire	Solvent treatment	Finished	7,200
Canonie	Canon	Bridgewater, Massachusetts	Solvent recycling	Contracted	5,900
Canonie	South Kearny	South Kearny, New Jersey	Solvent recycling	Finished	16,300
Canonie	McKin	Gray, Maine	Waste treatment & disposal	Finished	16,300
Chemical Waste Mgt.	confidential	northeast, United States	PCB spills	Contracted	31,800
Ensco	Union Carbide	Seadrift, Texas	Chemical manufacturing	Contracted	
Ensco	Lenz Oil	Lemont, Illinois	Waste oil	Finished	23,600
Ensco	Sydney Mines	Brandon, Florida	Waste oil lagoon	Finished	9,100
Ensco	NCBC	Gulfport, Mississippi	Herbicide storage	Finished	20,000
Ensco	Bridgeport	Bridgeport, New Jersey	Used oil recycling	Ongoing	90,700
Ensco	Smithville	Canada	PCB transformer leaks	Contracted	6,350
GDC Engineering	Rubicon	Geismar, Louisiana	Chemical manufacturing	Ongoing	47,200
Harmon	Bog Creek	Howell Twp., New Jersey	Paint/solvent disposal	Ongoing	20,400
Harmon	confidential	Alabama	Gasoline tank leak	Finished	540
Harmon	Prentiss	Prentiss, Mississippi	Wood treatment	Finished	8,300
IT Corporation	Motco	Lamarque, Texas	Styrene tar disposal pits	Ongoing	72,600
IT Corporation	Cornhusker AAP	Grand Island, Nebraska	Munitions plant pits	Finished	40,800
IT Corporation	Louisiana AAP	Minden, Louisiana	Munitions plant lagoon	Finished	90,700
IT Corporation	Sikes Pits	Crosby, Texas	Chemical waste pits	Contracted	309,400
Kimmins	La Salle	La Salle, Illinois	PCB capacitor manufacturing	Contracted	62,600
Ogden	confidential	Sacramento, California	Town gas site	Contracted	20,400
Ogden	Swanson River	Kenai, Alaska	Oil pipeline compressor oil	Ongoing	72,600
Ogden	Stockton	Stockton, California	Underground tank oil leak	Ongoing	14,500
O.H. Materials	Goose Bay	Goose Bay, Canada	PCB's	Ongoing	3,600
O.H. Materials	Gas station	Cocoa, Florida	Petroleum tank leak	Finished	900
O.H. Materials	Rail yard	Pennsylvania	Repetitive spills	Finished	1,400
O.H. Materials	Twin City AAP	New Brighton, Minnesota	Munitions plant	Finished	1,800
O.H. Materials	Rail yard	Pennsylvania	Diesel tank spill	Finished	1,200
O.H. Materials	Florida Steel	Indianatown, Florida	Steel mill used oils	Finished	16,300
O.H. Materials	Rail yard	Cleveland, Ohio	Refueling station	Finished	1,400

Table 2-3. (Continued)

Vendor	Site Name	Site Location	Source of Contamination	Project Status	Site Size (tonnes)
Site Recl. Systems	Koch Chemical	Kansas	Tank bottoms	Contracted	600
Site Recl. Systems	Gulf Oil	multi-sites	Oil spills	Contracted	16,300
Site Recl. Systems	Sun Oil	multi-sites, South Carolina	Oil spills	Contracted	
Soil Remediation Co.	multiple sites	multi-sites	Gas and oil leaks/spills	Finished	2,700
SoilTech	Waukegan Harbor	Waukegan, Illinois	Marine motor manufacturing	Contracted	18,100
TDI Services	Chevron	El Segundo, California	API sludges	Contracted	27,200
Thermodynamics Corp.	S. Crop Services	Delray Beach, Florida	Crop dusting operation	Finished	1,600
U.S. Waste Thermal Processes	gas station	Temecula, California	Petroleum tank leak	Finished	900
U.S. Waste Thermal Processes	confidential	California	Oil spills	Contracted	6,800
U.S. Waste Thermal Processes	confidential	San Bernadino, California	Oil spills	Finished	490
Vertac site contractors	Vertac	Jacksonville, Arkansas	Chemical manufacturing	Contracted	5,900
Vesta	Nyanza	Ashland, Massachusetts	Dye manufacturing	Finished	900
Vesta	Rocky Boy	Havre, Montana	Wood treatment	Ongoing	1,600
Vesta	S. Crop Service	Delray Beach, Florida	Crop dusting operation	Finished	1,600
Vesta	Am. Crossarm	Chehalis, Washington	Wood treatment	Finished	800
Vesta	Fort A.P. Hill	Bowling Green, Virginia	Army base	Finished	180
Westinghouse/ Haztech	Peak Oil	Tampa, Florida	Used oil recycling	Finished	6,350
Westinghouse/ Haztech	La Salle	La Salle, Illinois	Transformer reconditioning	Finished	27,200
Weston	Revenue	Springfield, Illinois		Finished	900
Weston	Letterkenny	Chambersburg, Pennsylvania	Army depot	Finished	450
Weston	Tinker AFB	Oklahoma City, Oklahoma	Air Force base	Finished	900
Weston	Paxton Avenue	Chicago, Illinois	Waste lagoon	Ongoing	14,500
Weston	Lauder Salvage	Beardstown, Illinois	Metal scrap salvage	Finished	7,700

thermal input to the kiln rather than the mass load. The heat source is either a hazardous waste or an oil or natural gas flame directed axially down the kiln. The typical hazardous waste secondary chamber is sized sufficiently to achieve a 2 second residence time for combustion gases at 2,200 °C.

Electric infrared incineration systems use silicon carbide elements to generate thermal radiation beyond the red end of the visible spectrum. Waste to be treated passes through the unit on a noncorrosive steel belt and are exposed to the heat generated by the radiation. Organics are driven from the waste material. Off-gases pass into a secondary chamber that is heated via supplemental gas or fuel oil for complete destruction of the organics. Flue gases are treated by a scrubber system and the residual ash is collected for further treatment and/or disposal. Normal operating temperatures are 1,600 to 1,800 °C in the

primary chamber and 1,900 to 2,200 °C in the secondary chamber.

Fluidized bed incinerators consist of a refractory-lined vessel containing a bed of inert, granular, sand-like material. In operation, combustion air is forced upward through the bed, which fluidizes the material at a minimum critical velocity. The heating value of the waste plus any auxiliary fuel maintains a desired combustion temperature in the vessel. The heat of combustion is transferred back into the bed, and the agitated mixture of waste, fuel, and hot bed material in the presence of fluidizing air provides a combustion environment that resists fluctuations in temperature and retention time due to moisture, ash, or Btu content of the waste.

A variation of the fluidized bed is the circulating fluidized-bed (CFB) combustor. This process uses higher air velocity and circulating solids to create a larger and highly turbulent combustion zone for the efficient destruction of organics and the retention of resultant acid vapors. The key to this combustion technology is the hydrodynamic behavior of the fluidized bed. Conventional fluidized beds are generally well understood. They are characterized by the clearly defined gas bubbles. Units of this type operate at gas velocities of 2 to 3 m/s (depending on particle size). The main difference between circulating and fluidized beds is the gas velocity. CFB's operate at gas velocities from 5 to 10 m/s. These gas velocities give rise to rapid carry over of solids from the top of the vessel. In order to replenish solids in the vessel, the CFB systems have developed a solids separation and return loop. This enables the bed material to be in constant contact with the waste material.

Fluidized bed technology can be operated at lower temperatures than other thermal systems because of the high mixing energies aiding the combustion process. This mixing offers high thermal efficiency while minimizing auxiliary fuel requirements and volatile metal emissions.

Liquid-injection incineration systems are usually refractory-lined chambers (horizontal, vertical up or down), generally cylindrical, and equipped with a primary combustion and secondary chamber. The waste is burned directly in a burner or injected into the flame zone or combustion zone of the incinerator chamber through nozzles. Critical to the operation of this type of incineration system is the atomizing nozzle used to convert the liquid stream into finely atomized droplets.

Multiple-hearth incinerators are used for destroying solids and heavy sludges. Waste material enters the combustion chamber at the top and drops through a series of refractory hearths until noncombustible residues fall to the bottom of the unit. This method is useful for the recovery of metals from the waste feed. Plasma systems use a plasma-arc device to create extremely high temperatures (25,000 °C). Gaseous emissions (primarily hydrogen and carbon monoxide), acid gases in the scrubber, and ash components in the scrubber water are the residuals. These systems are applicable to liquid waste only because of the injection systems employed.

In situ vitrification (ISV) uses an electric current to melt soil or sludge at extremely high temperatures of 1,600 to 2,000 °C. This destroys organic pollutants by pyrolysis. Inorganic pollutants are incorporated within the glass-like vitrified mass. Water vapor and organic pyrolysis by-products are captured in a hood, which draws the contaminants into an off-gas treatment system that removes particulates and other pollutants.

The vitrification process begins by inserting large electrodes into contaminated zones containing sufficient soil to support the formation of a melt. An arrangement (usually square) of four electrodes is placed to the desired treatment depth in the volume to be treated. Because soil typically has low electrical conductivity, flaked graphite and glass frit are placed on the soil surface between the electrodes to provide a starter path for electric current. The electric current passes through the electrodes and begins to melt soil at the surface. As power is applied, the melt continues to grow downward, at a rate of 2.54 to 5.08 cm/h. Individual settings (each single placement of electrodes) may grow to encompass a total melt mass of 907 tonnes and a maximum width of 10.7 meters. Single-setting depths as great as 7.6 meters are considered possible.

Depths exceeding 5.8 meters have been achieved with the existing large-scale ISV equipment. Adjacent settings can be positioned to fuse to each other and to completely process the desired volume at a site. Stacked settings to reach deep contamination are also possible. The large-scale ISV system melts soil at a rate of 3.6 to 5.4 tonne/h. Because the void volume present in particulate materials (20 to 40 percent for typical soils) is removed during processing, a corresponding volume reduction occurs. After cooling, a vitrified monolith results, with a silicate glass and microcrystalline structure. This monolith possesses structural and environmental properties.

2.2 Case Studies Chosen

The following discussion summarizes the thermal projects in this NATO/CCMS Pilot Study by participating countries.

2.2.1 Case Study 2-A: Rotary Kiln Incineration, The Netherlands

A national inventory taken in 1981 revealed that the soil contamination problem in The Netherlands was far greater than was first thought. The survey identified about 4,000 cases of possible soil contamination. However, this figure has since risen to around 7,500.

Since 1982, much experience has been gained with soil cleanup techniques. In particular, thermal and extraction processes passed the technological development stage and are applied on a large scale for various types of soil contamination.

Ecotechniek has two thermal soil treatment plants, one in Utrecht, and one near Rotterdam. The latter installation has a maximum treatment capacity of 50 metric tons per hour. The contaminated soil is treated in the rotary kiln by direct heating at a temperature of up to 550 °C with a residence time of about 7-15 minutes. The resulting vapors are afterburned at a temperature of 850-1,000 °C and a residence time of 1-2 seconds. The afterburner limits the emission of hydrocarbons, CO, and HCN. Heat exchangers permit the reuse of the energy released. Measures to limit emission include a wet scrubber (SO_2) and a fabric filter (dust). The wash water from the wet scrubber is cleaned and partly recycled for cooling the cleaned soil. The process is suitable for the removal of aromatic and aliphatic hydrocarbons (up to 10,000 mg/kg), cyanides (up to 400 mg/kg), and polynuclear aromatic hydrocarbons (PAHs) (up to 800 mg/kg).

The installation is suitable for all types of soil. It is especially the moisture content, the organically-bound nitrogen and sulfur content of the soil, and the type of contamination that influence the costs. These vary between Dfl 100 and Dfl 190 per metric ton. (One Dfl is approximately U.S. $0.5, October 1987.)

To date, much experience has been gained for the treatment of contaminated soil from former gasworks sites and soil contaminated by leaking fuel tanks. A trial cleanup of soil contaminated with chlorinated hydrocarbons is planned. The treatment of two types of soil have been evaluated in particular with respect to:

- "Easy to clean" soils: sandy soil, chiefly contaminated with cyanides and polynuclear aromatic hydrocarbons (PAHs), derived from a former gasworks site; and

- "Difficult to clean" soils: clayish soil and rubble, chiefly contaminated with PAHs and mineral oil, derived from a site where various wastes had been dumped.

They were evaluated with respect to cleanup of the soil and air emission during the treatment.

The results showed that residual concentrations of mineral oil and cyanides amply met the requirements for both types of soil. For some of the PAHs, the quite strict requirements were not met for soil originating from the dump site. In the case of the gasworks soil, higher residual concentrations of (Borneff) PAHs were allowed. As expected, no removal of heavy metals took place.

The results of air pollution monitoring show that the requirements set for emissions onto the air were met during the treatment of both types of soil. (For more information on this project, see Appendix 2-A.)

2.2.2 Case Study 2-B: Indirect Heating in a Rotary Kiln, Germany

The Ruhr Valley of Germany has several former gasworks and coking plants. Contamination at these sites is due to process waste as well as spills. The soil is contaminated with aromatic and aliphatic hydrocarbons. The site at Unna-Boenen is a former coke oven plant with an area of 250,000 m^2. The site is divided into three areas: coal area site, coking oven site, and acid resin storage. Volatile organic compounds (VOC's) may be as high as 5 percent of the waste by weight. Other contaminants such as pesticides, PCB's, and heavy metals are present up to 1 percent by weight of the soil. In addition to the examination of various technologies for the cleanup of the site, an indirect thermal heating technology was investigated.

This system, designed by Ruhrkohle Umwelttechnik of Unna Boenen (Germany), is based on a closed-cycle indirect thermal treatment (pyrolysis) process. Treatment of contaminated soil begins with mechanical crushing of the soil (to a maximum size of 50 mm). The crushed soil is stored in a feed hopper and travels from the hopper to the kiln by means of a double helix screw conveyer. This permanently filled conveyer seals the kiln system at approximately 1.5 mbar depression, which prevents the escape of dust or pyrolysis gas. The crushed soil then passes through a rotary kiln 22 meters in length. In the kiln, temperatures between 450 and 600 °C release volatile material. Temperatures are obtained by heating the outer shell of the rotary kiln with 18 natural gas burners. Water cools the treated soil that is returned to the original site. Post-combustion of the released gases occurs in a secondary chamber. In this chamber temperatures reach a maximum of 1,300 °C. After quenching and scrubbing, the gas exits through the exhaust stack.

The system was completed in May 1988 and began shakedown in July. Over 2,720 tonnes of soil have been decontaminated in the trial testing. The effectiveness of the soil decontamination increased for grain sizes less than 50 mm in diameter. Operational problems with the ash removal screw, which resulted in overheating of the ash removal system and subsequent obstruction, have been corrected. The design of the plant enables it to be transported and reused at different locations. The operators planned full-time operation of the system with the ability to process approximately 45,360 tonnes of contaminated soil per year. (For more information on this project, see Appendix 2-B.)

2.2.3 Case Study 2-C: Off-site Soil Treatment, Japan

The electro-chemical industrial facility was used from 1917 to 1979 primarily for the production of soap, bleaching powder, hydrogen chloride, organic compounds, and, later, sodium hydroxide. It is located in a residential area in Tokyo and is highly contaminated with mercury and lead; this contamination was discovered in 1979 when the company stopped operation and dismantled the facility in order to relocate the factory. The mercury contamination was generally limited to the surface soils with an average concentration of 36,800 ppm (maximum concentration of 156,000 ppm). About 56,000 m^3 of contaminated soil with mercury levels above 2 mg/kg were required to be treated before redevelopment of the site could occur. Based on the level of mercury contamination, off-site thermal treatment and on-site containment processes were selected. All soils with mercury levels above 10 mg/kg were to be sent off-site for incineration. All other soils below this level were treated on-site using immobilization and containment.

About 6,000 drums of contaminated soils were sent to the Nomura Kosan Co., a firm specializing in the refining of mercury. Cost of the thermal treatment was US$330/tonne plus a transportation cost of US$81/tonne. The treatment facility is equipped with a vertical multistage rotary furnace called a Herreshoff Furnace. The mercury contaminated soil was treated at temperatures from 600 to 800 °C. Volatile mercury vapors were condensed on the inner wall of a condenser. Crude mercury was recovered from the soot and refined into a commercial grade product with a purity of 99.99 percent. Slag from the furnace was placed in an on-site secure landfill. Trace amounts of mercury and acid gas components in the flue gas were removed from the exhaust gas by adsorption and neutralization. (For more information on this project, see Appendix 2-C.)

2.2.4 Case Study 2-D: Electric Infrared Incineration, United States

Beginning in the 1950's, Peak Oil, an oil refiner, operated a used-oil processing facility in Brandon, Florida. Various waste streams from the refining operation were dumped into a natural lagoon located on the property. The lagoon quickly became contaminated with PCB's and lead from the waste material. This led to the contamination of the shallow aquifer system that was the source of the local drinking water supply. Because of the continuing contamination of the aquifer from the lagoon, the United States Environmental Protection Agency (U.S. EPA) initiated a project to remove the contents of the lagoon and the contaminated soil under and around the lagoon. This amounted to approximately 7,000 tonnes of sludge and soil contaminated with PCB's and lead.

The U.S. EPA selected electric infrared incineration for the cleanup operation. In November 1986, a transportable unit was brought to the site on five separate trailers. Once on-site, the units were connected together on new or existing concrete pads prepared for the cleanup operations. The connected components formed the 22-meter long primary combustion unit (PCC), the 24-meter long secondary combustion unit (SCC), an emission control system, and a process management and monitoring center.

Electric infrared incineration technology (originally developed by Shirco Infrared Systems, Inc. of Dallas, Texas) is a mobile thermal processing system that uses electrically powered silicon carbide rods to generate heat for volatilization of organics from waste in the primary incineration chamber. Waste is fed into the primary chamber on a wire mesh belt and exposed to temperatures up to 1010 °C by the infrared radiant heat. Ash material from the primary is quenched and gas emissions are put through a control system for neutralization and particulate removal. Technology demonstrations were conducted on the full and pilot-scale units at two Superfund sites: Peak Oil site in Florida and Rose Township site in Michigan. Both sites contained PCB's and high concentrations of lead. In both cases, testing and evaluation proved that the technology could successfully destroy PCB's; the system achieved greater than 99.99 percent DRE's (destruction and removal efficiencies). In addition, the system was tested for its ability to retain and fix lead in the ash. The lead in the ash was not fixed since it could be easily removed via leach testing. This was determined by the Toxicity Characteristic Leaching Procedure (TCLP) which is a United States testing procedure.

This technology is applicable for the treatment of organic contaminants contained in soils or sludges. Since the waste is fed into and through the system on a wire mesh belt, only solid material can be processed through the unit. Liquid organic wastes can only be handled if they are mixed with a solid material before processing.

Testing has demonstrated the ability of the electric infrared incineration technology to:

- Achieve organic destruction greater than the Resource Conservation and Recovery Act (RCRA) standard of 99.99 percent DRE

- Achieve destruction of dioxins and furans greater than the RCRA standard of 99.9999 percent DRE

- Achieve destruction of PCB's greater than the Toxic Substances Control Act (TSCA) standard of 99.9999 percent

- Achieved HCl RCRA performance standard of 99 percent removal

■ Achieved RCRA particulate emission standard of 180 mg/dscm (dry standard cubic meters).

(For more information on this project, see Appendix 2-D.)

2.2.5 Case Study 2-E: *In Situ* Vitrification, United States

In-situ vitrification (ISV) involves the in-situ melting of contaminated solids in soils. An array of four electrodes is placed to the desired treatment depth. As current flows through the soil, it is heated to the melting temperature of the soil (typically 1600-2000 °C). Once molten, the mass becomes the primary conductor and heat transfer medium, allowing the process to continue. The molten mass grows downwards and horizontally as long as power is applied. A recent test treated a zone 8 m (27 ft) square by about 6 m (20 ft) deep (about 900 tonnes at a bulk density of 2,200 kg/m³) and took 7 to 10 days to complete. The treated mass takes several months to a year or more to cool, although the collection hood can be removed after a few hours. Once one setting is completed, the equipment is moved to an adjacent area; neighbouring blocks will fuse together. The process may be applied to contaminated natural soils, but also to other naturally occurring soil-like materials and solid process wastes, including silts, sediments, sludges and tailings.

As a result of the ISV process, individual contaminants may:

■ Undergo chemical and/or thermal destruction

■ Enter the off-gases from which they can then be removed

■ Be chemically or physically incorporated into the resultant solid product.

In tests at various scales, it is claimed that the process is applicable to soils containing volatiles, semi-volatiles, and refractory (non-volatile) organic compounds and inorganics (heavy metals), a variety of radioactive materials, and a broad range of combustible, metallic, and inorganic scrap materials (e.g. paper, plastic, wood, drums, concrete, rock, asphalt). It is also claimed that drummed organic wastes can be treated.

The ISV process results in a 20 to 40 precent reduction in volume for typical soils. Once processing is completed, clean backfill is placed over the residual monolith to restore site levels. As cooling continues additional subsidence may occur.

In the United States this technology is available from only one commercial vendor (Geosafe Corporation) and has been under development by Battelle Memorial Institute since 1980. However, the main clean-up project that the technology was to complement could not go ahead because the vendor of the technology withdrew it from the market. This decision was prompted by an accident that occurred in March 1991 during large scale testing which resulted in a fire and destruction of some equipment. The company took the view that although the accident "involved only non-hazardous materials, .. such an event could have unacceptable consequences if it were to happen at a hazardous waste site." The company did "not consider it prudent to proceed with commercial large-scale operations if there is any reasonable chance of recurrence of this event.." However, some work is continuing with the U.S. Department of Energy. (For more information on *in situ* vitrification, see Appendix 1-C.)

2.3 Background of the Case Studies as a Group

Thermal treatment has been used for many years to treat a variety of waste products generated from the manufacturing of products. Over the last several years, thermal treatment has been used widely in the cleanup of remediation sites. Primarily, this technology has been used in the treatment of contaminated soils, sludges and sediments; in addition it is sometimes used to treat liquids. Principally, this technology is used to treat organic contamination. However, one case study reports on the recovery of mercury from contaminated soil.

The case studies represent a cross section of problems that may be found at sites throughout any country and also represent thermal technologies that are currently available. Three case studies (Germany, The Netherlands and United States) report on problems that are very common to all countries. These case studies represent the treatment of aromatic and aliphatic hydrocarbons (former gasworks site), waste oil contaminated with PCB's (former waste oil refiner), and various other organic contamination that was improperly disposed of at these facilities. As can be seen from the results, thermal treatment offers a very high level of destruction of the organic waste. The other case study (Japan) discusses the removal of mercury from soil from a former electro-chemical facility.

In each case study, defined cleanup goals were met. However data on the effectiveness of each case study varies widely. Very little information was provided on waste feed preprocessing or residual handling. Cost information that documented the complete cost of using thermal technologies was also missing. More information on performance and costs are needed to accurately assess the technology overall.

2.4 Performance Results

When properly designed, constructed and operated, thermal technologies should be able to treat waste to appropriate regulatory levels while address-

ing other technical issues and operating as a cost-effective unit.

General examination of performance data for thermal technologies indicate that various types of system problems occur. One parameter which usually affects the performance of a thermal unit is the compatibility of the feed with the feed system. The feed system can consist of belt conveyors, augers, hoppers, chutes, pumps, screw conveyors, and ram systems. The feed system must be reliable and capable of continuous operation even when the feed varies widely in size, density, moisture content, and other properties. The feed system must also be capable of reducing the size of the incoming feed if necessary and must be reliable. If this is not the case, both the technical performance of the unit and the projected cost to operate the unit will be affected. A feed system which constantly fails or can not produce the projected throughput to the thermal unit will adversely affect the project. In general, problems of this nature will lengthen the time to complete the job and this will negatively affect the project economics.

In addition to the feed system, other operating conditions that can have impact on the operation of the unit are: waste pretreatment; type of combustion unit; air pollution control equipment used to treat products of incomplete combustion, particulate emissions, and acid gases; and residue handling and disposal for both ash and liquids.

Results from the NATO/CCMS case studies show that soils of smaller grain sizes are the most successful. Also, transportation (either moving a mobile incinerator system to the site or transporting the waste feed to an off-site incinerator) is critical in the selection, efficiency, and economics of a system. Most of the case studies discussed obtained a destruction and removal efficiency of 99.99 percent. In addition to these results, Table 2-4 shows design and operating parameters and performance data for various thermal units in the United States; see also Table 2-3 for more site information on these projects.

2.5 Residuals and Emissions

Actions undertaken to remediate a site using incineration or to operate a hazardous waste incineration facility must meet specific performance and regulatory requirements and will require monitoring to assure compliance. The following may be required to protect human health and the environment:

- Performance, design, or action-specific requirements such as air emission standards, water discharge standards, and land disposal requirements for the ash. In general, each country has developed their own standards for this category.

- Ambient/chemical-specific requirements which set health risk-based concentration limits based on emission limits and ambient air quality standards.

- Other regulatory (local) requirements that pertain to the construction or operation of such an incineration system.

Incineration systems will also require monitoring to assure compliance with any regulatory requirements that have been imposed on the operation of the system. Incineration systems will generally be required to perform continuous monitoring for CO and NOx. In addition, continuous monitoring will generally be required for combustion temperature (primary and secondary chamber), waste feed rate, SO_2, particulates, HCl, and various other parameters based on the waste feed and on permit requirements.

Under RCRA in the United States, standards for incinerator performance include:

- Principal organic hazardous constituents (POHC) of each waste feed must be destroyed and/or removed to a removal efficiency (DRE) of 99.99 percent. These hazardous organics are the most abundant and most difficult to burn. Dioxins and PCB's must achieve a DRE of 99.9999 percent.

- Particulate emissions must not exceed 180 mg/dscm, corrected to 7 percent oxygen in the stack gas.

- Gaseous hydrogen chloride (HCl) emissions must be controlled to a maximum of 8.8 kg/h, or be removed to 99 percent efficiency.

RCRA standards for incinerator operation, monitoring, and inspection, as well as procedures for granting permits are also specified. Incinerator owners and operators must also comply with general facility standards and administrative requirements for all hazardous waste management facilities. In the United States, many states also have their own standards which are more stringent than the national RCRA standards. In this situation the more stringent standards must be met.

Compliance with the above specifications and requirements is determined by incinerator performance during trial burns or during probationary operation. This operation also determines the incinerator's performance and the optimal operating conditions.

The collected data is then submitted to the U.S. EPA with the application for permit. After review by the U.S. EPA and by state agencies, a RCRA permit is developed. The permit establishes operating requirements, standards for carbon monoxide in the stack exhaust gas, waste feed rate, combustion temperature, and combustion gas flow rate. The permissible values of each of these may be unique to each incinerator. Performance data submitted by the applicant ensures

Table 2-4. Performance data for various U.S. hazardous waste incinerator projects.

Vendor	Site name	Indicator compound	Contaminant conc. in treated soil (mg/k)	Trial burn required	Particulate emissions (mg/dNm³ @7% O_2)	RCRA permit	TSCA permit
AET	Valdez	Petroleum hydrocarbons					
Canonie	Ottati & Goss	Volatile organics	<0.2	Yes	<69	No	No
Canonie	Canon Bridgewater	Total VOC	<0.1	No		No	No
Canonie	South Kearny	Volatile organics		No		No	No
Canonie	McKin	Trichloroethylene	<0.1	Yes	<69	No	No
Chemical Waste Mgt.	confidential	PCB's	<2.0				
Ensco	Union Carbide			Yes		Yes	
Ensco	Lenz Oil	Hydrocarbons	<5.0	Yes	14		
Ensco	Sydney Mines	Hydrocarbons	<5.0	No			
Ensco	NCBC	Dioxin	<15	Yes	39		
Ensco	Bridgeport Rental	PCB's		Yes			
Ensco	Smithville	PCB's		Yes			
GDC Engineering	Rubicon			Yes		No	No
Harmon	Bog Creek			Yes	34		No
Harmon	confidential	Petroleum hydrocarbons	<100	No		No	No
Harmon	Prentiss Creosote	PAH's	<2	Yes	25	No	No
IT Corporation	Motco	PCB's		Yes		No	No
IT Corporation	Cornhusker AAP	Trinitrotoluene	<1.3	Yes	39	No	No
IT Corporation	Louisiana AAP	Trinitrotoluene	<1.3	Yes		No	No
IT Corporation	Sikes Pits	Total PNA's	<100	Yes	<183	No	No
Kimmins	La Salle	PCB's	<2.0	Yes		No	No
Ogden	confidential						
Ogden	Swanson River	PCB's	<0.1	Yes	<114	No	Yes
Ogden	Stockton	Total hydrocarbons	<1	Yes	<183	No	No
O. H. Materials	Goose Bay	PCB's		Yes		No	Yes
O. H. Materials	gas station	Benzene, toluene, xylene	<0.1	Yes	25	No	No
O. H. Materials	rail yard	Diesel oil	<100				
O. H. Materials	Twin City AAP	PCB's	<2	No		No	Yes
O. H. Materials	rail yard	Diesel oil	<100				
O. H. Materials	Florida Steel	PCB's	<2	Yes	128	No	Yes
O. H. Materials	rail yard	Petroleum hydrocarbons	<50	Yes	89	No	No
Site Recl. Sys.	Koch Chemical	Toluene, xylene					
Site Recl. Sys.	Gulf Oil	Benzene, toluene, xylene	<0.1	No		No	No
Site Recl. Sys.	Sun Oil						
Soil Remed. Co.	multiple sites	Petroleum hydrocarbons	<50			No	No
SoilTech	Waukegan Harbor	PCB's		Yes		No	No

Table 2-4. (Continued)

Vendor	Site name	Indicator compound	Contaminant conc. in treated soil (mg/k)	Trial burn required	Particulate emissions (mg/dNm^3 @7% O$_2$)	RCRA permit	TSCA permit
TDI Services	Chevron Refinery	BDAT		No		No	No
Thermodynamics Corp.	S. Crop Services	Pentachlorophenol	0.003	Yes	80	No	No
U.S. Waste Thermal Proc.	gas station	Total hydrocarbons	<10	No	18	No	No
U.S. Waste Thermal Proc.	confidential	Total hydrocarbons		No		No	No
U.S. Waste Thermal Proc.	confidential	Total hydrocarbons	<10	No		No	No
Vertac site contractors	Vertac	Dioxins		Yes	183	No	No
Vesta	Nyanza	Nitrobenzene		Yes	46	No	No
Vesta	Rocky Boy	Pentachlorophenol		Yes		No	No
Vesta	S. Crop Services	DDT	<0.2	Yes	69	No	No
Vesta	American Crossarm	Dioxin	<0.001	Yes	25	No	No
Vesta	Fort A. P. Hill	Dioxin	<0.001	Yes	46	No	No
Westinghouse/ Haztech	Peak Oil	PCB's	<1	Yes	<183	No	No
Westinghouse/ Haztech	La Salle	PCB's	<2	Yes	<183	No	No
Weston	Revenue	PAH's	<0.33	No		No	No
Weston	Letterkenny Depot	Benzene, toluene, xylene	<1	No		No	No
Weston	Tinker AFB	Trichloroethylene		No		No	No
Weston	Paxton Avenue	RCRA constituents		Yes		No	No
Weston	Lauder Salvage	PCB's	<2	Yes	46	No	Yes

compliance with the permit. Performance data reported for each test run includes:

- Carbon monoxide in the stack exhaust gas
- Waste feed rate
- Combustion temperature
- Combustion gas flow rate
- DRE results
- Particulate emissions results
- HCI results.

Normal fluctuations in the parameters should also be reported.

Table 2-5 lists the European Community (EC) requirements for new municipal incinerator plants. Again, these are not the only standards or the most stringent standards. Before these standards were implemented, a more stringent set of standards had been proposed for Germany. Table 2-6 lists typical incinerator operating conditions in the EC.

The incineration system must not only meet emissions standards, but it must also meet other cleanup standards. Methods to develop these standards vary between countries and within countries. Table 2-7 summarizes some of these.

2.6 Factors To Consider for Determining Applicability of the Technology

Waste properties affect incineration performance. Treatability testing using the specific waste from the contaminated site will allow investigation and identification of these potential problem areas and will provide data on the applicability of the actual waste stream for a specific technology. Prior to treatability testing, complete laboratory analysis for the following key physical and chemical properties of the waste feed matrix are recommended: density, moisture content, heating value, noncombustible ash content, particle size analysis, flash point, elemental analysis/composition, pH, metal species and concentrations, and organic species and concentrations. Treatability testing that includes bench or pilot scale testing will establish

Table 2-5. European Community emission limits for municipal incinerators.

	New Plant**		Existing Plant**		
	≥ 5	<5	≥ 6	1-6	<1
Total dust	30	100	100	150	600
Metals					
Pb+Cr+Cu+Mn	5	5			
Ni+As	1	1			
Cd	0.1	0.1			
Hg	0.1	0.1			
HCl	50	100			
HF	2	4			
SO_2	300	300			
CO	100	100	100	100	100
Total organics (as C)	20	20			

*Concentrations in mg/m^3 at 273 °K, 101.3 kPa, 11% O_2 or 9% CO_2, dry.
**Capacity, in tonne/h.

the range of recommended operating parameters for the field/commercial unit to assure optimum operation within regulatory requirements. For incineration technologies, information necessary for treatability testing includes:

- Chemical composition of the waste feed
- Heat of combustion of the waste feed
- Viscosity
- Corrosivity
- Ignitability
- Reactivity
- Polymerization
- Solids content of waste feed

- Metal content of waste feed.

Once treatability tests are conducted, data developed from the tests will help in deciding what additional information is needed. This could include:

- Feed preparation data (materials handling)
- Baseline operating conditions (residence times and temperature in the primary and secondary chamber)
- Energy consumption estimates
- Ash storage and post treatment requirements.

These treatability tests and appropriate analyses will provide data on the expected performance of a

Table 2-6. Typical incinerator operating conditions in the EC, as reported by manufacturers.

Incinerator type	Combustion zone temperature, °C	Combustion gas residence time, S	Excess air, % stoichiometric
Liquid injection	980-1650	0.3-2.0	120-250
Fume	700-820	0.3-0.5	50-200
Rotary kiln	650-1260	2 hours (solids)	50-250
Afterburner hearth	1100-1370	1.0-3.0	120-200
Primary chamber	650-980	--	30-200
Secondary chamber	760-1200	1.5-2.5	200-400
Fluidized bed	760-1100	1.0-5.0	100-150

Table 2-7. Methods to develop cleanup standards by country.

Canada

Only Quebec has a formalized approach. A comprehensive list of generic criteria adapted from the "Dutch List" (see The Netherlands) is used for initial guidance and screening, with site-specific risk assessments as appropriate.

Denmark

No national approach; control by local governments. Use "Dutch List" for general guidance and screening as well as existing Danish standards where available. Final decision on a particular site based on site-specific considerations. Formalized risk assessment methods now under development.

France

No national approach; control by local governments. Use qualitative risk assessments. If pollution is by natural substance, must reference background levels. Development of standards for soil pollution now under consideration.

Germany

No national approach; control by provincial governments. Use of "Dutch List" with consideration given to local conditions. German "Guides/Threshold" values for soil contamination now under development based on soil protection policy initiated in 1985.

The Netherlands

National policy for maintaining soil "multi-functionality." Generic criteria (A-B-C levels) for evaluating significance of pollution enacted in 1983 (often referred to as the "Dutch List"). Reference values for good soil quality (new A-level) enacted in 1987. Contaminated land must be cleaned to multi-functional quality (A-level) unless it is technically or financially unfeasible or environmentally harmful to do so.

United Kingdom

No national system. National guidance on "Trigger Concentrations" for some contaminants commonly found on industrial sites often considered for redevelopment.

United States

For NPL (National Priorities List) sites (i.e. Superfund), use federal and state requirements where available and formal site-specific risk assessment methodologies. For non-NPL sites, procedures vary widely by state and government jurisdiction, and include either generic criteria background levels, or levels determined by site-specific formal risk assessment methodologies.

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commercial scale unit. This information will be used to determine compliance with regulations on incineration technologies. Before any treatability testing starts, performance criteria for the technology and limits on the various emission streams needs to be determined. For thermal technologies, the following need to be considered for regulatory compliance monitoring:

- Physical and chemical characteristics of the feed

- DRE levels for designated compounds and the presence of PIC's (products of incomplete combustion) in the stack gas

- Levels of HCl and particulates in the stack gas

- O_2, CO, CO_2, NOx and SOx concentrations in the stack gas

- Levels of various compounds (metals, dioxins) in the ash

- Levels of various compounds (dioxins, PCB's, etc.) and other parameters (pH, TOC, etc.) in the scrubber water.

Following waste feed analysis and treatability testing, an assessment for compliance with governmental regulations for incineration must be conducted.

Based on the evaluation of technology performance parameters, information on both physical and chemical characteristics of the waste matrix is necessary to determine the suitability of that particular waste for thermal processing and the possible need for waste preparation and pretreatment. Table 2-8 presents a range of waste characteristics that are suitable for the electric infrared incineration system. An applicable range of waste characteristics needs to be prepared for each technology under consideration.

Site requirements for the operation of the various fixed or transportable incineration technologies are different, based primarily on the throughput of the technology. A thorough description of the technology including major components and on-site needs is required. At a fixed facility, many of these needs can be addressed in the design and location of the facility. However, the requirements for a transportable system can determine or affect the selection of a technology. When considering the use of any incineration system, the following characteristics are important considerations:

- Climate
- Geology
- Topography.

Other requirements include:

Table 2-8. Waste characteristics suitable for electric infrared incineration.

Characteristics	Applicable Range
Morphology	Solid (soil)
	Semi-solid
	Oily sludge (solid phase)
Particle size	5 microns (2 inch) diameter
Moisture content	0 - 50 %wt (no free liquids or free-flowing sludges)
Density	480 - 2082 kg/m^3
Heating value	0 - 23,244 Joules/g
Organics (including POHC's)	0 - 100 %wt (determined by pre-operation testing)
Chlorine	0 - 5 %wt
Sulfur	0 - 5 %wt
Phosphorous	0 - 300 ppm
pH	5 - 9
Alkali metals	0 - 1 %wt
Heavy metals	0 - 1 %wt (determined by pre-operation testing)

- **Utilities** including water, electrical, fuel, and telephone. Water will be required for the process, equipment and personnel decontamination, and drinking purposes. Electricity will be required for the process, offices, laboratories, and monitoring equipment. Telephone service is essential, especially for emergency response.

- **Support Facilities** including office and laboratory space, pad for setting up the system, pad for decontamination, sanitary facilities, parking area, and a visitors area must be defined.

- **Support Equipment** may include monitoring wells, excavation equipment, waste feed storage, decontamination equipment, sampling equipment, scales, forklift, analytical equipment, and health and safety equipment.

- **Services and Supply.** A security service may be needed to patrol the site when personnel are not on the site. Office supplies and sampling supplies will be needed.

- **Site Preparation, Equipment Setup, and Feed Preparation.** Site development needs and improvements must be complete before arrival of the unit and any field activities begin.

In addition to the site requirements, other preparations relating to the operation of the technology need to be considered. These are referred to as material handling requirements. They can include waste excavation, feed preparation, and ash handling systems.

2.7 Costs

Incineration costs will vary significantly from site to site. Unfortunately, costs are sources of controversy during site remediation. The relatively high costs of incineration often eliminate it as a treatment option. This being the case, it is very important to conduct an accurate cost assessment. The following provides some preliminary background information on this topic.

The total cost of an incineration system varies with several factors, including:

- System capacity
- Types of feedstocks
- Regime (i.e., slagging vs ashing)
- Length to diameter (L/D) ratio for rotary kilns
- Type of solids discharge system
- Type and capacity of afterburner
- Type of auxiliary fuel used
- Regulations.

The cost of waste treatment also varies considerably from site to site; any estimate should include the following:

- Site preparation
- Permitting and regulatory requirements
- Capital equipment
- Start-up
- Labor
- Consumables and supplies
- Utilities

Table 2-9. Typical costs of incineration of contaminated soils (in US$, 1988).

	Capacity (tonnes/h)	Unit cost ($/tonne)
Centralized rotary kiln system	Commercial unit	330 to 720
Onsite incineration		
Small site (<4,500 tonnes)	<4.5	1100 to 1360
Medium site (4,500 to 18,000 tonnes)	4.5 to 9.0	330 to 880
Large site (>18,000 tonnes)	>9.0	110 to 440

*Not including the cost of transportation, removal of soils from the ground, or storage.

- Effluent treatment and disposal
- Residuals/waste shipping and handling
- Analytical services
- Maintenance and modifications
- Demobilization.

Table 2-9 presents the estimated costs of incinerating contaminated soils in both on-site and off-site incineration systems. These costs do not include transportation, storage, or removal of the soil from the ground.

Thermal treatment vendors generally prefer to bid on projects where a processed waste is ready to feed into their unit. Quotes are also based on the assumptions that the residue from the unit will meet discharge standards and that the thermal unit can operate at capacity for the length of the job. Failure to adequately plan the technical requirements and estimate the costs of a site remediation project can result in cost overruns and possibly an incomplete remediation.

In addition to capital cost data, operational and maintenance (O&M) cost data from previous studies (pilot- or field-scale) need to be collected. O&M costs include labor, power, fuel, chemicals, and maintenance needed to operate the system. The O&M cost will also include costs for health and safety considerations, and regulatory requirements, such as permitting.

Because of the various types of thermal treatment technologies, prices will vary widely. The range in price between low temperature (thermal desorption

technology) and high temperature incineration varies widely. Reported ranges for thermal technologies are between US$60 and US$1,300 per tonne. To adequately assess the costs for an individual project, the above cost categories must be rigorously examined.

2.8 Future Status of Case Study Processes and Thermal Technologies as a Whole

Incineration has been a selected option for site remediation and for the destruction of organics for many years. Several incineration manufacturers have been in business for many years. Changes in the thermal technologies have been introduced as a result of changing environmental regulations. With the application of thermal technologies to site remediation, these technologies now must deal with a wide spectrum of organic and in some cases inorganic contamination in the waste matrix. With increasing environmental monitoring and further understanding of thermal destruction processes, manufacturers and operators of thermal technologies have kept pace in the design and operation of these units. Concerns over the transportation of waste off-site during site remediation has led to the development of mobile (transportable) units. Each of the types of units discussed in this chapter has undergone modification either by the original users or by others using the same technology. These modifications have addressed meeting or exceeding environmental standards and controlling the costs of operating thermal technologies.

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Stabilization/Solidification Technologies

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ABSTRACT

Cement-based stabilization/solidification (S/S) techniques attempt to prevent migration of contaminants into the environment by forming a solid mass. The techniques chosen in the Pilot Study were: (1) Hazcon (United States), applying *ex situ* treatment with Portland cement; (2) EIF Ecology (France), applying surface treatment with lime; and (3) TREDI (France), using the Petrifix process. Only one of them (Hazcon, presently IM-Tech) yielded enough information for evaluation.

The case study processes accepted in the NATO/CCMS Pilot Study all apply generic binders, such as cement, pozzolanic material, or lime. No case studies applying other binders were submitted. In all cases, the combination of metals mixed with organic components and a large site to be treated were the major incentives for applying S/S treatment.

S/S may lead to a substantial increase in the total volume of waste (more than 100 percent). Consequently, it is possible that the treated material cannot be accommodated at the original site. Heavy metals in these processes are retained in the stabilized product by physical entrapment and precipitation.

In the Hazcon case, extensive leaching data exist on the treated soil. However, only limited leaching data are available, on the original untreated wastes. This makes an evaluation of the process difficult. From the available data it can be concluded that the process leads to a strong reduction of the leachate concentrations. A reduction factor of 100 for lead, the predominant metal at the site, was seen during a demonstration on site, using the TCLP test. Similar results were observed for zinc. For organic contaminants the process is generally not effective.

The Hazcon case provided extensive cost data from which an indication of the general cost factors may be obtained.

3.1 Introduction

3.1.1 Place of the Techniques in a Broad Sense

Stabilization/solidification (S/S) refers to techniques that attempt to prevent migration of contaminated material into the environment by forming a solid mass. The two terms are generally used together. Stabilization refers to rendering the material insoluble; solidification refers to the process of converting a liquid or sludge-like waste into a solid form by adding a binder. Even for materials already in solid form, like soil, the process is referred to as "S/S" treatment. In practice the terms stabilization and immobilization are often used as shorthand for stabilization/solidification. Solidification solely to improve handling characteristics will not be considered in this chapter.

Many S/S technologies have been proposed and tried in the past ten years. Some of them are proprietary, involving the addition of adsorbents and solidifying agents. The S/S binders can be divided into two major groups:

- Inorganic binders, such as cement, lime, kiln dust, fly ash, silicates, clay, and zeolites

- Organic binders, such as asphalt, polyethylene, resins, epoxies, urea formaldehyde, polyesters, and organophilic clays.

This chapter deals with stabilization processes using generic binders, such as Portland cement, lime, and fly ash.

The advantage of organic binders often is their ability to stabilize highly soluble wastes and to chemically bind organic contaminants. This is not possible with cement and pozzolanic materials. Organic binders, however, are more expensive than cement and pozzolans, and may be undesirable from an environmental point of view. Their application, therefore, has been limited to specific wastes, such as nuclear waste and highly toxic industrial waste.

Besides the use of binders for immobilization of contaminants, thermal methods (vitrification) may be used. Vitrification is a promising technique, since it combines destruction of organic contaminants with the incorporation of metals in the resulting glass-like matrix. See Chapter 2 for a general description of this technology. The high cost involved in treatment and the difficulty of permitting, however, are likely to hamper the application of vitrification on a large scale.

S/S may be used in a variety of applications. *In situ* treatment is used when excavation is undesirable for health reasons (e.g., dust emissions) or simply to avoid the cost of excavation. It refers to mixing the soil *in situ* with a hollow auger mixer through which the water-binder mix is pumped into the soil. This technique will not be described in this chapter.

Another application is S/S surface treatment, in which only the top layer of contaminated soil is treated. This application attempts to reduce the amount of water penetrating the waste, and does not stabilize the complete waste. Surface treatment reduces leaching of contaminants from the untreated waste underneath, but has too limited neutralization capacity for long-term durability. Surface treatment will be briefly discussed in one of the case studies. S/S treatment is mainly used in the United States, Canada, and France. In countries where waste is evaluated on the basis of concentration limits rather than on leaching behavior, S/S technology may be used, for those wastes which cannot be treated otherwise, to produce a material that can be more easily landfilled.

3.1.2 The Stabilization/Solidification Process

Conceptually, S/S treatment with cement, pozzolanic material, or combinations of them is simple. It consists of mixing the contaminated material with a binder after or during the addition of (often proprietary) chemicals. This is followed by the setting and hardening of the mix. The added chemicals may alter the solubility or redox potential of the waste to be stabilized or may prevent retardation of the hydration process. This, in turn, may improve the binding of the contaminants to the matrix. The essential elements in the process are: (1) pretreatment, (2) mixing, and (3) casting and curing.

1. Pretreatment. In *ex situ* applications, the material is sieved down to a certain particle size that can be accommodated in the process equipment. If the waste characterization indicates that the contaminants are concentrated in a particular particle fraction of the waste, pretreatment should also seriously be considered to reduce the amount of waste to be treated. If the waste contains a large amount of water, dewatering may be necessary to remove excess water that cannot be accommodated in the final solidified waste form. Contaminants present in the excess water may be precipitated and stabilized as well. Homogenizing the waste improves the consistency of the stabilized product and the performance of the process. Before mixing the waste with the binders, chemicals can be added to convert the contaminants to a non toxic or a less soluble form.

2. Mixing. Mixing waste and binders can be done *ex situ* or *in situ*. *Ex situ* mixing is more controllable and attempts to produce a stable waste form by pumping the mix into a mold. Mixing is the most critical step in the process. Although it is conceptually simple, many vendors have difficulty in executing this step for two reasons:

- Insufficient homogeneity of the original waste

- Insufficient capability to adequately disperse the waste in the binder mix.

Insufficient mixing leaves waste forms that have a large variability in performance and may contain large clumps of pure waste. This lowers the integrity of the final waste form.

3. Casting and curing. The waste-binder mix is pumped into a mold or a lagoon. When cast into a small mold, the mix should preferably set rapidly, so that the mold is available for a new cast quickly. In case of a lagoon hardening, timing is less critical, but still important since the mix is introduced in the lagoon in layers that should set before the next layer is introduced.

If the stabilized material is deposited on a noncontrolled landfill the integrity of the material, as well as the leachate concentrations, should be monitored. It may be necessary to treat the waste a second time if the release increases to unacceptable proportions.

Although many experts believe that the major part of the contaminants will ultimately be released, the concentrations in the leachate at any one time can be low enough to pose no direct hazard to the environment. However, if the waste leaches for an extended period of time, the environment will become largely loaded with contaminants unless the contaminants are

remineralized and components are incorporated into soil organic matter.

3.2 Case Studies Chosen

Knowledge about S/S treatment processes is rapidly increasing. The case studies discussed in this chapter do not represent the most recent status of the technology. Furthermore, the technologies presented do not, by far, represent the full range of S/S technology now available. The technologies chosen for the NATO/CCMS Pilot Study only serve as a general illustration of the available technology.

Three case studies in which three different vendors applied their technology where chosen for the NATO/CCMS Pilot Study. These are:

- EIF Ecology (France), applying surface treatment with lime
- TREDI (France), using the Petrifix process
- Hazcon (United States), applying *ex situ* treatment with Portland cement.

The problems handled by the manufacturers are summarized in Table 3-1. The rationale behind the choice of these technologies is indicated below.

3.2.1 Case Study 3-A: In Situ Lime Stabilization (EIF Ecology), France

In this study, described in Appendix 3-A, on-site stabilization at two sites in France was evaluated (Sites A and B in Appendix 3-A). The immobilization process consisted of mixing the material with lime. The sites are contaminated with a variety of hydrocarbons and heavy metals. The study was chosen because the NATO/CCMS members felt it useful to evaluate the practice of S/S treatment in France. Since the remediation was already completed at the start of the NATO/CCMS Pilot Study, these sites provided limited information.

3.2.2 Case Study 3-B: Petrifix Process (TREDI), France

The Petrifix process was used by TREDI to stabilize contaminants at two sites in France. These sites are also described in Appendix 3-A as Sites C and D. Site C is a former industrial disposal site, contaminated with a variety of contaminants, mainly chromium, sulfates, and sulfides. The study was chosen for the same reasons as the EIF process.

3.2.3 Case Study 3-C: Portland Cement (Hazcon, presently IM-Tech), United States

The Hazcon process (presently IM-Tech) is a proprietary process using a patented nontoxic chemical called Chloranan (U.S. EPA 1989). Chloranan is claimed to neutralize the inhibiting effects that organic contaminants normally have on the hydration of ce-

ment-based materials. The process is described in Appendix 3-B and was chosen for three reasons. First, because the study resulted in a detailed evaluation of the process, and can be regarded indicative of the results to be obtained with other cement stabilization techniques. Second, because the technique was applied on a waste containing large amounts of organic components. Third, because the process is available on a commercial scale making an economic evaluation possible. (For more information on this project, see Appendix 3-B.)

3.3 Background of Case Study Sites as a Group

The cases accepted in the NATO/CCMS Pilot Study all apply cement, pozzolanic material, or lime. These binders are the most generic ones used to date. No case studies applying other binders were submitted. In all case studies, the combination of metals mixed with organic components plus a large site to be treated was the major incentive in applying S/S treatment.

3.4 Performance Results

Leachability of the contaminants after S/S treatment is largely reduced due to the insoluble state of the contaminants, physical encapsulation in the waste form, and chemical binding to the matrix. The performance of S/S treatment is primarily measured by standard leaching tests, as required by regulatory authorities. At present, only short-term tests are available. Ongoing international research in predicting the release rate as a function of environmental variables (such as soil pH, chemical composition of the contacting ground water, waste characteristics, and binder characteristics) should lead to more adequate tests. Major improvements in this area can be expected in the years to come.

A wide variety of leaching tests is available at present. Most are required by regulatory agencies, but have a poor scientific background. Test results are, therefore, difficult to compare and it is usually unclear what they measure, since leaching mechanisms are still poorly understood. Examples of leaching tests are:

- Toxicity Characteristic Leaching Procedure, or TCLP (United States)
- Multiple Extraction Procedure, or MEP (United States)
- American Nuclear Society test method 16.1, or ANS 16.1 (United States)
- Waste Extraction Test, or WET (United States)
- SOSUF test (The Netherlands)

Table 3-1. Problem handled in these NATO/CCMS case studies.

Process/technique	Lime stabilization	Petrifix	Portland cement
Manufacturer	EIF-Ecology	TREDI	Hazcon (presently IM-Tech)
Country	France	France	United States
City	Site A: Marais de Ponteau-Lavera Site B: Bourron Marlotte	Site C: Nesle-Somme Site D: Bellay-Ain	Douglassville, PA
Area (m²)	Site B: 4,200		Total of five areas in the site: 200,000
Depth (m)	Site B: 6-7	Site C: 5 Site D: 2.5	Unknown
Amount of soil to be treated	Site A: 22,000 m³ Site B: 22,680 tonnes	Site C: 6,804 tonnes Site D: 8,165 tonnes	200,000 m³
Source	Site A: Industrial residues of the Lavera petrochemical plant (sludges and sediments) Site B: Industrial residues from an old refinery plant (mainly acid tars and filtration residues)	Site C: Industrial residues Site D: Sludges from tannery plant wastewater treatment	Oil recycling facility, with wastewater sludge, recycling oil, and filtercake
Type of soil	Site A: Not known Site B: Top layer - light and viscous material; middle layer - aqueous liquid; bottom layer - sticky material (composition unknown)	Site C: Black-colored sludges and silty material Site D: Not known	Five different wastes: Site A: Oily sludge from wastewater treatment Site B: Oily filtercake Site C: Oil and oily water Site D: Sludge (landfarming area) Site E: Plant processing area
Type and concentrations of contaminants	Site A: Not known Site B: Not known	Site C: Concentrations in leachate: COD up to 450 mg/l; iron up to 47 mg/l; ammonia up to 80 mg/l; traces of copper and zinc (concentrations in the material itself unknown) Site D: Chromium 8,700 mg/kg; sulfide 475 mg/kg; sulfates 500 mg/kg; nitrogen 350,000 mg/kg (35%)	Lead 3,000 - 22,000 mg/kg (0.3-2.2%); oil and grease 10,000 - 250,000 mg/kg (1-25%); VOC's 0-150 mg/kg; semivolatile organics 12-530 mg/kg; PCB's 1.2-54 mg/kg; pH 2.6-7.0
Main lesson learned	Absence of data concerning the original waste characteristics and concentrations makes evaluation and technology transfer impossible.		Leachate characteristics of treated material along are not sufficient for a good evaluation; leachate quality from both treated and untreated waste was identical. The raw material feed system and the blender may be critical in the process.

- AfNOR Standard Test X31 210 (France). This test, to be used in France, strongly resembles the United States TCLP.

Since leaching tests only provide limited information concerning long-term performance, several other tests, relating to the integrity of the waste form under various environmental conditions may be carried out, such as:

- Homogeneity of the final product, which is also an indicator of the performance of the mixing operation

- Physical performance, such as strength

- Influence of weather conditions, such as freeze-thaw and wet-dry performance

- Acid neutralization capacity, which relates to the ability of the stabilized product to neutralize acids.

Although the formation of a monolith is desirable to guarantee the encapsulation of the contaminants, it is recognized that the performance of nonmonolithic or "soil-like" waste forms may be as good or better than monolithic waste forms (Barth and McCandless 1989).

EIF Ecology. The information provided by this vendor was too limited to be able to evaluate the performance.

TREDI. As in the EIF Ecology stabilization, little is known about the performance of the TREDI stabilization.

Hazcon. The primary goal of the evaluation of the Hazcon process was to compare contaminant mobility of the untreated versus treated soil. Although extensive leachate data exist on the treated soil, only limited data are available on the original untreated wastes. This makes a comparison difficult. From the available data it can be concluded that the process leads to a strong reduction of the leachate concentration. A reduction factor of 100 for lead, the predominant metal at the site, was seen during the SITE demonstration using the TCLP. Similar results were observed for zinc. For organic contaminants, the process is generally not effective. In most cases the extracts from the TCLP leaching tests of untreated soil were found to be identical to those of the treated soil. Some data available on the treatment of petroleum refinery wastes, however, showed sharp reductions in leachate concentration after waste treatment (U.S. EPA 1989). This indicates that there might be selected applications where immobilization of organics occurs. During the project, numerous operating difficulties were encountered by Hazcon. Main shortcomings were encountered in the raw material feed system and in the blender. It is believed that improvements in this field can largely improve operations.

3.5 Residuals and Emissions

Stabilization/solidification leads to a strong increase in the total volume of waste. Since increases of more than 100 percent are normal, the treated material often cannot be accommodated in the original site and must be landfilled elsewhere. If the treated waste is very wet, a part of the process water must be cleaned. The resulting sludge, however, may be recycled back into the system.

The S/S process produces heat, which can lead to emission of hazardous components. Most of the VOC's were volatilized during the Hazcon operation. In cases where a large amount of VOC's is present, the process should be executed in a closed system, where the VOC's can be trapped and subsequently treated.

An inherent feature of solidified waste is its leaching ability. If improperly landfilled, most of the contaminants may eventually leach out. If the stabilized waste is properly landfilled, (i.e., the landfill is properly lined to prevent contact with ground and rain water) leaching into the environment is not a problem. Adequate maintenance of a landfill in this respect is of major importance.

3.6 Factors to Consider for Determining the Applicability of the Technology

3.6.1 Limitations and Restrictions on the Use of the Technology

S/S technology can be considered for two major reasons. The first is that no other treatment methods are available for the particular site. This is specifically true for wastes containing heavy metals mixed with small amounts of organic contaminants. The second reason is that the technique is more cost effective than other techniques.

Generally the cement- or lime-based binders have not been proven successful in stabilizing organic components. Although it may be possible to treat material containing organic components by adding certain chemicals to prevent the unwanted effect of the organic contaminants on the cement hydration, the organic contaminants themselves are not well retained in the stabilized waste form. Cement-based stabilization techniques are, therefore, only applicable to wastes in which metals are the main source of contamination and where the release of organic contaminants is not considered a main problem. The technique should not be applied when the organics are highly toxic or where large amounts of volatile organic contaminants are present.

A drawback of S/S technologies is their questionable long-term durability. Analyses of crushed samples show that there often is hardly any chemical binding, which implies that most of the contaminants in the solidified waste form are essentially mobile and will

eventually leach out of the stabilized material. Physical entrapment and adsorption, however, strongly reduce the velocity of release.

Another drawback of S/S technology is that it requires large amounts of chemicals and leads to substantial volume increases of the stabilized products. Especially for dry materials like soil, an increase of more than 100 percent can be expected. Volume increases up to 140 percent have been reported. This means that the disposal site needs to be more than double the size of the original site. In designing dump sites this factor will have to be taken into account.

A summary of the limitations related to the case-study projects is given in Table 3-2.

concentrations. The metals, however, are essentially mobile. The stabilized material should, therefore, be deposited on a controlled dump site with adequate drainage and treatment facilities to prevent migration into the environment.

3.6.2 Steps in Determining the Applicability of S/S Treatment

A general five-phase investigation, to assess the possible application of immobilization, is given by Barth and McCandless (Barth and McCandless 1989) and consists of:

Table 3-2. Limitations of the case study techniques.

Manufacturer	EIF-Ecology	TREDI	Hazcon (presently IM-Tech)
Technique	Lime Stabilization	Petrifix	Cement plus additives
In/Ex situ	In situ	In situ	Ex situ
Feature of process used	Heavy metals are partly encapsulated; buffering capacity is the main cause of delayed release.	Heavy metals are encapsulated and precipitated; some chemical binding may occur.	
Long-term effect	If the waste is not stored dry, contaminants will be released	If the treated waste is not stored dry, contaminants will be released.	
Release mechanism	Release is partly governed by diffusion. The waste form easily disintegrates, enlarging surface area. Utilization of acid neutralization capacity is the major release factor.	Release is partly governed by diffusion and accelerated when the waste form breaks up, due to increase of surface area. Utilization of acid neutralization capacity is thought to be a major release factor.	
Type of soil; fraction of fines, organics and rubble	No limitations	No limitations	No limitations
Type of contaminants	Organics are not immobilized; volatile organics may be released.		
Concentration of contaminants	No limitations	No limitations	No limitations
Volume increase	Depends largely on water content; dry solids will lead to an increase of 100-140%.		

In the EIF Ecology process, the contaminants are essentially trapped due to the low solubility in the high pH environment of the mix. Release, therefore, strongly depends on the acid neutralization capacity of the stabilized product. In general, lime as a sole binder is not very effective.

In the Hazcon process, heavy metals are retained in the stabilized product mostly by physical entrapment and precipitation. The buffering capacity of the stabilized material leads to a strong reduction in leachate

1. Site sampling
2. Waste acceptance/project planning
3. Waste characterization
4. Binder screening
5. Performance testing.

1. Site sampling. Many techniques are available for taking a representative sample. In most cases, site sampling for bench testing can be aimed at obtaining either a "worst case" sample and/or an "overall

average" sample. The choice depends on the nature of the waste and the quality and amount of data available to the planner. For the treatability study, a sample of at least 130 kg is recommended (Barth and McCandless 1989). An assessment of variability of the waste is important for determining the size and number of samples to be taken.

2. Waste acceptance. Generally, laboratory permits are restricted to certain components and wastes. An analysis of a representative sample should give information on the type of laboratory needed for the treatability study. Furthermore, the waste acceptance investigation should provide information about possible health aspects that have to be accounted for in the study.

3. Waste characterization. Prior to binder screening and performance testing, the waste is characterized to obtain information needed to plan S/S treatment. Important objectives of the waste characterization are to:

■ Assess the possibility of applying additional techniques in order to reduce the amount of waste to be treated. In case the contaminants are concentrated in a fraction of specific particle size, a separation technique might be considered.

■ Obtain information concerning components that are known inhibitors to the hydration and setting of cement and pozzolans.

Leaching behavior of the original waste is important because it gives information on the potential effectiveness of the S/S treatment. In some cases it has been established that leaching rates after stabilization were higher than before treatment, making the application of S/S somewhat dubious. Establishing the original concentration of the total and soluble fraction of the contaminants to be immobilized is important in terms of interpretation of leachability studies.

4. Binder screening. Since S/S represents a relatively new alternative in remediation, little technical information, empirical or otherwise, is available to assess its potential (Barth and McCandless 1989). Many factors influence the performance of the waste-binder mix. Some important factors are: soil type, contaminant type, and contacting liquid (rain water, acid leachate, sulphate-containing ground water, etc.).

A first step in the possible consideration of immobilization is mix design. The basis of a mix design is the assessment of binder characteristics and waste characteristics, separately and in combination, leading to an estimate of appropriate mix compositions. Center Hill Research Laboratories (University of Cincinnati 1990) establishes so-called design windows (possible compositions), derived from pH-solubility curves and acid neutralization capacity-pH curves. Although the establishment of design windows yields information on waste-binder mixes, treatability studies are a necessary second step in the assessment of immobilization as an environmentally sound remedial alternative. Since only limited theoretical information is available on selection of binders for a specific waste, trial and error approaches are followed. In general, three binder mixes are considered: Portland cement, cement-kiln dust mixtures, and lime fly ash mixtures. Apart from possible ad-hoc combinations, a standard trial combination of binder-to-waste mixes may be applied. Barth and McCandless (Barth and McCandless 1989) propose trying the nine possible combinations of the three most widely used binders (Portland cement type I, cement kiln dust, and lime fly ash type F) and three binder-to-waste ratios (0.1, 0.3, and 0.6).

Other parameters, such as the water-to-cement ratio (W/C factor) and slump, are assessed according to established civil engineering practices. Based on the results of the trial mixes, further optimization is carried out.

5. Performance testing. After the composition of the binder mix is determined in the laboratory, the stabilized specimen must be tested on a larger scale. In laboratory tests, performance testing aims at improving the binder mix and determining the expected leachate concentrations as measured by standard leaching tests and physical integrity tests. The laboratory tests generally result in a fine tuning of the binder-waste mix under optimal conditions. Since in practice the actual stabilization is performed with field equipment under less ideal circumstances, pilot tests are necessary to obtain information on the performance of the actual field stabilization. Mixing, for instance, may be the critical step in the field.

3.7 Costs

3.7.1 General Cost Factors

Currently (1991), little cost information is publicly available. In the NATO/CCMS case studies, costs of treatment were only available for Hazcon. The costs of this particular process are summarized in section 3.7.2 below. However, the following general cost factors for applying S/S treatment should be taken into account, at a minimum.

Costs of treatability studies. S/S, more than other technologies, is an art rather than a science. The performance of the technology is established by trial and error, rather than by design. Consequently, treatability studies may represent a substantial part of the total costs, and the cost of these studies may be an impediment to the application of the technology.

Barth and McCandless (Barth and McCandless 1989) give an indication of the costs involved in assessing the potential of an S/S technique. These costs are summarized in Table 3-3 and apply only to metal-containing wastes. Two cases are indicated in Table 3-3: for wastes containing metals only, and for wastes

Table 3-3. Summary of estimated treatability costs for metals (x1000 US$, 1989).

	Metals Only			Metals Plus Non-Volatile Organics		
	Labor	Analysis	Total	Labor	Analysis	Total
Site sampling*	8.0	--	8.0	8.0	--	8.0
Waste acceptance	13.1	3.9	17.0	13.1	3.9	17.0
Waste characterization	7.7	5.2	12.9	7.7	13.5	21.2
Binder screening	14.9	3.8	18.7	18.9	25.9	44.8
Performance testing	16.1	5.8	21.9	17.6	39.6	57.2
TOTAL ESTIMATED COSTS	59.8	18.7	78.5	65.3	82.9	148.2

*Estimated average; highly project-specific.

containing a combination of metals and nonvolatile organics. It should be realized that the estimated costs only serve as an indication of the potential costs involved. As can be seen, the analytical costs are by far the most significant factor in the total cost of a treatability study when complex wastes are involved.

Regulatory costs. The costs of permitting and environmental monitoring of operations for any regulatory authority may be substantial. Costs vary widely in each country. In countries following a federal system (e.g., Germany and the United States), the regulations may vary substantially within the country as well.

Site preparation costs. These costs include access to feedstocks and providing utilities needed for the plant to operate. They also include installation of equipment to support the operation such as storage tanks, pumps, and piping. Site preparation costs can be strongly influenced by site geology, proximity to residential areas, quantity and type of contaminants, and local costs of labor, utilities, and raw materials.

Treatment costs. These costs are generally given by the vendor of the technology. In the Hazcon case, operations are assumed to be 7 days per week and 24 hours per day. Any reductions in this schedule would add to the remediation costs by increasing the costs per tonne of treated waste. A vendor generally incorporates a profit factor of about 10 percent into the estimated costs.

Costs for additional landfilling and cleaning of process water. The site may not be able to accommodate the largely increased volume of the waste after treatment (more than 100 percent). Costs for additional landfilling of the treated material can be substantial.

Site completion. This includes the removal of support equipment at the completion of the cleanup as well as activities related to further use of the site and possible long-term monitoring.

3.7.2 Costs Of The Hazcon Treatment System

A cost analysis of the Hazcon system (now IM-Tech) has been made by the U.S. EPA (U.S. EPA 1989). A summary of these costs is given in Table 3-4. It should be noted that Table 3-4 only provides an indication of some of the costs involved in S/S treatment.

3.8 Future Status of Case Study Processes and the Technology as a Whole

The future status of the stabilization technology as a whole largely depends on the policies adopted in a specific country. Countries relying on concentration-based threshold values to evaluate hazardous waste are not likely to adopt the stabilization technology. In some countries, mixing a waste with another material is considered dilution of waste and is prohibited even if this dilution brings the concentration below certain threshold values.

In general, it can be stated that stabilization techniques (i.e., landfilling of stabilized waste) should be avoided if treatment techniques are readily available. However, in many current industrial processes, as well as in households, large amounts of unspecific mixed waste are produced. To clean these wastes would require so many conventional treatment steps, that treatment in these cases is not a realistic option. As long as industry continues to produce these untreatable mixed wastes in large amounts, landfilling will be necessary. Stabilization techniques to pretreat these wastes may be an option to consider.

The processes discussed in this chapter are not yet optimized. Fundamental research is needed in a number of areas, such as development of adequate test methods to assess the long-term durability of stabilized waste, assessment of binding mechanisms in

Table 3-4. Estimated costs for the Hazcon System (in US$, 1989).

	Demonstration Test chemical consumption[2]				Reduced chemical consumption[2]			
	136 kg/min		1044 kg/min		136 kg/min		1044 kg/min	
	on-stream factor[3]		on-stream factor[3]		on-stream factor[3]		on-stream factor[3]	
	90%	70%	90%	70%	90%	70%	90%	70%
Equipment								
Support	2.25	2.25	6.75	6.75	2.25	2.25	6.75	6.75
Equipment rentals	8.05	10.36	1.05	1.35	8.05	10.36	1.05	1.35
Contingency	0.25	0.32	0.11	0.13	0.25	0.32	0.11	0.13
Startup and fixed costs								
Operator training	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Site mobilization	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Depreciation costs	0.25	0.32	0.11	0.13	0.25	0.32	0.11	0.13
Insurance and taxes	0.25	0.32	0.11	0.13	0.25	0.32	0.11	0.13
Labor costs								
Salaries and living expenses	50.32	64.70	6.56	8.44	50.32	64.70	6.56	8.44
Administration	0.25	0.32	0.11	0.13	0.25	0.32	0.11	0.13
Raw materials								
Cement	50.00	50.00	50.00	50.00	33.33	33.33	33.33	33.33
Chloranan	66.67	66.67	66.67	66.67	44.44	44.44	44.44	44.44
Utilities								
Fuel	1.00	1.29	0.23	0.29	1.00	1.29	0.23	0.29
Electricity	0.03	0.03	-	-	0.03	0.03	-	-
Water	0.08	0.08	0.07	0.07	0.08	0.08	0.07	0.07
Other costs								
Analytical	5.65	6.50	2.26	2.40	5.65	6.50	2.26	2.40
Facility modifications	0.25	0.32	0.12	0.14	0.25	0.32	0.12	0.14
Site demobilization	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
TOTAL[4]	188	206	137	139	149	167	98	100

[1]Estimated accuracy of the reported costs is -30% + 50% or less.

[2]A higher amount of chemicals was used during the demonstration test. The reduced chemical consumption refers to 33% of the demonstration test amount used.

[3]The stream factor indicates the continuing performance of the installation (a lower on-stream factor produces higher costs per ton of treated material).

[4]Rounded to whole dollars.

Source: adapted from U.S. EPA 1989.

stabilized waste forms, and methods to improve binding. Engineering improvements such as providing adequate mixing in the field and assessment practices such as characterization of the raw wastes should be further standardized and improved.

In terms of scientific advancement, it would be desirable to have leaching tests that have a sound scientific background. Most presently used tests do not provide fundamental information about the leaching process. Because waste-binder mixes are not required to be specified to a great extent, test results from different waste-binder mixes can be related only very marginally.

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Soil Vapor Extraction Technologies

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ABSTRACT

Soil vapor extraction (SVE) has been useful for soils contaminated with gasoline, solvents and other volatile organic compounds, and some semivolatile organic compounds.

SVE technology uses a fairly simple design: air is drawn through pores in the contaminated soil and carries the vapor away. SVE is used in conjunction with other technologies since it transfers contaminants from soil and ground water to the air and to condensed wastewater streams. It can also be used with microbial treatment.

The effectiveness of this venting operation depends on the chemical characteristics of the contaminant, the rate of the vapor flow through the unsaturated zone, and the flow path of the carrier vapors relative to the location of the contaminant.

This chapter discusses case studies related to the NATO/CCMS Pilot Study and identifies additional studies implemented in the United States. Commercially available processes for destruction of the vented air emissions are also discussed.

4.1 Introduction

Soil vapor extraction (SVE), also known as *in situ* venting (ISV), can be a cost-effective remediation process for soils to remove volatile organic compounds (VOC's) and some semivolatile organic compounds (SVOC's) from the vadose zone. The vadose zone is the subsurface soil zone located between the surface soil and the top of the water table.

SVE technologies have been used to remove vapor from landfills since the 1970's. During the 1980's, SVE was used extensively to remediate contaminated soil from leaking underground storage tanks. Only recently has SVE been used to remediate contaminated hazardous waste sites. This technology can be useful at sites where there are interferences or obstructions, such as buildings and highways that generally have sub-bases of porous material. In general, SVE is used in conjunction with other technologies since it transfers contaminants from soil and ground water to air and to condensed wastewater streams.

The process of SVE is characterized by air being drawn through the soil. As the air passes through the series of soil pores, it follows paths of lower resistance (i.e., through zones of high air permeability). Air, which is drawn through pores that contain contaminated vapor and liquids, carries the vapor away (advent the vapors). Contaminants will vaporize from one or more of the condensed phases (aqueous, adsorbed) replacing the vapors that were carried away in the air stream. Continued vaporization occurs to maintain the vapor-condensed phase equilibrium that was established before the contaminants were removed. This process will continue until all of the condensed phase organics are removed from the higher permeability soil. Contaminants in lower permeability zones will not be removed by advection since the air stream will continue to flow through the higher permeability soil. If the contamination is located some distance from the air flow, the vapor must diffuse to the air stream before it can be removed. The diffusion

process would then limit the rate of contaminant removal by the SVE process (U.S. EPA 1991a).

The basic phenomena controlling the performance of SVE systems are, therefore, based on vapor transport mechanisms. The effectiveness of this venting operation is dependent on three main factors:

- The chemical composition of the contaminant

- The rate of the vapor flow through the vadose (unsaturated) zone

- The flow path of the carrier vapors relative to the location of the contaminant (Hutzler, Murphy and Gierke 1988).

Compounds exhibiting vapor pressures over 0.5 mm Hg can be most readily extracted using SVE (U.S. EPA 1991a). When expressed in terms of the air-water partitioning coefficient, compounds that have values of dimensionless Henry's Law constants greater than 0.01 are more likely to be removed by vapor extraction systems (Hutzler, Murphy and Gierke 1988).

Figure 4-1 illustrates a basic soil vapor extraction system which consists of the following:

- One or more extraction wells

- One or more air inlet or injection wells (optional)
- Piping or air headers
- Vacuum pumps or air blowers
- Flow meters and controllers
- Vacuum gauges
- Sampling ports
- Air/water separator (optional)
- Vapor treatment (optional)
- A cap (optional).

Typically, extraction wells are designed to fully penetrate the unsaturated zone to the capillary fringe. If the ground water is at a shallow depth or if the contamination is confined to near-surface soils, then the extraction wells may be placed horizontally. Extraction wells usually consist of slotted, plastic pipe placed in permeable packing. The surface of the augured column for vertical wells or the trench for horizontal wells is usually grouted to prevent the inflow of air along the walls of the wells.

Since the air conductivity of the contaminated soils controls the rate at which air can be drawn from the soil by the applied vacuum, conductivity is a key design criterion. Important properties for determining air conductivity are grain size, moisture content, soil
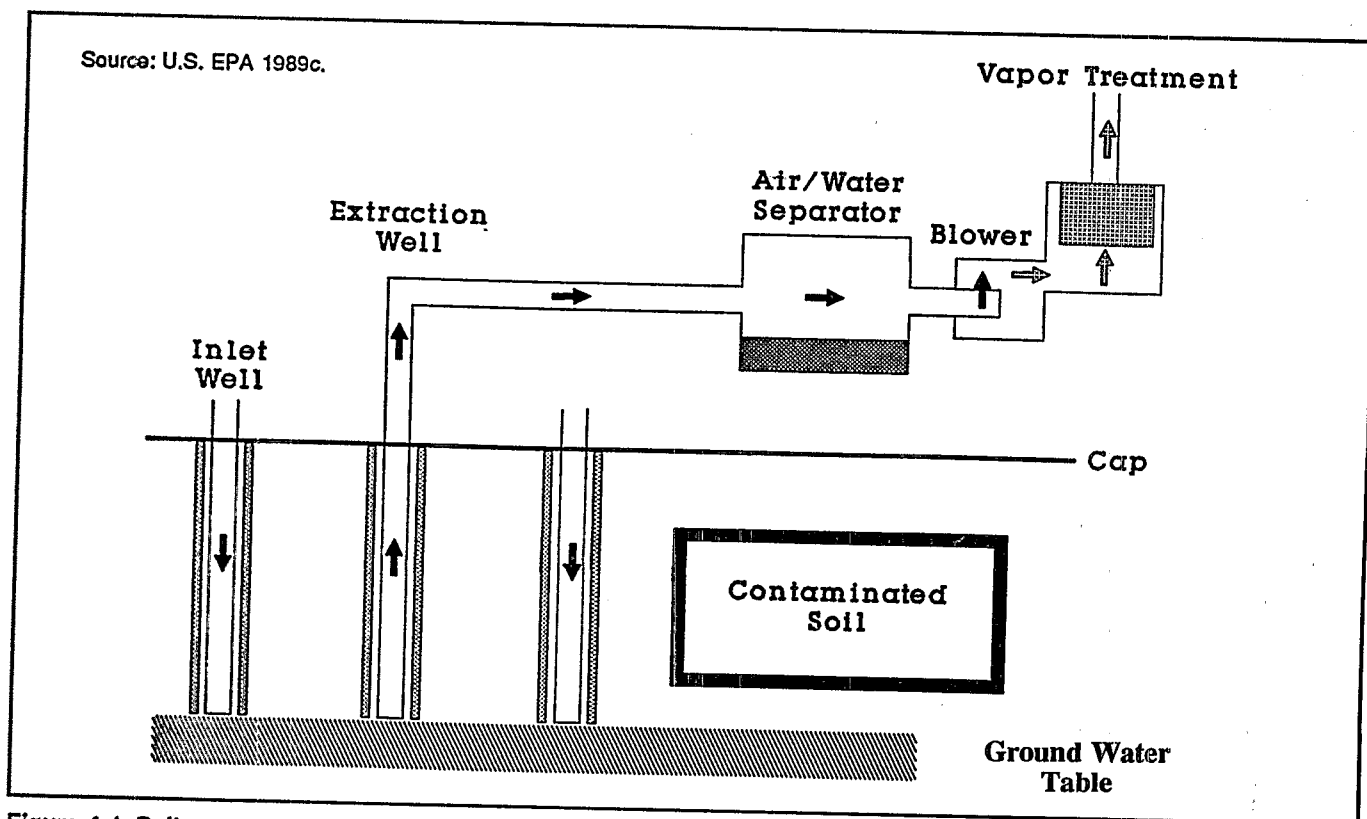
Figure 4-1. Soil vapor extraction system.

aggregation, and stratification. Soil moisture content or degree of saturation is important because it is easier to extract vapor from drier soils. As the size of a soil aggregate decreases, the time required for the diffusion of the chemical out of the immobile regions also increases. Clayey or silty soils may be effectively ventilated by the usual levels of vacuum developed in a soil vapor extraction system (Camp, Dresser and McKee 1987; Terra Vac 1987). (The levels of vacuum developed in SVE systems can range from 7 to 760 mm Hg; however, usual levels range from 50 to 130 mm Hg [Hutzler, Murphy and Gierke 1988].)

It must be recognized that soils with high clay or humic content generally provide high sorption potential for VOC's and thus can inhibit the volatilization of contaminants (U.S. EPA 1991a). The success of the soil vapor extraction in these soils may depend on:

■ The presence of more conductive strata as would be expected in alluvial areas

■ Relatively low moisture contents in the finer-grained soils (Hutzler, Murphy and Gierke 1988).

Application of proper scientific and engineering principles are necessary for reliable cost-effective system design and to ensure desired treatment results. Design considerations include the number of installation wells, well spacing, well location, and well construction, including the vapor treatment system. To date, a typical SVE system design consists of a single extraction well network which feeds a common vapor treatment system. However, modular system designs can be used to remove VOC's from specific contaminated areas or from areas with differing contaminant concentrations. Modular system design, although more capital intensive, allows for rapid changes in operations; this allows for optimizing the system. It permits the shutdown of various segments of the system once remediation of that area has been completed, thereby reducing operating costs. It also allows the operation of one segment of the system to be continuous while another segment is operated on an intermittent basis.

In some cases, subsurface soil conditions can be modified to facilitate the application of the SVE technology. For example, it may be necessary to lower the ground water level to enlarge the unsaturated zone; this would allow adsorbed volatile organics an opportunity to vaporize. At sites where the ground water is lowered, the extracted ground water may require treatment. In some cases, application of techniques such as radio frequency (RF) heating can be considered to increase soil temperature; this would increase the volatility of the contaminants and enhance contaminant removal.

In addition to extracting VOC's, SVE can be used to stimulate biodegradation of less volatile contaminants by supplying air (oxygen) to the subsurface soils at the same time. Although oxygen is usually the rate limiting parameter for aerobic biodegradation, other biological factors, such as availability of nutrients, require evaluation when considering using SVE in this way. (See the chapter on microbial treatment, below, for further discussion of this application.)

After the contaminated vapors have been removed from the subsurface soil, treatment may be required to condense/concentrate or destroy the contaminants in the air/vapor stream before it can be discharged into the atmosphere. There are a variety of technology options available for treating these vapors. For vapor streams with high concentrations of VOC's, condensation, thermal incineration, or catalytic oxidation are applicable options. For more dilute vapor streams, gas-phase activated carbon adsorption can be used. For very dilute vapor streams, if local regulations permit, direct discharge into the atmosphere may be allowed. Other methods, such as biological treatment, ultraviolet oxidation, and dispersion also have been applied. The type of treatment chosen will depend on the composition and concentration of the contaminants in the extracted vapor stream (U.S. EPA 1991a).

As operational experience with the SVE technology has developed, it has been learned that vapor/liquid separators are frequently needed prior to the vapor treatment device. Such separators need to be sized large enough to provide ample protection for the vapor treatment system which follows. This means that vapor/liquid separators should be slightly oversized, rather than sized specifically for the downstream equipment. The separated ground water and condensate collected from the vapor treatment may have to be treated as a hazardous waste.

In the remainder of this chapter, case studies are presented to illustrate specific applications of the SVE technology. In addition, residuals and emissions, costs, factors to consider for determining applicability of the technology, and the future status of the SVE system are discussed.

4.2 Case Studies Chosen

The case studies which are presented in the following discussion are intended to illustrate how SVE has been applied to a wide range of site and soil conditions, as well as to various contaminant types and concentrations. These include three case studies chosen for this NATO/CCMS Pilot Study and three additional studies from the United States. The latter are included to provide a broader information base on the SVE technology.

4.2.1 Case Study 4-A: In Situ Soil Vacuum Extraction, The Netherlands

This case study has two sites, known as Site 1 and Site 2. Site 1 was contaminated with solvents (up to 2200 mg/kg d.m. toluene); Site 2 was heavily con-

taminated with gasoline (11,000 to 18,000 mg/kg d.m.). There were two objectives of this project: to study the SVE removal effectiveness for contaminants located beneath structures as well as to study the effectiveness of *in situ* biological degradation of residual organics stimulated by the perfusion of air into the subsurface soils. The contaminants at both sites were in fine- to coarse-grained sands. Details of this case study are presented in Appendix 4-A.

4.2.2 Case Study 4-B: Vacuum Extraction of Soil Vapor, Verona Well Field Superfund Site, United States

The Verona Well Field site located in Battle Creek, Michigan had several distinct contaminated areas within 100 acres. During routine testing of the city's drinking water supply, volatile organic compounds (VOC's) were discovered in 10 of the 30 production wells. The contamination plume extended over an area of approximately 1.3 km² (0.5 mi²) and contained VOC concentrations as high as 1,800 ppb in both the ground water and soil. The contaminated soil consisted of fine- to coarse-grained sand with traces of clay and silt. The objective of the project was to remove VOC's from the unsaturated zone within the contaminated boundary (Danko, McCann and Byers 1990). To accomplish this, the ground water had to be lowered from 2 meters to 3 meters below the ground surface to enlarge the unsaturated zone. An abstract of this case study is presented in Appendix 4-B.

4.2.3 Case Study 4-C: Venting Methods, Hill Air Force Base, United States

The United States Air Force Engineering and Services Laboratory began a research project with Oak Ridge National Laboratory to conduct a full-scale test of *in situ* soil venting at a jet fuel (JP-4) spill site. The site chosen for the test was a fuel yard at Hill Air Force Base (AFB), Utah where a 100,000 liters (27,000 gallon) JP-4 spill had occurred. The site was selected for several favorable characteristics, including nearly ideal geohydrology, significant JP-4 contamination in the soil, logistical support, and the opportunity to undertake tests of different venting configurations. A summary of this case study is presented in Appendix 4-C.

4.2.4 Additional Case Studies, United States

The following case studies are presented to typify other applications of SVE. These case studies have been well documented and therefore provide comprehensive evaluations of performance results for different SVE system configurations and site and contaminant conditions.

Groveland Well Site, Massachusetts. A performance evaluation of the Terra Vac, Inc.'s vacuum extraction system was conducted during a 56-day demonstration test run at a Superfund site in Groveland, Massachusetts. This site was contaminated with degreasing solvent and cutting oils. Total contamination at the site was estimated at between 1,360 to 13,600 kg (3,000 and 30,000 lb) of VOC's with much of the heavy subsoil contamination located beneath a building (U.S. EPA 1989a).

The objectives of this field test were:

■ To determine how well the technology would remove VOC's from the vadose zone

■ To assess effectiveness in various soil types

■ To correlate declining recovery rates with time

■ To correlate VOC concentration in soils with those in extracted vapors.

This case study is summarized in Appendix 4-D.1.

Paint Warehouse Fire, Dayton, Ohio. An undetermined quantity of paints and paint solvents escaped into the soils at a paint warehouse in Dayton, Ohio, as the result of a catastrophic fire. Even though water was not used to fight the fire, uncombusted material still penetrated the soil and spread through the unsaturated zone. Less than six weeks after the fire, several VOC's were detected in nearby city wells. Rapid VOC removal from the porous soils in the vadose zone was needed to reduce further contamination of the ground water.

The objective of this project was to document the use of SVE for the rapid removal of the VOC's. In addition, the modular SVE system configuration developed for remediating the site was also the subject of study. Refer to Appendix 4-D.2 for the case study abstract.

Twin Cities Army Ammunitions Plant (TCAAP). This case study covers two site locations (Site D and Site G), at the TCAAP located at New Brighton, Minnesota. Site D was a solvent leaching pit/burn area and covered an area of 0.2 hectare (0.5 acre). Site G consisted of landfill material contaminated with VOC's and some metals. The SVE systems used for remediating both of these sites began operation in 1986 and are the longest operating and the largest SVE systems to date (U.S. EPA 1990a). The criteria used in selecting these sites for study were:

■ Duration of the SVE system operations

■ Quality of the initial site characterization

■ Amount and availability of operational data

■ Willingness of site owners/operators to participate in the project

■ Site characteristics, such as soil type, contaminant type, and size.

Two separate pilot systems were installed to test several design and performance variables. System 1 was designed to evaluate tetrachloroethylene TCE

Table 4-1. Summary of SVE case study information.

Case study	Principal contaminant	Level of contamination	Soil type	Depth to ground water	Vapor treatment
The Netherlands					
- Site 1	Toluene	2,200 mg/kg	Fine to coarse sand	7 meters	Activated carbon
- Site 2	Petroleum products	11,000-18,000 mg/kg d.m.*	Fine to gravel sand	2 meters	Biological purification
Verona	VOC's	1 mg/kg	Fine to coarse sand	7.5 meters	Activated carbon then catalytic oxidation
Hill AFB	Jet fuel	Not specified	Medium to fine sand	Not specified	Catalytic incineration
Groveland	TCE, MC	TCE:2,500 mg/kg	Medium sand to gravel	Not specified	Vapor-liquid separator, activated carbon
Dayton fire site	Toluene	Not specified	Sandy soil with clay strata	13.5 to 15 meters	Vapor-liquid separator
TCAAP					
- Site D	TCE, TCA, toluene	VOC's: 50 to 8,000 mg/kg	Arsenal sand	49.5 meters	Vapor carbon system
- Site G	TCE	VOC's: 22 to 960 mg/kg	Fill with underlying clay	39 meters	Activated carbon

*d.m. = dry matter or dry weight (d.w.)

removal from soils with relatively low VOC contamination (less than 2.3 mg/kg). The second system was a larger design to remove TCE with higher concentrations up to 5,000 mg/kg. Appendix 4-D.3 contains an abstract of this case study.

4.3 Background of the Case Study Sites as a Group

Table 4-1 summarizes the applications of SVE for the various case studies. The case study sites share several common traits. They all involve the extraction of volatile organic compounds from porous to moderately porous vadose zone soils. The contaminated soil types found at the case study sites were principally soils characterized by their high air conductivity. In general, these were fine- to coarse-grained sands, although other soil types including some silts and clays were present. Typically, the soil hydraulic conductivities ranged between 10^{-3} to 10^{-8} cm/s.

The sources of contamination varied between sites. They include releases of contaminants from underground storage tanks, landfills, waste handling practices, and contamination resulting from a fire.

The contaminants requiring remediation included:

- Chlorinated solvents
- Gasoline
- JP-4 (a jet fuel)

- Nonhalogenated solvents.

These classes of compounds are typical of those for which SVE is used. They all have a majority of constituents which are highly volatile.

These case studies also represent a diversity of site-specific conditions for SVE application. For example, they illustrate the application of SVE for rapid remediation of sites recently contaminated to prevent ground water contamination; the remediation of sites with contaminants which have resided in the environment over time; and the remediation of sites which have obstructions such as buildings that limit the application of invasive techniques. Additionally, they illustrate the differing system configurations, using vertical and horizontal venting, that can be used. Also, these case studies demonstrate how SVE can be used to stimulate *in situ* biological degradation to effect removal of less volatile contaminants as well as residual volatile contaminants remaining in the soil.

The SVE processes were used at each of the sites as an integral part of a treatment train. One of the most significant differences between the SVE systems presented involves the treatment techniques used for the off-gases. Depending on the contaminant concentrations in the extracted vapor stream, the treatment of the off-gases included:

- Direct discharge for air streams which contained very dilute VOC concentrations

■ Vapor phase activated carbon for low volume/low-to-moderately contaminated air streams

■ To catalytic oxidation for more highly contaminated air streams.

4.4 Performance Results

For each of the case studies performance results of the SVE system were collected. The following discussion presents these results, and the key design criteria and analytical procedures used in their determination.

4.4.1 Analytical Procedures

To evaluate the performance of SVE systems, it is important to quantify the amount of VOC's removed, the amount of these contaminants remaining in the soil, and the time for remediation. Further, additional data is needed for operating the air pollution equipment used to treat the extracted vapors. The following discussion illustrates some of the techniques used for accomplishing these tasks.

The techniques used at the Groveland site typify the procedures used to measure VOC removal. The quantification of VOC's removed was done by measuring:

■ The gas volumetric flow rate by rotameter, and wellhead gas VOC concentration by gas chromatography (GC)

■ The amount of VOC's adsorbed in the activated carbon canisters by desorption into CS_2, followed by GC.

VOC flow rates were measured and tabulated for each well section separately.

In general similar approaches were used in all of the case studies to determine residual contaminants in the subsurface soils. These included the collection of soil, soil gas, and ground water samples, and analyzing these samples for the parameters of concern. At the TCAAP site soil gas probes were used in boreholes drilled during the initial site assessment to determine the residual soil gas in the subsurface. Because these were already drilled the number of boreholes required later for assessing the SVE performance was reduced, thereby reducing costs associated with this testing.

To collect data about the extracted vapors, vapors extracted from both SVE systems at the TCAAP were continuously monitored for moisture content, temperature and pressure. Similar data was collected in most of the case studies which required vapor treatment. Additionally, air emissions were monitored throughout the operation, initially on a daily basis, and then on a weekly basis. The frequency of sampling was adjusted when the data reflected trends indicating a stability of the extraction process. To gain an understanding of the SVE process, in addition to evaluating the performance of the system, other procedures were used at The Netherlands Site 1. These were the modeling of the SVE action duration, the study of the horizontal versus vertical aerodynamical conductivity of the soil, and the measurement of bacterial activity. For the duration factor, the input parameters were the estimated air flow in the subsoil, the sorptive properties of the subsoil in relation to the contaminants, and the physical/biological properties of the contaminants at soil temperature. Air flow and tracer velocity measurements in relation to the applied negative pressure gradient in the subsoil were made for use in the model. At this site, the horizontal directional aerodynamical conductivity of the soil was found to be about 150 meters per day (500 ft/d); in the vertical direction, it was about 70 to 90 meters per day (230 to 300 ft/d).

4.4.2 General Effectiveness of the SVE Process

SVE worked best at sites contaminated with VOC's having Henry's Law constants greater than 0.01 or vapor pressures greater than 0.5 mm Hg. However, less volatile constituents can also be removed by SVE, but removal efficiencies are reduced as the volatility decreases. SVE has been shown to remove VOC's from fine- to coarse-grained sands with permeabilities ranging between 10^{-3} to 10^{-8} cm/s. Although permeability (hydraulic conductivity) is frequently used as a criterion for SVE applicability, air-filled porosity of a soil is a more important factor.

In general, SVE has been demonstrated to be effective for the removal of VOC's from vadose zone soil up to depths of 180 meters (600 ft). Soil with moisture content up to 30 percent can be effectively remediated. (Ground water levels can be lowered to increase the vadose zone.) Soils with high clay and/or humic content will tend to adsorb the VOC's present and thereby slow vaporization. Thus adsorption can affect the level of remediation obtainable in such soil; that is, the soil cleanup levels may not be achievable by SVE alone.

Johnson, et al. (1990) suggest that SVE is capable of removing approximately 90 percent of the volatile contaminants with a vapor pressure greater than 0.5 mm Hg. This rule of thumb is generally supported by the case study data and provides a starting point for estimating how much material can be removed and how much will remain in the subsurface.

To date, insufficient data exists to permit development of empirical relationships for VOC removal efficiencies for specific contaminants in various soil types. Based on the case studies presented, the mass removal rates vary greatly from site to site. The mass removal rates were observed to range up to 2300 kg/d (5000 lb/d). Average mass removal rates typically ranged between 5 and 30 kg/d. The rate at which contaminants were removed over the project life differed. In several of the case studies, there was an initial

sharp decline in the VOC mass removal rate followed by a period of gradual decline; this ultimately leveled off as residual contaminant concentrations approached zero. It is believed that this is characteristic behavior for sites where the contaminants have resided in the subsurface for some time and in which the moisture content of the soil is low. In other cases, mass removal rates increased over time and then declined gradually before leveling off as the VOC concentrations in the extracted vapor approached zero. Preliminary indications are that this occurs at sites where the moisture content is high and the soil porosity is low. Since only limited data exist on SVE applications, the performance results for the case studies can only provide an indication of the effectiveness of SVE applications for given contaminants and specific site conditions.

Operationally, the Groveland case study indicates that once the VOC concentration in the extracted vapor leveled off (as it approached zero), the extraction process can be terminated for approximately two days and then restarted. (The time required to reach this leveling-off point was estimated to be 150 to 200 days, based on modeling.) By stopping the extraction process, equilibrium in the air spaces can be reestablished. If, when the extraction process is begun again, the VOC concentration does not increase above the concentration which was observed when the process was stopped, it can be concluded that the maximum removal efficiency achievable by the SVE process has been obtained. If, however, an increase in the VOC concentration is observed in the extracted vapor, it can be concluded that vaporization is still occurring. At this point, intermittent operation of the SVE system can be used until the concentration of the extracted vapor does not increase after the process has been stopped.

4.4.3 Removal of Nonhalogenated Solvents

Performance results from Site 1 in The Netherlands show that, within four months of operation, approximately 580 kg (1300 lb) of toluene was withdrawn from the contaminated area. Initial concentrations of toluene in the fine- to coarse-grain sand ranged up to 2200 mg/kg. Concentrations of up to 8000 mg of toluene/m^3 were measured in the withdrawn soil vapor (up to 40 g/m^3 in a specific extraction well).

At the Dayton Site, the soil volume to be treated was divided into four cells, based on the air flow rate which could be provided by a pumping unit. Each of the four cells was brought on line for two week intervals. The system recovered 1690 kg (3720 lb) of VOC's during the first 73 days of operation. After 56 weeks of operation, over 3600 kg (8000 lb) of VOC's had been recovered from the site. By April 1988, composite off-gas VOC measurements had fallen to less than 1 ppm. At the same time, VOC concentrations in the unconfined aquifer had, for almost two

months, been at nondetectable levels for all hydrocarbon species identified prior to treatment. By June 1988, all off-gases extracted from the shallow, unsaturated soil were below 1 ppm. All perched water extracted from the vacuum wells yielded VOC concentrations below action levels accepted by Ohio's EPA and the cleanup activities were halted. (Ground water VOC action levels were established for the ketones as follows: acetone, 810 µg/L; MIBK, 260 µg/L; and MEK, 450 µg/L.)

4.4.4 Removal of Gasolines and Jet Fuels

At The Netherlands Site 2, the soil was heavily contaminated with 11,000 to 18,000 mg/kg petroleum products. Over the first year of operation, the SVE system extracted approximately 1,900 kg (4200 lb) of volatile organics from the soil, and approximately 800 kg (1800 lb) was broken down in the soil by microbial action; (thus, a total of nearly 2,700 kg (6000 lb) of gasoline was removed or broken down). Nine months after beginning the SVE process, the soil-air vapor withdrawal rate was increased from 25 to 50 m^3/h (15 to 30 cfm). The concentration of volatile gasoline compounds was 3 g/m^3. After an additional ten weeks, the SVE air extraction rate was increased once again to 63 m^3/h (37 cfm). To keep the concentrations of the contaminants in the extracted-air at about the same level, the extraction rate was increased during the clean up period. This was necessary for the efficient operation of the biological treatment plant. There were no limitations caused by the geological situation.

At Hill AFB, approximately 50,000 kg (110,000 lb) of JP-4 hydrocarbons had been extracted in the vented soil gas between start-up in December 1988 and October 1, 1989. The contaminated area was determined to be 37 meters by 37 meters (122 ft by 122 ft) to a depth of 15 meters (50 ft) below the land surface. The highest soil gas hydrocarbon concentrations had dropped from 179 percent of the lower explosion limit (LEL) in February 1989, to 88 percent LEL in April 1989. Also, the concentration of hydrocarbons in extracted gas from the entire venting system dropped from 38,000 ppm hexane equivalent in December 1988, to 500 ppm hexane equivalent in October 1989 (Downey and Elliott 1990).

During these 9 months of operation at Hill AFB, SVE volatilization removed 47,500 kg (105,000 lb) of VOC's and another 6,800 to 9,000 kg (15,000 to 20,000 lb) were converted by biodegradation. Soil hydrocarbon levels were reduced by 95 percent, and a corresponding drop of 99 percent was noted in soil gas levels. Only 7 percent of the post operation soil samples exhibited total hydrocarbon levels greater than the 100 mg/kg cleanup criterion used.

At the Verona Well Field site, VOC's at concentrations as high as 1800 mg/kg were located in a plume covering approximately 1.3 km2 (0.5m^2) and extending

downward from the surface to 7.5 meter (25 ft). Results described here come from both the pilot and full-scale operation at the Verona Well Field site. The pilot system, which operated for 69 hours during a 2-month period beginning in November 1987, extracted about 1360 kg (3000 lb) of VOC's from the vadose zone. The full-scale SVE system began operation in March 1988 and, after 25 months of operation, had removed approximately 19,500 kg (43,000 lb) of VOC's. The TVOC's extracted per day dropped from 49 kg/d (108 lb/d) initially to less than 45 kg/d (100 lb/d) by May 1990. By September 1990, this amount became less than 2.2 kg/d (5 lb/d).

4.4.5 Removal of Halogenated Solvents

At the Groveland Well site, analysis indicates that a total of 588 kg (1,297 lb) of VOC's were extracted over the 56-day test period. The soil porosity ranged from 40 to 50 percent, and was nearly the same for both the clay and sands over the 7-meter (24 ft) depth of the wells. The permeability/hydraulic conductivities ranged from 10^{-4} cm/s for the sands to 10^{-8} cm/s for the clays. The majority of the contamination resided above the clay layer. Table 4-2 shows the reduction of weighted average TCE levels in the soil during the 56-day demonstration test. This weighted average level was obtained by averaging soil concentrations obtained every 0.9 meters (2 ft) by split spoon sampling methods over the entire 7-meter (24-ft) depth of the wells. The largest reduction in TCE soil concentration, about 95 percent, occurred in Extraction Well 4, which had the highest initial level of contamination. The majority of the soil borings taken after the test gave VOC levels that were not detectable (U.S. EPA 1989a).

The two SVE systems at TCAAP have shown the ability to remove significant quantities of VOC's from the soils. The Site D system removed a total of 49,200 kg (108,460 lb) of solvents between January 1986 and May 1990; and VOC concentrations at Site D decreased generally four orders of magnitude. The pretreatment concentrations of TCE varied widely over the site and ranged from nondetectable up to 7 million μg/kg. Of the 26 post-treatment soil samples collected, only five detected TCE above the detection limit; the highest concentration was 29 μg/kg.

TCAAP Site D soils consist of predominantly silica sand with a porosity ranging from 36.7 to 39 percent and permeabilities ranging between 5.7×10^{-4} and 3.5×10^{-3} cm/s. The soil moisture content ranged from 1.7 to 14 percent. Over the first four months of operation, the mass removal rate ranged from 7 to 16 g/d. After four months of operation, a deep vent was installed, 46 meters (150 ft), and removal rates increased to 24 g/d. At this site, because the soil was silica sand, soil adsorption did not play a significant role; thus, the volatilization phenomenon was the rate controlling factor.

Table 4-2. Reduction of weighted average TCE levels in soil, Groveland Well Site (TCE concentration in mg/kg).

	Pre-treatment	Post-treatment	Percent reduction
Extraction Well			
1	33.98	28.31	13.74
2	3.38	2.36	30.18
3	6.89	6.30	8.56
4	96.10	4.19	95.64
Monitoring Well			
1	1.10	0.34	69.09
2	14.75	8.98	39.12
3	227.31	84.50	62.83
4	0.87	1.05	--

Source: U.S. EPA April 1989

VOC concentration in TCAAP Site G soils and fill materials decreased generally two orders of magnitude. The pretreatment concentrations varied from non-detectables up to 400,000 μg/kg of TCE. Many samples were in the 10,000 to the 100,000 μg/kg range. As of May 17, 1990, an estimated 45,000 kg (100,000 lb) of VOC's had been removed from Site G since remediation began in January 1986. Of the 245 post-treatment soil samples collected, only seven indicated TCE concentrations above the detection limit with the highest concentration being 420 μg/kg (U.S. EPA 1990a).

Initially, the removal rates at Site G showed a sharp decline and a more gradual decline during later operations. Mass removal rates, beginning at approximately 2300 kg/d (5000 lb/d), decreased to 450 kg/d (1000 lb/d) within 14 days. After 76 days, mass removal rates had dropped to approximately 90 kg/d (200 lb/d). They then dropped to 23 kg/d (50 lb/d) after 195 days, and to 0.45 to 4.5 kg/d (1 to 10 lb/d) after 1060 days of SVE operation.

The soil types present in the landfill area (Site G) were heterogeneous and consisted of fill material, construction debris, office trash and industrial waste. As a result, adsorption of contaminants onto landfill material played a more important role in the release of the VOC under SVE application.

4.4.6 Usefulness for Enhancing *In Situ* Biodegradation

Another important mechanism of remediation using SVE is biodegradation which can directly affect the

amount of residual organic contamination remaining in subsurface soil. The increased oxygen levels in the soil gas due to infiltration of atmospheric air can stimulate biological activity. In the case studies which evaluated this effect, the SVE process enhanced *in situ* biodegradation of nonhalogenated materials such as toluene, gasoline, and aviation fuels. In the other case studies, the effect SVE may have had on biodegradation was not evaluated. However, it would be expected that, if microbial populations and sufficient nutrients were present, degradation may have been occurring simultaneously with vaporization. Thus, in recent spills where microbial populations have not had a chance to develop, it is less likely that SVE will stimulate biodegradation than at sites where the contaminants have resided in the subsurface for an extended period of time.

At Hill AFB, it was found that bioactivity was responsible for 13 to 17 percent of the total hydrocarbon removal during the first 70 days of venting. Over the 9 months of operation, a total of 6,800 to 9,000 kg (15,000 to 20,000 lb) were converted by biodegradation. Over the study period, the percent of total hydrocarbon removal attributable to biodegradation remained essentially the same.

Similarly at the two sites associated with The Netherlands case study, biodegradation was used to enhance remediation efforts. At Site 1, under aerobic conditions, toluene and other hydrocarbons were found to biodegrade *in situ* under the conditions provided by the SVE perfusion of air. The rate of biodegradation of toluene, per kilogram of soil, was estimated to be approximately 2 mg C/kg/d (Spuy et al. 1990; U.S. EPA 1990b). At Site 2, *in situ* biodegradation of the less volatile fraction of the gasoline was enhanced by application of the SVE process. It was estimated that, over the first year of operation, approximately 800 kg (1800 lb) of the gasoline constituents in the soil were biologically degraded without the addition of nutrients.

Although halogenated solvents are not as readily biodegradable as nonhalogenated solvents, they still can be broken down in the subsurface environment. No observations of subsurface biological activity were noted, or sought, in the case studies involving halogenated VOC's. Those case studies for which an assessment of *in situ* bioremediation activities associated with SVE applications have been conducted involved nonhalogenated volatile organic contaminants, such as those found in solvents and fuels

4.5 Residuals and Emissions

Air emission problems could be created by using the SVE system if the vapor stream were not treated. In some cases, vapor treatment may not be required for systems that produce a very low emission rate of easily degradable chemicals. The decision to treat

vapor must be made in conjunction with air quality regulators. If vapor treatment systems are required, technologies available for this purpose include liquid/vapor condensers, gas-phase granular activated carbon, incinerators, and catalytic converters.

Liquid/vapor condensers (separators) are generally used for raw material recovery and/or as a pretreatment device for removing VOC contaminants prior to other control devices. For SVE systems, condensers are used to protect blowers and increase the efficiency of the vapor treatment system. Condensers are also used as the primary control device for emission streams with concentrations greater than 5,000 ppm. Variability in VOC concentration will decrease the overall control efficiencies of condensers. Removal efficiencies for condensers are typically less than that for the other three techniques, ranging from about 50 to 80 percent using chilled water. Removal efficiencies approaching 90 percent are possible using subzero refrigerants such as ethylene glycol or freon, but this significantly increases capital and operating costs (U.S. EPA 1989c). The entrained ground water and condensate brought up through the SVE system may have to be treated as a hazardous waste, depending on the types and concentration of the contaminants.

Once entrained or condensed material has been removed from the vapor stream, other treatment techniques can be used to remove the remaining VOC's from the vapor stream. Carbon adsorption is most commonly applied as a pollution control technique and/or for solvent recovery. It can be applied to very dilute mixtures of VOC's but typically performs better with concentrations exceeding 700 ppm. Carbon adsorption units can be designed to achieve efficiencies of 99 percent. Actual efficiencies may be somewhat lower, ranging from 60 to 90 percent, depending upon inlet concentration and factors such as stream temperature, moisture content (relative humidity), and maintenance. Usually, dehumidification is necessary if high humidity (i.e., relative humidity greater than 50 percent) is present. Cooling the stream is usually required if the stream temperature exceeds 65 °C (150 °F). Carbon adsorption can usually handle variable input stream conditions. Removal efficiencies are not affected when flow rates and concentrations vary significantly. Carbon adsorption performs best with compounds having a molecular weight between 50 and 150 g/mol, or organic compounds containing between four to ten carbon atoms.

If air emissions control or vapor treatment is required for an SVE installation, a vapor phase granular activated carbon (GAC) adsorber system probably will be the most practical system, depending on chemical emissions rates and VOC levels. Gas-phase GAC requires heating of the extracted air to control the relative humidity in order to optimize the carbon usage rate. As the fraction of water increases, the capacity for the target chemical decreases and the carbon replace-

ment rate increases. The spent carbon may be considered as a hazardous waste depending on the contaminants (Hutzler, Murphy and Gierke 1988).

Two different methods are used to apply carbon adsorption to SVE systems. One method uses a fixed bed regenerative system allowing reuse of the carbon bed, while the other uses carbon canisters which cannot be reused. Fixed bed systems have higher capital and annualized costs relative to carbon canisters. As such, fixed bed systems are generally used when high gas volumes require treatment, and cleanup duration is extended. Carbon canister systems are generally used for low gas volume extraction processes. (U.S. EPA 1991a).

Since carbon adsorption is a conventional technology for the removal of organics from a vapor stream, little emphasis was placed on evaluating its performance in the case studies. Only when the carbon adsorption systems were found to affect the overall cost of the remediation were they compared, in economic terms, with other vapor treatment systems.

Thermal incineration is widely used to control a variety of emission streams containing VOC's. This treatment is capable of handling a broader range of compounds compared to other techniques. Destruction efficiencies exceeding 99 percent for VOC concentrations above 200 ppm, as well as destruction efficiencies exceeding 95 percent for concentrations as low as 50 ppm, are obtainable. However, this system is not well suited for streams with variable flow rate conditions since this tends to change mixing and residence times from design values, and therefore lowers combustion efficiency. Therefore, the system performs best with relatively constant flow rates and with dilute mixtures of VOC's in the air stream. Supplemental fuel is required to maintain combustion, especially if treating dilute VOC streams. This tends to increase operating costs and makes this technique less desirable (U.S. EPA 1989c).

Catalytic converters are similar to thermal incinerators in design and operation except that they use a catalyst to enhance combustion. The catalyst allows the reaction to take place at lower temperatures, thereby reducing the amount of supplemental fuel necessary relative to thermal incineration. Typical design efficiencies for this technique are usually around 95 percent, although 99 percent is quoted in some cases. Actual efficiencies may be somewhat lower (e.g., 90 percent) depending upon operational and maintenance practices. This technique is not as broadly applicable as thermal incineration because the catalyst is more sensitive to pollutant characteristics and process conditions. In addition, compounds such as halogens (e.g., chlorinated hydrocarbons), lead, mercury, tin, zinc, and phosphorous may damage the catalyst and severely affect performance. Therefore catalytic converters are not usually selected as a VOC

control system when metals and/or halogenated contaminants are present. This method is usually chosen for nonhalogenated compounds over thermal incineration for SVE sites because of lower operating costs (U.S. EPA 1989c).

In two of the case studies, catalytic oxidation was used to destroy the organics present in the extracted vapors. At the Hill AFB demonstration, during the 9-10 month operation of the SVE system, 95 percent of the vapors extracted were passed through one of two catalytic oxidation units. The first unit was a 14 m^3/min (500 ft^3/min) fluidized bed unit that operated for eight months. The second was a 28 m^3/min (1000 ft^3/min) fixed bed unit that used a precious metal catalyst and was operated for six months. There was a period of four months when the two units operated together to treat the venting off-gases. The fixed bed was operated between 240 and 330 °C (470° and 625 °F) while the fluidized bed unit was operated between 330 and 370 °C (625 and 700 °F).

Results showed that the fluidized bed unit had an average 89 percent destruction efficiency and the fixed bed unit had a 97 percent destruction efficiency. In this study, it was found that the fixed bed system could not handle the large flow rate of highly concentrated VOC's. Because the process is one of oxidation or burning of the contaminants, the heat released in the process caused the fixed beds to get so hot that the end of the bed would melt. Temperature safety controls can be used to prevent this from happening. However, such controls limit the amount of contaminant that can be treated. Because of better heat transfer, the fluidized bed unit can handle the higher concentration flow rates. Its disadvantage is that the system needs a catalyst. At the Hill AFB site, approximately 70 kg (150 lb) of catalyst were added to the reactor over the eight month operation.

The Air Force, at Eglin AFB in Florida, conducted a pilot-scale catalytic oxidation unit test on fuel contaminants which had been air stripped from ground water. The unit used an electric preheater to raise the inlet gas temperature to 540 °C (1000 °F) before passing it through a precious metal fixed bed catalyst reaction chamber. Although this technology resulted in on-site destruction of the organic contaminants, hydrogen sulfide that was stripped out of the water caused a chemical reaction in the catalytic oxidation unit which effectively and rapidly deactivated the catalyst (U.S. EPA November 1990). This illustrates the need for a good understanding of the chemical constituents comprising the vapor stream and for assessing the impact of those constituents on the catalyst.

Catalytic oxidation was also used at the Verona Well site when activated carbon costs became excessive. From March 1988 to January 1990, the VOC contaminants were removed from the vapor stream by

activated carbon adsorption. At that time, the carbon vapor extraction treatment system was replaced by an on-site catalytic oxidation technology for cost reasons. (Carbon adsorption costs were three times as great as that for catalytic oxidation.) Of the VOC's present in the vapor stream, TCE proved to be the hardest to destroy by this technology and therefore was used as the indicator of destruction efficiency. At 415 °C (780 °F), average TCE discharge concentrations of 204 ppb were found in the stack emissions--this is about 60 percent of the discharge limit. At 446 °C (835 °F), the level of TCE dropped to 35 ppb. As a result of these findings, the catalytic oxidation system was operated at 427 °C (800 °F) without any difficulties.

In summary, vapor phase activated carbon was used for extraction systems where there was a low volume of gas extracted and remediation time was expected to be short. Limited data indicated removal efficiencies of 90 to 99 percent. Costs for activated carbon systems used to treat air streams with high VOC concentrations were found to be excessive. The major cost factor attributable to the high costs was associated with regeneration. In such cases, catalytic oxidation, an alternative to vapor-phase activated carbon, was found to be a more cost effective vapor treatment technique. In particular, at the Verona Well Field site, it was shown that catalytic combustion of off gases could reduce the emissions to below 100 ppb (the allowable discharge level) at approximately one third the cost.

As noted previously, other residuals produced can include aqueous waste streams from liquid/vapor separators and ground water extracted to lower the water table. Conventional treatment techniques including biological treatment and/or activated carbon can be used to treat these waste streams. At The Netherlands Site 2, however, these aqueous waste streams were treated with the vapor stream in a common biological treatment system.

In this single treatment process (referred to as a biological purification system), the gasoline vapor with an organic loading of approximately 210 g/h was treated along with extracted ground water which had an organic load of approximately 8 g/h (15 m^3/h at 0.5 g/m^3) (U.S. EPA 1990b).

4.6 Factors to Consider for Determining Applicability of the Technology

One must "realize that there are practical limitations on the final soil contamination levels that can be achieved with soil venting systems. Knowledge of these limits is necessary to realistically set cleanup criteria and design effective venting systems. Maximum efficiency of a venting operation is limited by the equilibrium partitioning of contaminants between the soil matrix and vapor phases. The maximum removal rate is achieved when the vapor being removed from an extraction well is in equilibrium with the contaminated soil" (Johnson et al. 1990). Models for predicting this maximum removal rate have been presented by Marley and Hoag (1984) and Johnson et al. (1988). The former considered only compositions in a residual free-phase, while the latter also considered the effects of sorption and dissolution processes (Johnson et al. 1990).

Venting also presents the possibility of inducing migration of off-site contaminant vapors toward the extraction wells. If this occurs, the scope, cost and time for remediation can be significantly impacted, due to the influx of these off-site contaminant vapors. A possible solution to this problem is to install a vapor barrier, using vents, at the perimeter of the contaminated zone. Alternatively, by allowing vapor flow into the perimeter ground water monitoring wells, a vapor barrier would be formed to block the migration of these off-site contaminants. In some situations it may be necessary to install passive air injection wells, or trenches (Figure 4-2a) (Johnson et al. 1990).

Application of vacuum extraction systems may also cause a water table rise. When contaminated soils lie just above the water table, they can become saturated by the rise in the water table. Where the water table rise equals the vacuum (that point expressed as an equivalent water column height, i.e., in mm H2O) the maximum rise occurs. The recommended solution is to install a dewatering system, with ground water pumping wells located as close to the vapor extraction wells as possible. The dewatering system must be designed to ensure that contaminated soils remain exposed to vapor flow (Figure 4-2b) (Johnson et al. 1990).

Uncertainties which appear to limit SVE include lack of precise information on site heterogeneities and contaminant location; inability to predict cleanup schedules; and uncertainty regarding the ability of the technology to achieve cleanup goals. These areas of uncertainty must be recognized when conducting treatability tests, pilot testing, when performing detailed analysis of alternatives, and when implementing the technology for site remediation (U.S. EPA 1991b). Figure 4-3 (Johnson et al. 1990) provides a guideline for deciding if a soil vacuum extraction process is applicable to a particular site.

Table 4-3 summarizes the factors that limit SVE application. It discusses reasons for the potential limitations, presents the data collection requirements that identify these limitations, and indicates at which phase of the technology selection process it becomes important. In the United States, this process consists of:

- A prescreening phase, where all possible appropriate technologies for the given contaminants are identified
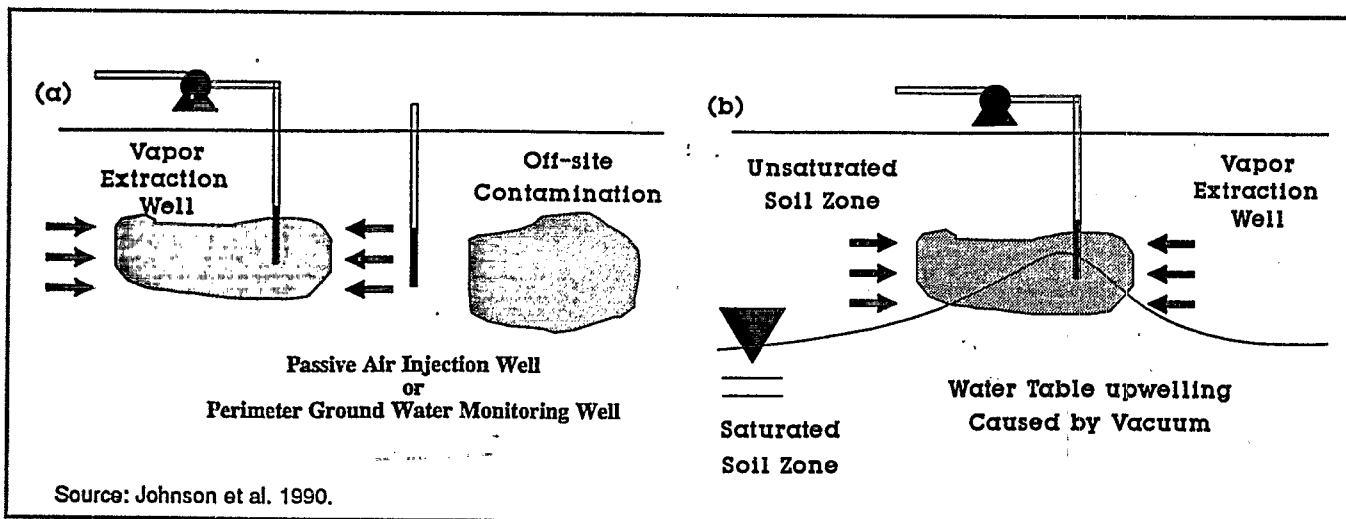
Figure 4-2. Two types of soil venting systems. (a) Use of passive vapor wells to prevent migration of off-site contaminant vapors. (b) Water table rise caused by the applied vacuum.

- A remedy screening phase, where the number of technologies considered is reduced to a manageable number based on site-specific conditions

- A remedy selection phase, where the remaining viable technologies are evaluated for technical and economic merits to permit technology selection

- A remedy design phase, which involves those treatability studies and design activities needed to permit the construction of the facilities.

Some requirements apply before the prescreening phase is initiated. These consist of the compilation of data from literature and data base sources, and from site-specific assessments, investigations, and characterizations. (See related discussion in the chapter below on selecting remedies at a complex hazardous wsate site.)

4.7 Costs

Treatment costs for sites depend on various conditions such as:

- Site size, and extent of contamination
- Regulatory requirements for permits, and operation
- Site-specific and chemical-specific conditions
- Site cleanup criteria.

Therefore, costs should be estimated on a case-by-case basis.

Treatability data collected can be very useful in generating cost estimates. These estimates will be more precise when they are based on pilot-scale data. Table 4-4 relates data collected during treatability

studies to the major components affecting SVE costs. The cost of pumping which is associated with the number of wells, can be significant. Instrumentation, and analytical costs for monitoring the process will also affect system costs (U.S. EPA 1991a).

In general, a cost analysis addresses both capital costs, and operating and maintenance costs. Capital costs include both depreciable and nondepreciable cost elements. Depreciable costs include direct costs for site development, capital equipment, and equipment installation. Indirect costs include:

- Engineering services prior to construction
- Administrative tasks, such as permitting
- Construction overhead and fee
- Contingencies.

Nondepreciable costs include those direct costs associated with purchased engineering and technical services for the development of operating procedures manuals and operator training, etc. (U.S. EPA 1989a).

Operating and maintenance costs include variable, semivariable, and fixed cost elements. Variable operating cost elements include utilities and residual/water disposal costs. Semivariable costs include unit labor and maintenance costs, and laboratory analyses. Fixed costs include depreciation, insurance, and taxes (U.S. EPA 1989a).

An economic model for the Terra Vac vacuum extraction system at the Groveland Well site is presented in Table 4-5. This model illustrates the relative distribution of capital, operating and maintenance and fixed costs and the major elements of each. The costs presented are based on the transportable skid-mounted unit that may not be permanently installed at the site.

44
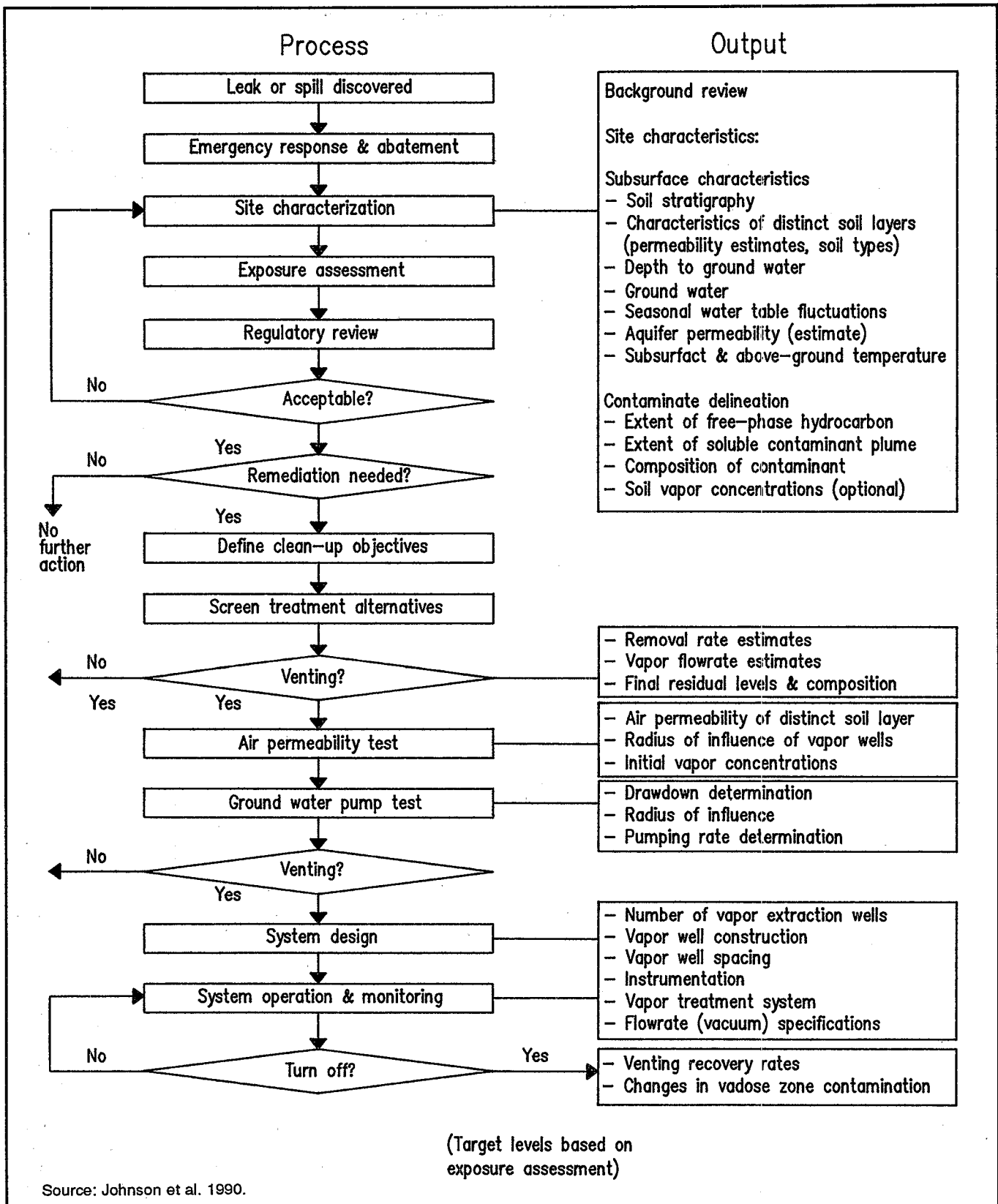
Figure 4-3. Guidelines for deciding if SVE is applicable.

Table 4-3. Characteristics limiting SVE feasibility - contaminant, soil, and site characteristics.

	Reason for limiting application	Data collection requirements	Application of data
CONTAMINANTS			
Low volatility (vapor pressure)	Indicative of low potential for contaminant volatilization	Contaminant identification	Remedy screening
High density, high water solubility	Tendency to migrate to saturated zone which is less efficient for SVE	Contaminant identification	Remedy screening
SOIL			
Low air permeability	Hinders movement of air through soil matrix	Field air permeability test	Remedy selection
High humic content	Inhibits volatilization, high sorption of VOCs, need for column test verification	Analysis for organic matter	Remedy screening
High moisture content	Hinders movement of air through soil and is a sink for dissolved VOC's. May require consideration of water table depression	Analysis of soil moisture content	All phases
Low temperature	Lowers contaminants' vapor pressures	Soil temperature	All phases
High clay content	Loss of structural support through the drying of clay	Shrinkage limit tests	Remedy screening
	Hinders movement of air through soil; need for field permeability tests	Field air permeability, moisture content	Remedy selection
pH	Material selection		Remedy design, remedy selection
Low porosity	Hinders movement of air through soil; need for field air permeability tests	Porosity (calculated) specific gravity, bulk density	All phases
SITE			
Distribution and quantity of contaminants	May not be cost effective; will require overall definition of contamination and potential NAPL* pools; need pilot-scale verification	Soil mapping, soil gas survey, site characterization	Remedy selection
Variable soil conditions/characteristics	Inconsistent removal rates "short circuiting" or bypassing contaminated zones	Soil mapping and characterization (type, particle size, porosity)	Remedy screening
Stratigraphy, heterogeneity	Affects well design and placement, and SVE design; need field air permeability tests and/or pilot-scale verification	Field air permeability (distribution) tests	Remedy selection
Buried debris	Inconsistent removal rates; need field air permeability and/or pilot-scale verification	Site history, geophysical testing	Remedy screening

*Non-aqueous phase liquids

Source: U.S. EPA March 1, 1991

To provide an indication of SVE project costs, three examples from the case studies cited are presented. Table 4-6 identifies the costs for the Verona Well Field Site work in Michigan. These costs indicate the overall costs for various aspects of the project. Of interest is the comparison of the activated carbon vapor treatment system, which was initially installed, to the catalytic oxidation process which later replaced the ac-

Table 4-4. Factors affecting SVE treatment costs.

Component affected	Factors governing component selection	Data required
Number of extraction wells	Radius of influence	Pressure profile from air permeability and pilot tests; mathematical model to optimize selection[1]
	Extent of contamination	Contaminant distribution
Passive wells (inlet) and air injection wells	Air flow distribution	Air permeability tests; pilot tests, number of vapor extraction wells
Depth of wells	Depth to impermeable layer	Depth to bedrock[2]; depth to water table
Vacuum pump or blower	Vacuum level and air flow rate	Air permeability tests, pilot tests, number of vapor extraction wells
Vapor/liquid separator	Liquid (water) removal rates	Moisture content, vapor flow rates (oversized mist eliminator recommended)
Surface seals	Air flow distributions	Air permeability tests, pilot tests, mathematical modeling of air flow patterns
	Surface water infiltration	Rainfall, permeability for surface soils
Water table depression pumps	Depth to water table	Depth to water table
	Water infiltration rates	Site hydrological behavior
Off-gas treatment	Contaminant removal rates, contaminant identities, moisture content after vapor/liquid separation	Air permeability tests, pilot tests; moisture content during pilot tests
Liquid (water) treatment	Site water removal rates	Site hydrological behavior, moisture content in off-gas, contaminant concentrations in water
Operating costs	Size of SVE system, cleanup time, analytical costs, and residuals disposal costs	All of the above plus cleanup time predictions based upon mathematical modeling and prior experience

[1]In general, specify more wells than predicted by the mathematical model as optimum because of uncertainties in the contaminant location and subsurface conditions.

[2]On some sites, SVE may be the only available technology for application to fractured bedrock. These wells will be much more costly than wells bored into soils.

Source: U.S. EPA March 1, 1991

tivated carbon system for vapor treatment (McCann 1990).

Construction and operating cost summaries for the TCAAP case study (Site D and G) are presented in Tables 4-7 and 4-8, respectively. Remediation of Site D soils have been estimated at US$451,000 or US$22/m^3 (US$17/yd^3) soil. Air emission controls were not required for the Site D system. Site G soils have been treated at an estimated cost of US$969,000 or US$17/m^3 (US$13/yd^3) soil.

To provide general assistance in developing a rough SVE cost estimate, Table 4-9 presents capital, and operating and maintenance costs for each of the SVE system components over typical operating size ranges. Capital and certain operating costs may be approximated by determining the system size and multiplying unit size estimates by the values given in the table (U.S. EPA 1991a). It also presents costs for polyvinyl chloride (PVC) and stainless steel (SS) materials of construction for extraction well construction. The compatibility of the contaminant and other soil chemical characteristics with the well and piping materials needs to be assessed before system construction. For example, stainless steel will not perform well under very corrosive or high chloride conditions. Similarly, PVC may be attacked by certain organic compounds. The surest way to establish the appropriate materials of construction is to consult vendors of these products. It should be noted that vapor/liquid separators have been included as an in-

Table 4-5. Terra Vac economic model (in US$, 1989).

Cost components	$/tonnes
Site preparation	3.12
Permitting and regulatory	--
Equipment Contingency (10% of direct costs)	.31
Startup and fixed cost Operations procedures/training Mobilization and shakedown Depreciation (10% of direct costs) Insurance and taxes (10% of direct costs)	.44 .92 .31 .31
Labor costs	3.05
Supplies - Raw materials	--
Supplies - Utilities Electricity	.44
Effluent treatment	14.14
Residual disposal	8.27
Analytical During operation Pretest and posttest analyses	1.59 18.36
Facility modifications (10% of direct costs)	.31
Site demobilization	.36
TOTAL	51.93

*Based on equipment capital cost of $50,000 for treating approximately 5,440 tonnes of contaminated soil. Does not include profit for the contractor.

Source: U.S. EPA July 1989

Table 4-6. Verona Well Field SVE costs (in US$, 1990).

COST COMPONENTS	
Design of pilot-scale unit, full-scale construction, and startup	$500,000
Carbon adsorption system and total cost of carbon	$610,000
Catalytic oxidation system	$187,000
Operations including utilities, process monitoring and maintenance	$305,000
UNIT COSTS	
Cleanup of contaminated soil	$30/m³
Cleanup of contaminants	$79/kg

Source: Personal communication

tegral part of the SVE system. However, vapor treatment processes which are dependent on the contaminants and concentrations are not included.

4.8 Future Status of Case Study Processes and the SVE Technology as a Whole

At the Dayton site and the two sites in the Twin Cities Army Ammunitions Plant case study, SVE remediation has been completed; at the Verona Wells, Hill AFB and the Groveland sites, remediation continues.

Future technology applications seems highly promising as the process has several advantages. Soil vapor extraction can be effectively used for removing a wide range of volatile chemicals under a wide range of conditions. The process can be part of a remediation effort and used along with other treatment processes. Air injection has the advantage of controlling air movement, but injection systems need to be carefully designed. Volatile chemicals can be extracted from clays and silts but at a slower rate. Intermittent operation is more efficient under these conditions. The intermittent blower operation is probably more efficient in terms of removing the most chemical with the least energy. The design and operation of these systems can be flexible enough to allow for rapid changes in operation, thus, optimizing the removal of chemicals. Equipment used for SVE systems is readily available and easy to operate. To protect down stream air pollution control equipment, air/water separators should probably be installed in every system. Such devices are inexpensive and easy to construct.

As with any *in situ* process, it is usually impossible to do a complete materials balance on a given site because most sites have an unknown amount of VOC's in the soil and in the ground water. As a result, it is difficult to establish when the cleanup has been completed. To determine if contaminants are continuing to vaporize, SVE processes could be operated on an intermittent basis for a period of time after the VOC concentrations in the extracted vapors have approached zero. This technique can help to limit the soil boring and ground water data on residual contamination required to demonstrate that cleanup objectives have been attained. Although many aspects of the SVE technology are understood, additional information which would be of assistance to engineers and operations personnel needs to be developed. Documentation of case studies where difficulties resulting from the misapplication of the technology or operating problems would be useful. All too often, only success stories are documented. However, failures or marginal successes can provide more insights into factors which need to be considered in other applications. These can be particularly useful when a thorough investigation/ as-

Table 4-7. TCAAP Site D — Estimated construction and operating costs (in US$).

Description	Units	Cost/Unit ($)	Cost ($)	Total ($)
CAPITAL				
System installation			257,000	
Subtotal				257,000
OPERATIONS AND MAINTENANCE[2]				
Labor[3]				
Professional labor	1000 hours	50/h	50,000	
Craft labor	1500 hours	30/h	45,000	
Subtotal				95,000
Operations				
Electricity	1,770,000 kWh	0.04/kWh	71,000	
System monitoring	160 samples	175/sample	28,000	
Subtotal				99,000
TOTAL				451,000

[1]Cost information supplied by TCAAP (U.S. EPA July 1990). Does not include design, construction supervision, vent sampling, or safety monitoring.
[2]Total over operating period (February 86-May 90).
[3]Estimated as 70 percent of Site G information (see Table 4-8).

sessment of the failure identifies the cause(s) of that failure.

It is known that temperature affects the volatility of organic compounds and therefore the efficiency of the SVE process. Under what conditions and for what contaminants would it be cost effective to consider technologies such as RF heating to increase the soil temperature in order to extract organic contaminants or speed remediation? Would heated air injection serve the same purpose, and what effect would it have on extraction rates? How would implementation of such techniques change the overall efficiency of the process for different soil types?

Table 4-8. TCAAP Site G — Estimated construction and operating costs (in US$).

Description	Units	Cost/Unit ($)	Cost ($)	Total ($)
CAPITAL				
System installation			257,000	
Vapor treatment system			213,000	
Subtotal				470,000
OPERATIONS AND MAINTENANCE[2]				
Labor				
Professional Labor	1400 hours	50/h	70,000	
Craft labor	2200 hours	30/h	66,000	
Subtotal				136,000
Operations				
Electricity	2,400,000 kWh	0.04/kWh	96,000	
System monitoring	180 samples	210/sample	38,000	
Carbon changeouts	16 changes	14,300/change	229,000	
Subtotal				363,000
TOTAL				969,000

[1]Cost information supplied by TCAAP (U.S. EPA July 1990). Does not include design, construction supervision, vent sampling, or safety monitoring.
[2]Total over operating period (February 86-May 90).

Table 4-9. Capital cost estimation of SVE components (in US$, 1990).

Component	Capital		
	PVC[1]	304 SS[2]	Other
Extraction Well Construction			
Drilling			$2,000 to $5,000/well
Casing			
5 cm	$7-$10/m	$39-$46/m	
10 cm	$10-$16/m	$75-$82/m	
15 cm	$23-$29/m	$118-$131/m	
Screen			
5 cm	$7-$13/m	$49-$56/m	
10 cm	$16-$23/m	$89-$102/m	
15 cm	$33-$49/m	$134-$151/m	
Sand or gravel			$20-46/m^3
Piping			
5 cm	$3-$7/m	$31-$36/m	
10 cm	$7-$13/m	$72-$82/m	
15 cm	$20-$33/m	$111-$125/m	
20 cm	$39-$52/m	$171-$180/m	
Valves (ball)			
5 cm	$60	$1,000	
10 cm	$150	$2,000-$2,200	
15 cm	$700	$3,200	
20 cm	$1,300	$5,000	
Joints (elbow)			
5 cm	$11	$20	
10 cm	$50	$52	
15 cm	$100	$300	
20 cm	$460	$560	
Water table depression pumps (45-95 gpm)			$3,700
Surface seals			$99/m^2
Bentonite			$2.70/m^2
Polyethylene (.254 mm)			$6/m^2
HDPE			$6/m^2
Asphalt			
Blower (rotary or ring)			
0-28 dNm^3/min			$5,000 to $25,000
8-14 dNm^3/min			$13,000
28 dNm^3/min			$40,000
Vapor/liquid separators (3,800 L to 7,600 L)			$3,500 to $17,500
Instrumentation			$50-$75
Vacuum gauge			$300
Flow (Annubar)			$20-$30
Sampling port			$20,000 (if purchased; usually rented)
Gas chromatograph/FID			

[1]Polyvinyl chloride
[2]Stainless steel

Source: U.S. EPA March 1, 1991

At this time, SVE systems are often designed with flexibility so that changes can be made during remediation. Although such system flexibility is desirable, it also can increase costs. Since there have been numerous installations of the SVE system under a wide range of site, soil and contaminant conditions; it appears that an analysis of these applications could provide useful information to design engineers as well as operating personnel. Johnson et al. (1990) have supplied a beginning for the development of such guidelines. This needs to be expanded to reflect "lessons learned" from SVE applications. For example, operating criteria need to be established outlining those conditions when a system should be operated in the intermittent extraction mode rather than a continuous extraction mode.

Little attention has been paid to the effect of naturally occurring organics on extraction rates or the ultimate removal efficiencies. Since such soil components can adsorb organic contaminants, to what extent do they reduce the effectiveness of the process?

It has been found that SVE can be used to enhance *in situ* biodegradation of a number of nonhalogenated VOC's and other semivolatile compounds in subsurface soil. Similar information is needed for a wider range of organics and site conditions. And more work is needed to examine SVE and bioremediation as a process rather than looking at each technology individually.

Since buildings and other interferences can be found at many sites where VOC contamination occurs, it is likely that it will be necessary to remediate contaminated soils near these structures. What special techniques (e.g., horizontal drilling) could be used under these conditions? Would using SVE result in transporting vapors into the building or could they be vented away? Additionally, at the Dayton, Ohio fire site, it was found that VOC vapor could be transported through concrete. Is asphalt similarly affected? The answers to these questions would be useful in determining what cap configurations and construction materials should be used.

Other technical issues that need to be resolved include the effectiveness of forced or passive vapor injection wells; other means of controlling vapor flow paths; well-documented demonstrations for removing contaminants from low-permeability soils; the possibility of decreasing residual contaminant levels in water-saturated zones by air sparging/vapor extraction; and optimal operation schemes for multiple vapor extraction well systems (U.S. EPA 1991a).

Alternative treatment methods for off-gasses provides another area for future investigations. For example, an Advanced Oxidation Process is being studied for the destruction of VOC's in air; this work is being conducted at the Lawrence Livermore National Laboratory under U.S. EPA Superfund Innovative Technology Evaluation (SITE) program. The destruction mechanism is based on photolytic oxidation of contaminants using a newly developed ultraviolet (UV) light source, consisting of a pulsed-plasma xenon flashlamp that generates extremely intense UV emissions. These UV emissions are better suited for organic contaminant destruction than conventional mercury-based UV lamps because the photon flux is shorter in wavelength and higher in intensity. Preliminary experimental results indicate that the proposed UV flashlamp treatment scheme will yield high VOC destruction rates. This process can be coupled to the gas venting system and creates no secondary waste stream.

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Physical/Chemical Extraction Technologies

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ABSTRACT

Six case studies, covering a broad spectrum of techniques, were chosen for this NATO/CCMS Pilot Study: *ex situ* extraction (two case studies); *in situ* acid extraction (one case study); *in situ* jet cutting followed by oxidation (one case study); electro-reclamation (one case study); and debris washing (one case study).

The *ex situ* extraction techniques (Klöckner and Harbauer) mainly differ in scrubber technology and the combination of particle separation techniques. The two techniques clean the soil mainly through removal of the heavily contaminated fines from the soil. Their best result is generally obtained for sandy soils. Both techniques are available on a commercial scale.

The applicability of *in situ* extraction techniques in general, where removal of the heavily contaminated fine particles is not possible, is limited to sandy soils. The *in situ* acid extraction technique (TAUW/Mourik) is applicable for sand only. The site contained cadmium pollution and was ideally suited for the technique (sandy soil, low adsorptive capacity, homogeneous). The cleaning results were better than expected; the results are considered an ideal case. The technique is available on a full scale.

The *in situ* jet cutting technique (Keller) is capable of removing contaminated soil with the simultaneous replacement of clean stabilized soil. This makes the technique in principle applicable for cleanup activities underneath buildings. The oxidation was applied on the easily oxidizable contaminants (e.g., phenols) in the removed soil. The technique is available on a pilot scale.

In situ electro-reclamation (Geokinetics) is a new technique for heavy metals removal. Whereas the other techniques are applicable to sandy soils, electro-reclamation can be applied to clean clayey soils contaminated with heavy metals. At present no other technique exists for heavy metals removal from clayey soils. The technique uses the flow of water which is induced by applying an electrical field to the soil, but the removal mechanism is not yet fully understood. A full-scale system is operable. Promising results have been obtained with cleanup of soil and sludge contaminated with copper, zinc, lead, and arsenic.

5.1 Introduction

5.1.1 Place of the Techniques in a Broad Sense

This chapter concentrates on *ex situ* and *in situ* extraction, *in situ* jet cutting followed by oxidation, and *in situ* electro-reclamation. These techniques were submitted as case studies to the NATO/CCMS Pilot Study.

The case study techniques belong to a group generally referred to as physical-chemical treatment techniques. They aim at removal or destruction of contaminants and are generally executed in an aqueous environment. Examples of other techniques in this group are: particle separation techniques, flotation techniques, and reduction and dechlorination techniques.

Ex situ extraction, as presently applied in soil cleaning, mainly refers to a combination of particle separation techniques and dissolution and dispersion in an

aqueous environment. This chapter only deals with aqueous extraction agents. The use of organic solvents to, for instance, extract PCB's from soils and sediments, is in development and approaching commercial scale. When organic solvents are used, the technique is referred to as solvent extraction. Solvent extraction is not discussed in this section.

The term "extraction" was adopted in the early stages of development, beginning in the 1980's, because it was believed that contaminants could easily be extracted from the soil. At present we know that, because contaminants are heavily adsorbed onto the fines (particles smaller than 63 m), the cleaning in these installations is mainly due to the separation of these heavily contaminated fines from the bulk of the soil. Therefore the term "classification" techniques would have been more appropriate.

In situ extraction has been applied to a limited extent, because separation of heavily contaminated fines is not possible. It is, therefore, limited to those cases where the soil does not contain adsorptive materials. The case study described in this chapter is an example of such an ideal site.

In situ jet cutting followed by oxidation is a rather unique case study in that the soil is removed by jet cutting as opposed to being excavated, and backfilled after treatment. In the case study described in this chapter, no particle separation techniques were applied. The easily oxidizable contaminants were ideal for applying this technique. It may, therefore, be considered a best case example.

Electro-reclamation has very recently been introduced in the field of soil treatment. Little experience with this technique has been gained so far. The technique applies an electrical field to the soil. It either creates an electrical driving force for the contaminants themselves, called electro-phoresis, or it induces water flow, called electro-osmosis, in which dissolved contaminants may be entrained. This technique is especially suitable for removal of heavy metals from clayey soils. There are presently no other techniques available for these "difficult" soils.

5.1.2 Principle of Extraction Techniques

The basic processes in extraction installations consist of (1) pre-screening of the soil, (2) mixing with an extracting agent, (3) fluid-solids separation, (4) treatment of the cleaned soil, and (5) water purification and sludge treatment. (See Figure 5-1.)

Extraction installations may incorporate a variety of other techniques besides the actual extraction. In general, particle separation techniques (separation on size and/or density), chemical treatment (mainly oxidation), and flotation techniques are integral components of extraction installations. In principle the same process scheme will be applied for the oxidation technique, but without significant separation of the fines
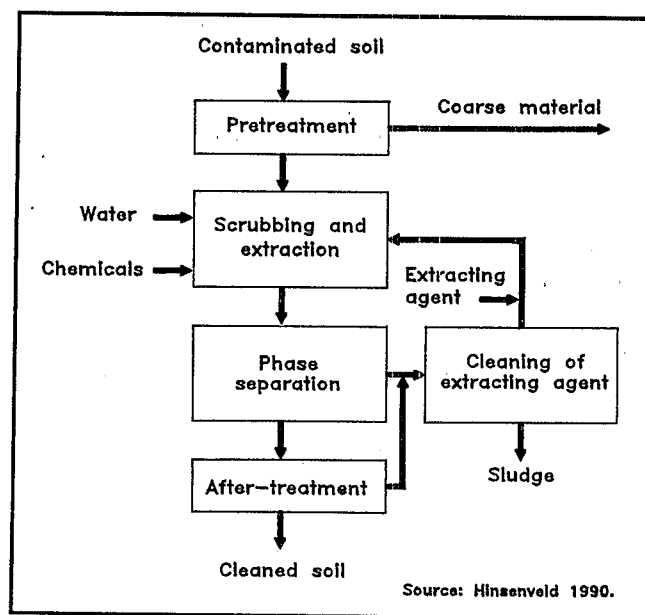
Figure 5-1. The basic processes in extraction installations.

and with the water purification step consisting of oxidation only.

Flotation techniques in the present extraction installations are only used to clean the process water, but they may also be used to clean soil. This latter application, however, requires special knowledge, so that only a few firms have specialized in this (very powerful) technique. Most firms using extractive methods do not have the required knowledge for this application. Flotation as a soil cleaning technique is available on full scale in The Netherlands, but is not referred to in this chapter.

Most of the cleaning efficiency in extraction installations, in general, is from the removal (separation) of the heavily contaminated fines from the soil. The chemicals added in the scrubber, mostly NaOH and some soaps, mainly serve as dispersing agents to keep these fine particles in suspension.

The process of extraction-classification can economically be applied to soils with a combined fines and organic matter content of less than about 30 percent. There is a simple reason for this limitation: fines are difficult to dewater and lead to huge amounts of sludge. For example: one tonne of soil containing 30 percent fines leads to about 0.6 tonne of contaminated sludge (compared to the original soil, the water content of the fines is roughly doubled) and 0.7 tonne of clean soil; the waste stream has been reduced by only 40 percent. In exceptional cases, the contaminants contained in the fines may be destroyed by oxidation or other techniques. In that case there is no limitation on the amount of fines. In general, however, part of the fines will consist of organic matter, and removal of the

fines prior to oxidative treatment will largely reduce the amount of oxidants to be used for destruction of the contaminants.

It will be clear from the above that the applicability of *in situ* extraction techniques is quite limited because removal of heavily contaminated fine particles is often not possible.

5.1.3 Principle of Electro-reclamation

Electro-reclamation is a rather new technique for heavy metals removal from soils *in situ*. The principle of the movement of water, charged particles, and ions in a saturated porous medium when subjected to an electrical field is well known. The principles of electrophoresis and electrolysis are widely used in analytical measurements; the movement of water is utilized in practice and includes dewatering and con- solidation of soils in foundation engineering (Casagrande 1983). The technique has also been used for desalting agricultural land. The possibilities and limitations in environmental applications, however, are still a subject of research.

Researchers do not quite agree on whether the primary removal mechanism for the heavy metals from soil is electro-osmosis, electrophoresis, electrolysis, or a combination of mechanisms. The removal efficiency can possibly be improved by using acoustic waves in addition to the electrical field - a technique known to enhance dewatering of sludges or leaching of waste (U.S. EPA 1990) - or by the addition of acid (Lageman et al. 1990). Oxidation and reduction reactions in- duced by the electrical field are also a subject of study.

Electrochemical studies have shown that an acid front is generated at the anode, migrating in time from the anode towards the cathode (U.S. EPA 1990). Metallic electrodes as well as metallic objects (e.g., drums and pipes) in the soil will either corrode and thus interfere with the removal of heavy metals or be coated with metals. Therefore, graphite electrodes are often used in the field and metallic objects should be removed prior to treatment.

In general the flow of water will be directed from the anode to the cathode due to the net positive charge of the solute. Depending on this charge, the complexes will either move to the cathode or to the anode. Water flowing towards the cathode is pumped off, together with the dissolved ions. A solution of HCl or NaCl is infiltrated at the anode to replace the removed ions, preventing an equilibrium from establishing. Promis- ing results have been obtained when cleaning up soils and sludges contaminated with heavy metals like Cu, Zn, Pb, and As. In principle, the technique is applicable for most types of soil, but is particularly applicable to cleaning clayey soils. For cleaning very permeable and sandy soils, a conventional *in situ* extraction might be cheaper. The technique also shows possibilities for cleaning soils and sludges in storage facilities.

5.2 Case Studies Chosen

The five case studies chosen for this pilot study cover a broad spectrum of techniques:

- *Ex situ* extraction (two case studies)
- Oxidation (one case study)
- *In situ* extraction (one case study)
- Electro-reclamation (one case study).

In this section, a brief description of each of the case studies will be given.

5.2.1 Case Study 5-A: High Pressure Soil Washing (Klöckner), Germany

The high pressure soil washing system was developed in The Netherlands by BSN in the middle 1980's and adapted by Klöckner to German specifica- tions. The installation has a commercial scale of about 13 to 36 tonne/h. A description is given in Appendix 5-A. The most characteristic aspect of the process is the use of a high pressure water jet to scrub the soil particles. Nozzle pressures of up to 350 bar can be applied. Pretreatment of the soil is purely mechanical, consisting of sieving the rubble fraction (lumps greater than 6 cm) on a coarse screen. The fraction smaller than 6 cm is fed to the high pressure water jet in which the aggregated particles are disintegrated. The process was selected in the NATO/CCMS Pilot Study for a number of reasons. Firstly, because of its simplicity: pretreatment is simple and no chemicals are added. Secondly, because of its large scale and the experience built up over the past 5 years. Up to the present, some 300,000 tonnnes of contaminated soil have been treated with this and the following installa- tion. The installation can be purchased and is fully commercial. Thirdly, the process can be used to treat soils contaminated with a combination of volatile or- ganic contaminants (which are stripped out of the soil by the air entrained in the water jet) and heavy metals. Volatile components are not removed in extraction in- stallations that do not apply high pressure.

5.2.2 Case Study 5-B: Vibration (Harbauer), Germany

This case study, reported in Appendix 5-B, involves the cleaning of soils contaminated with oil residuals. The primary characteristic of this process is the use of a mechanical vibration scrubbing system. The case study was chosen for a number of reasons; the most important was its claim of being able to clean the soil down to a particle size of 0.015 mm (usually conven- tional extraction installations can go down to about 0.050 mm). This low cut off size leads to a strong reduction in the amount of sludge produced. The ven- dor claims that the exceptionally low particle size of 0.015 mm can be reached by a combination of a wide

variety of particle separation techniques. The installation has a commercial scale.

5.2.3 Case Study 5-C: Jet Cutting Followed by Oxidation (Keller), Germany

This case study describes the oxidation of soil contaminated with phenols and cresols. The soil is removed from the underground by a cutting water jet and simultaneously replaced by clean soil. The actual cleaning is done *ex situ*. Originally the technique was used for stabilizing the underground for foundation purposes, but it has been adapted for treating contaminated soils. The contaminated soil that is brought up by the water jet could be cleaned by a number of wet techniques, but the company involved has no experience in doing so and chose to use a simple oxidation technique. The study was selected for the NATO/CCMS Pilot Study because of the possibility of applying a wet cleaning technique for soils underneath buildings without the need of tearing these buildings down. In this respect it could be classified as an *in situ* technique. The technique is also interesting because, by using only an oxidation technique without any separation techniques, no sludge is produced.

5.2.4 Case Study 5-D: Electro-reclamation (Geokinetics), The Netherlands

This case study describes the use of an electrical field to remove heavy metals from clay soils. The study is reported in Appendix 5-D, including an excellent description of the principle of the technique. The site studied in this case was contaminated with arsenic caused by a former timber preservation impregnating plant. Field experiments have been conducted by a number of researchers, but problems at the electrodes occurred. Geokinetics claims to have mastered this problem. The case study was chosen because of the application of this new technique which can be applied *in situ* to remediate clayey soils contaminated with heavy metals. For these soils, no alternative technique is presently available.

5.2.5 Case Study 5-E: *In Situ* Acid Extraction (TAUW/Mourik), The Netherlands

This case study, the results of which are described in Appendix 5-E, deals with the *in situ* cleaning of a sandy soil contaminated with cadmium. The cadmium contamination, caused by a photographic paper factory, was bleached into the soil in a liquid form. This case study was chosen because the problem studied here represents a best case for *in situ* extraction: a very mobile contaminant in a permeable soil having low adsorptive capacity.

5.2.6 Case Study 5-F: Debris Washing, United States

This technology applies to the decontamination of metallic debris, such as transformer casings, drums, and miscellaneous scrap metal which is often found at hazardous waste sites. Because the rest of this chapter discusses technologies for the cleaning of soil, greater detail about debris washing will not be included in this chapter. However, considerable detail on debris washing can be found in Appendix 5-F.

5.3 Background of the Case Study Sites as a Group

Table 5-1 shows an overview of the different case study sites. It can be concluded that there is little resemblance between these sites, showing the wide range of application of physical chemical techniques. As can be expected, however, most sites applying extraction contain sandy soils, leading to an acceptable amount of sludge produced. Acceptable may be defined to mean that cleanup costs plus the cost of sludge disposal are less than or equal to the disposal of the contaminated soil. For the Klöckner installation (Case Study 5-A), the fraction smaller than 0.063 mm ends up in the sludge, whereas for the Harbauer system (Case Study 5-B) only the fraction smaller than 0.015 mm becomes sludge. The site on which *in situ* extraction was applied (Case Study 5-E) was extremely sandy and is an exceptional site. The electro-reclamation study (Case Study 5-D) involved clayey soils. This technique is exceptional in a sense that it is the only technique capable of cleaning these difficult soils.

In the *in situ* acid extraction (Case Study 5-E), there were no fines and no organics at all present in the soil. The amount of organics in the jet cutting oxidation case study (Case Study 5-C) did not seem to influence the performance of the oxidation process. The case study on electro-reclamation and the *in situ* acid extraction case study can be regarded as opposites in that electro-reclamation works with clay soils having a low permeability, whereas *in situ* acid extraction only works when the soils are very sandy and show a high permeability. If soil is very permeable and has a low adsorptive capacity, extraction is cheaper than electro-reclamation. Electro-reclamation is needed in case the soil is very impermeable.

5.4 Performance Results

In extraction, cleaning results strongly depend on the form in which contaminants are present in the soil and the grain size distribution. Generally difficult to clean are soils containing a large fraction of particles smaller then 0.060 mm or soils containing a large amount of organic material. In *ex situ* extraction, the fines end up in the sludge. A small fraction of highly adsorptive particles in the soil make the *ex situ* extraction easier, because separating this fraction from the soil removes most of the contaminants as well.

Table 5-1. Problems handled in the NATO/CCMS case studies.

Process/ Technique	High pressure soil washing	Vibration	Jet cutting/ oxidation	Electro- reclamation	In-situ acid extraction
Manufacturer	Klöckner	Harbauer	Keller	Geokinetics	TAUW/ Mourik
Country	Germany	Germany	Germany	The Netherlands	The Netherlands
City	Berlin	Berlin	Hamburg	Loppersum	Soestduinen
Area (m²)	unknown	16,000	unknown	unknown	6,000
Depth (m)	unknown	unknown	unknown	1-2	unknown
Source of contamination	Scrap metal, copper refinery	Oil recovery	Disinfectant factory	Timber impregnating plant	Photographic paper factory
Type of soil	Sandy soil, less than 20% clay	Sandy soil	Sand, clay and peat	Clay	Sandy soil
Type and concentration of contaminants	Heavy metals, halogenated hydrocarbons, non-halogenated hydrocarbons	Halogenated hydrocarbons, aromatics, oil	Phenols, cresols	Arsenic 400-500 mg/kg	Cadmium
Amount of soil to be treated (tons)	100,000	unknown	unknown	450	45,000
Main lesson learned	--	--	--	Presence of metal objects can have a large influence on cleaning results	Adsorptive capacity and permeability as measured in laboratory differs from practice

A major difficulty encountered in interpreting the results of the case studies was the absence of independently obtained data. Data available from the commercial vendors involved generally represent their best results (mostly in sandy soils). Presenting cleaning results of sandy soils generally leads to higher cleaning efficiencies than would be obtained on the average in practice. In the jet cutting oxidation case study (Keller, Case Study 5-C), only easily oxidizable contaminants were present.

The electro-reclamation case study has a somewhat different position in that the technique is used for soils that are difficult or impossible to clean with other techniques.

High pressure soil washing (Case Study 5-A, Klöckner). The case study of Klöckner, shows differences obtained in cleaning efficiency ranging from 35 to 100 percent. These differences cannot be explained, due to insufficient information provided by the vendor. The soil treated by Klöckner is an easily cleanable sandy soil containing about 1.6 percent particles smaller than 0.063 mm.

Vibration (Case Study 5-B, Harbauer). The soil cleaned with the Harbauer system contains more fines than the soil treated in the Klöckner case (37 percent smaller than 0.1 mm) and is probably more difficult to clean without getting a large amount of sludge. However, Harbauer claims to produce a residue of only 2 percent, meaning that most of the fines above 0.015 mm were not heavily contaminated or could be cleaned and subsequently separated. We have been unable to check these claims. The cleaning efficiency for mineral oil, PAH's, phenol, and cyanide ranged from 86 to 100 percent.

Water jet followed by oxidation (Case Study 5-C, Keller). In contrast to the two extraction techniques (Klöckner and Harbauer), no particle separation techniques were used in this project. The results show a destruction efficiency of more than 90 percent for phenol. Reaction time needed ranged from 0.5 h to 3 h, mainly depending on the degree of destruction and the amount of organic material in the soil.

Electro-reclamation (Case Study 5-D, Geokinetics). The Geokinetics case study shows that removal of arsenic from a clay soil is possible, bringing concentrations down from more than 250 ppm to about 100 ppm and lower. In particular, one part of the site was difficult to clean, due to the presence of metal objects that functioned as preferential conductors for the

electrical current, thereby delaying the movement of the contaminants in their vicinity.

An important lesson learned from this experience is the need to identify metal objects in the soil and remove them before electro-reclamation is applied.

In situ **acid extraction (Case Study 5-E, TAUW/Mourik).** The TAUW/Mourik case study can be regarded as an example of an *in situ* acid extraction under ideal conditions. The soil cleaned is very permeable and contains hardly any adsorbing material. The results of a trial were so good that the initial cleaning goal was brought down from 5 mg-Cd/kg to 2.5 mg-Cd/kg. It was found that the desorption of cadmium in practice was better than was expected on the basis of laboratory studies. The permeability of the deeper layers of soil was found to be quite different from the permeability of the top soil.

5.5 Management of Residuals

In *ex situ* extraction techniques the main cleaning mechanism, in general, is the separation of the fines from the soil. In most cases, fines are the fraction of particles smaller than about 0.063 to 0.030 mm (an exact definition of "fines" is not useful). Separating this fraction from the soil leads to the production of sludge, which is generally the main drawback of extractive methods. Sludge consisting mainly of fines is considered non-cleanable and is disposed of in a controlled dump site. Harbauer is the only vendor that claims to be able to clean the fraction between 0.050 mm and 0.015 mm, therefore producing only limited amounts of sludge. However, past experience in The Netherlands has shown that it is doubtful that this will hold true in general. In the relatively few cases where the contaminants are not heavily adsorbed to the fine fraction, the contaminants entered the soil in a solid form. (This could very well explain the exceptional result obtained in the Harbauer case study).

If oxidation is used, production of sludge can be avoided. This is, however, only possible for organic contaminants that are easily oxidizable, e.g., phenols. The *in situ* extraction techniques produce a sludge containing only the extracted contaminants and the added chemicals in a concentrated form, the volume of which amounts to only a small percentage of the soil cleaned. The electro-reclamation technique also produces a small amount of sludge from the water purification unit.

5.6 Limitations or Restrictions to the Use of the Techniques

If the right combination of particle separation processes are used in combination with extraction, there are few restrictions for these techniques in general. Contaminated soils are considered non-cleanable if the contaminants are equally adsorbed to the entire soil fraction (equal distribution over particle size and particle density) and when the contaminants are relatively insoluble, thus making separation of any fraction and flushing with a water-based solvent useless.

Application of the oxidation technique is limited to well oxidizable contaminants. Other oxidizable material present will largely increase the amount of oxidant used. Trials in using oxidants in The Netherlands showed very limited applicability.

For *in situ* techniques aiming at removal of contaminants, the contaminants must be readily soluble in an aqueous solvent and not be heavily adsorbed onto the soil particles. This will only be true for a limited number of cases, such as the TAUW/Mourik case described earlier. Since the mechanism of cleaning by electro-reclamation has not been explained, little can be said about its limitations in this respect.

Any soil that is cleanable *in situ* is also cleanable in installations, but there are additional costs for excavation and handling of the material. A major drawback of *in situ* techniques in general is the difficulty of determining accurate results because of the difficulty in obtaining, without significant cost, accurate concentration profiles, both before and after the remediation operation. Table 5-2 gives an overview of the limitations of the different techniques addressed in this Pilot Study.

5.7 Costs

In this section an overview is given of some major cost factors that determine the total cleaning costs in an extractive installation. The costs of electro-reclamation, *in situ* acid extraction, and jet cutting followed by oxidation were not available at this time.

The general overview of costs involved in extractive cleaning of soil has been drawn from past experience with extractive cleaning of soils in The Netherlands (Hinsenveld 1990). The costs apply to installations such as the Harbauer and Klöckner systems, each of which will be largely determined by cost factors mentioned in this section. The cost factors are applicable to a lesser extent to the Keller installation, since this installation is simpler than the other extraction installations from a treatment point of view.

This discussion of costs is not claimed to be complete and care must be taken to take cost factors into consideration that are not addressed here, such as cost factors that are specific for an installation, a project, a country, and so on.

The costs are given in 1990 US$.

5.7.1 Fixed Costs

Location. An extractive installation is constructed on an emission controlled site. The costs for such a site include:

Table 5-2. Limitations to the use of the case study techniques.

Process/Technique	High pressure soil washing	Vibration	Jet cutting/ oxidation	Electro- reclamation	*In situ* acid extraction
Manufacturer	Klöckner	Harbauer	Keller	Geokinetics	TAUW/ Mourik
Technique available in	Germany, The Netherlands	Germany	Germany	Australia, The Netherlands	The Netherlands
In/Ex situ	Ex situ	Ex situ	In situ soil cutting; ex situ treatment	In situ	In situ
Type of soil	Preferably sandy soils. Not suitable for clay	Preferably sandy soils. Not suitable for clay	Preferably sandy soils	Suitable for both sandy material and clay. For sand, flushing might be cheaper	Sand, with high permeability
Fraction of fines	Not more than 30% of the particles smaller than 0.063 mm and organics	Not more than 20% smaller than 0.015 mm Not more than 30% smaller than 0.063 mm and organics	No limitations	No limitations	Not more than a few percent smaller than 0.1 mm
Fraction of organics			High content of organic material leads to excessive oxidant use	No limitations	Must be very low or absent
Fraction of rubble	No limitations	No limitations	No limitations	No limitations	No limitations
Type of contaminants	No limitations	No limitations	Only easily oxidizable components i.e., phenol; heavy metals are not removed	Only proven for heavy metals	Only acid soluble heavy metals
Concentrations of contaminants	No limitations	No limitations	High concentrations lead to high oxidant use	High concentrations can lead to high use of electricity	High concentrations can lead to high flushing costs
Production of sludge	Double the amount of the fraction smaller than 0.015 and of the fines	Double the amount of the fraction smaller than 0.063 and of the organics	Not produced	Little; highly concentrated	Little; highly concentrated
Remarks	Buildings on contaminated site must be torn down.	Buildings on contaminated site must be torn down.	Technique can be used underneath standing buildings.	Technique can be used underneath standing buildings; Metallic objects in the ground leads to insufficient cleaning and high electricity costs.	Technique can be used underneath standing buildings.

Note: A large fraction means more than 30% of the contaminated soil.

- The annual costs of the installation site, including maintenance of the site itself. These amount to about US$150,000 to US$270,000. These costs also incorporate a number of facilities of which the most important are: the construction of fluid-tight underlining, runoff water control and a secondary impermeable barrier (about US$50 to US$80/m²; these costs are roughly doubled in case a hood is needed), and the facilities needed at the site. For a site of an average size of 10,000 to 20,000m², the investment, including fences, weigh bridges, a carwash facility etc., is estimated to be about US$750,000 to US$1,500,000.

- Catchment and treatment of percolation water. Percolation water from other parts of the site is generally caught separately. It includes surface runoff from the covered contaminated soil, surface runoff from parts of the site that are not in use, and surface runoff from roads. Only if the contamination is unacceptably high will this runoff be treated. Annual costs, depending on the size of the site and the type of contaminant range from about US$60,000 to US$90,000. This brings the total estimated annual costs of the location to about US$210,000 to US$360,000.

Water discharge. The costs of discharge are largely dependent on the size of the site and arrangements made by the local government. Estimated annual costs range from US$20,000 to US$30,000.

Installation of soil cleaning equipment. The investments needed for the soil cleaning installation, the sludge treatment unit, and the treatment of process water are difficult to specify for every unit separately, because of major differences between the installations. For installations presently used in The Netherlands, these costs range roughly from US$2,500,000 to US$4,500,000. With a depreciation of 5 years and including necessary maintenance and replacement, the annual costs amount to US$660,000 to US$1,200,000.

Operation of the installation. For a direct operation of a soil cleaning installation, treatment of process water, filter press sieving, and logistics, some four to six people are needed. In most countries, this personnel frequently must have completed on-site hazardous waste management training and be certified to work on the site. The training generally includes practice in the field of inhalation protection, first aid, and fire abatement. Annual costs amount to US$240,000 to US$300,000.

Process control and development. Process control, making and evaluating test cleaning, and the evaluation of technology developments are mostly done by an engineer of academic level. Annual costs amount to US$90,000 to US$120,000.

Shovels and trucks. Input of soil into the installation, on a coarse sieve, is done with help of a shovel or a front-end loader. Another truck is needed for removing the sludge from the containers. These vehicles generally need pressurized cabins and an air filter. The costs amount to US$90,000 to US$150,000 per year.

Licenses. Most commercial firms use one or more licenses. Different arrangements have been made in the past for payment. Payment at once, followed by a yearly depreciation or payment per year per tonne cleaned material are general practices. Estimated costs range from US$60,000 to US$90,000.

Canteen, showers, and offices. Buildings and normal costs like water, electricity, heating, telephone, and the cleaning of work clothes and offices amount to annual costs of about US$60,000 to US$90,000.

Other costs. In the field of soil remediation, costs of insurance, permits, administration, accountants, bank guarantees, etc., can be quite substantial. Furthermore, costs concerning the establishment and control of safety procedures, medical checkup of workers, advice from medical doctors as well as costs for depreciation of measurement devices must not be forgotten. These annual costs are estimated to range from US$90,000 to US$120,000.

Direction and acquisition. The pre-project acquisition and specification of the work can be quite difficult in this field. Estimated costs amount to US$60,000 to US$90,000.

A summary of fixed costs is given in Table 5-3.

These total fixed costs must be divided by the total amount of cleaned soil (approved tonnes). With an annual production of 22,700 tonnes at the lowest and 40,800 tonnes at the highest investments, the fixed costs amount to US$68 and US$63 per tonne, respectively of cleaned soil.

5.7.2 Variable Costs

Deposit of soil before treatment. The soil on arrival has to be deposited and covered at the site. The trucks used for this operation must be washed before leaving the site again. The cost of this operation strongly depends on the frequency of deposit. Costs are about US$1 to US$2 per tonne of soil.

Analysis. In order to verify the indicated concentrations and types of contaminant, as well as to assess the expected sludge to be generated after treatment of the soil, samples are taken and analyzed during the process of depositing the soil. Analyses are also conducted for assessing process parameters to minimize emissions and residues and to indicate the expected quality of the end product (e.g., cleaned soil, sludge). These costs strongly depend on the homogeneity of the soil and the amount of soil being cleaned. Estimated costs are US$2 to US$7 per tonne of soil.

Table 5-3. Summary of annual fixed costs (in US$ 1990).

Cost item	Lower values	Higher values
Location	210,000	360,000
Discharge	18,000	30,000
Install soil cleaning equipment	660,000	1,200,000
Operation of installation	240,000	300,000
Process control and development	90,000	120,000
Shovels and trucks	90,000	150,000
Licenses	60,000	90,000
Canteen, showers and offices	60,000	90,000
Other costs	60,000	120,000
Direction and acquisition	60,000	90,000
TOTAL ANNUAL FIXED COSTS	1,548,000	2,550,000
TOTAL PER TONNE SOIL	68	63

Electricity and water. Energy is needed for most of the unit operations. Water is needed, because the soil and the sludge leave the installation with an increased water content compared to the original soil. These costs strongly depend on the amount of soil cleaned per hour and the amount of sludge produced from the soil. More fines lead to both higher electricity costs as well as a higher water demand. Estimated costs range from US$2 to US$4 per tonne of soil.

Chemicals. Depending on the system used in the extractive soil cleaning installations, the following chemicals may be used: chemicals for pH conditioning, emulsifiers and demulsifiers, coagulants, flocculants, and flotation aids. The costs will be a function of the type and concentration of contaminants, the chemical composition of the soil, and the sludge content. Costs range from US$4 to US$7 per tonne of soil.

Filter material. Cleaning of process water and air is sometimes done by means of sand filters and active carbon filters. Both types of filters must be processed afterwards (i.e., regenerated or deposited). The costs involved strongly depend on the type and concentration of contaminants and are in the range of US$1 to US$3 per tonne of soil.

Safety and occupational health. Depending on the risk factors, personal protection is needed. In some cases the presence of a safety and occupational health specialist is required. Costs are estimated as US$2 to US$7 per tonne of soil.

Reuse of the cleaned soil. This is still a problem. In case the concentrations are very low (for instance, at the Dutch reference levels), the soil can be used multi-functionally. In many cases, the cleaning company pays for the transportation costs of this material. At higher residual concentrations, the cleaned soil can sometimes be used in asphalt production installations. The costs, therefore, depend on the type and concentration of the residual contaminants and on the transport distance. Typical costs in The Netherlands range from zero to US$10 per tonne of soil.

Ultimate disposal of cleaned soil depends on regulatory requirements. It should be noted that even when the soil is cleaned to trace concentrations of contamination, the public will likely be very reluctant to allow reuse of the cleaned soil (psychological factors).

Reuse of rubble, etc. Rubble and gravel mixed with other soil particles which are separated from the soil may require treatment, depending on the composition. These coarse materials may be reused in road building, but are often deposited at a landfill site. The costs per tonne of material depend on the composition of the material, type and concentration of the contaminants, and the distance of transport. A range may be indicated as US$17 to US$66 per tonne of rubble. For soil containing 10 percent rubble and other non-soil materials, this amounts to US$2 to US$7 per tonne of soil.

Reuse of sludge. The mineral fraction (mostly the fraction smaller than 0.063 mm to 0.030 mm) is transferred from the soil to the water phase and finally ends up in the sludge. Usually the sludge will be processed by a mechanical dewatering unit. The sludge, in general, contains the larger part of the contaminants (most contaminants are heavily adsorbed on this fraction). Deposit of this material may be expensive due to its high concentrations of contaminants, such that only controlled and permitted landfills will accept the sludge. The cost of disposal will be dependent on the amount of the minimal fraction in the soil (fraction smaller than 0.063 mm to 0.030 mm), the distance of transport, and the cost of landfilling. A soil with 10 percent mineral content leads to estimated costs of disposal of US$7 to US$46 per tonne of soil. If the sludge has to be treated before deposit, by solidification/stabilization techniques for example (see Chapter 3), the costs will be a multiple of the above mentioned figures.

A summary of variable costs is given in Table 5-4.

5.7.3 Total Costs

From the inventory above it is clear that the costs of cleaning soil depend on a large number of factors. This inventory is based on experience in The Netherlands; this should be borne in mind when calculating the costs for other countries. Some of the item costs probably will be very different and the costs given here

Table 5-4. Summary of variable costs per tonne soil (in US$, 1990).

Cost item	Lower values	Upper values
Deposit of soil before treatment	1	2
Analysis	2	7
Electricity and water	2	4
Chemicals	4	7
Filter material	1	3
Safety	2	7
Reuse of cleaned material	0	10
Reuse of rubble, etc.	2	7
Deposit of sludge	7	46
TOTAL VARIABLE COSTS	21	93

should, therefore, not be used as a direct reference for estimating costs. Furthermore it is expected that a number of other costs not mentioned here might be added to the calculation for certain countries. The above method of calculating the treatment costs should, therefore, only serve as an example of how a

Table 5-5. Total costs of extractive treatment per tonne soil (in US$, 1990).

	Lower values	Higher values
Total fixed costs	68	63
Total variable costs	21	93
TOTAL COSTS OF TREATMENT	89	156

rough calculation might proceed. The total costs of treatment are indicated in Table 5-5.

In general, the costs for treatment in The Netherlands on the basis of 10 percent rubble and 10 percent sludge will vary between US$89 and US$156. In the above mentioned inventory, general administration costs and the costs of profit have also been omitted. Commercial firms add in general about 10 percent to 15 percent to the above mentioned figures for this purpose. In addition research and development costs have been omitted.

5.8 Future Status of Case Study Processes and Extraction Technologies as a Whole

As indicated, extractive methods are suitable for a large range of soils and a large range of contaminants. The *ex situ* extraction methods are powerful techniques for soils containing heavy metals as well as organic contaminants. For soils containing a combination of metals and organics, there are presently no other techniques available. For soils containing only organics, thermal techniques are generally more effective. A further improvement of the extraction installations by using new separation techniques is expected. The use of organic solvents and supercritical extraction techniques are being investigated at the moment. These techniques might further enlarge the applicability of the extraction techniques, but are generally more expensive. The Keller technique, using only oxidation, has a limited applicability. The jet cutting method used in the cleanup operation, however, might be useful to reduce the costs of cleanup under buildings, because the buildings would not need to be dismantled.

In situ extraction techniques will probably continue to play only a marginal role in the cleanup of contaminated sites due to their limited applicability.

However, the electro-reclamation technique could prove to be a powerful technique for solving problems associated with cleaning clayey soils and sludges, but is still under development. For *in situ* cleaning of clay soils containing heavy metals, electro-reclamation is the only technique available at the present time. For that reason, electro-reclamation deserves to be investigated intensively in order to assess its potential.

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Pump and Treat Ground Water

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ABSTRACT

Four pump and treat ground water case studies were chosen for the Pilot Study. The first three deal with an evaluation of treatment technologies. The first of these evaluates the use of more conventional processes: air stripping and activated carbon adsorption at full scale; the second concerns advanced photo-oxidation technology (at pilot scale). Generally, the types of contaminants treated were volatile organic compounds and a few other nonvolatiles, such as phenols and PCB's. The third evaluates the use of precipitation and clarification for removing cadmium and zinc from contaminated ground and surface waters from an old zinc smelting operation.

The final case study deals with minimizing the quantity of water to be treated with a concurrent reduction in the amount of contaminants to be treated. A particular well pumping technique was examined also at pilot scale at the waste site in Denmark.

6.1 Introduction

This chapter deals with pump and treat technology, with the primary emphasis on treatment technologies for pumped ground water. Outlined in this chapter are four case studies, the performance of various technologies, lessons learned, costs, factors to be considered for using the technologies and, finally, the future of the technologies demonstrated.

Pump and treat technology consists of the extraction of contaminated ground water from the subsurface, followed by treatment of the ground water at the surface to remove the contaminants. Treatment can be by means of physical/chemical technologies, biological treatment technologies, or any appropriate combination of these.

The application of pump and treat technology can be considered for essentially two cases: containment of the contaminants in the ground water to within a confined zone thereby preventing the spread of the contamination, and decontamination of the aquifer. In this latter case, injection wells may be installed "upstream" of the pumping well(s) to help flush the contaminants from the aquifer. In addition, contaminants that are adsorbed or held by the soil particles may be desorbed from the soil particles, maintained in solution in the ground water, and pumped out at the extraction well.

In all cases, for decontamination to be effective, sources contributing to the contamination of the ground water must be removed, such as, sludge ponds, buried drums, and nonaqueous phase liquids in the soil matrix.

6.2 Case Studies Chosen

In terms of system design for pump and treat, the hydrogeological and geochemical properties of the aquifer must be known, as well as the behavior of the contaminants within the aquifer and the ground water. Extraction wells can be designed from basic hydrologic principles to ensure that an appropriate "cone of influence" exists.

There are a number of factors to be considered in designing a treatment system. These are indicated briefly here and elaborated on in Section 6.6. One

consideration is the actual treatment process(es) that will be used. The treatment processes will be a function of the type and quantity of contaminants present as well as the volume of ground water to be treated. The quantity of contaminants and volume of water to be treated can also impact significantly on treatment costs. This factor may be overlooked but it is highly desirable to examine the possibility of reducing the volume of water to be treated and, if possible, the quantity of contaminants to be treated. It is essential that the treated ground water and any residuals or emissions meet the regulatory requirements.

To partially illustrate these points, four case studies were chosen. One case study illustrates flow and contaminant minimization and the other three illustrate various ground water treatment technologies.

One other case study is outlined in Chapter 8 below which also relates to this chapter on pump and treat technologies. This case study is biological pretreatment of ground water, The Netherlands (Lindane/Bunschoten). An additional project report is included in Appendix 1-C: on-site *in situ* reclamation: membrane filtering and biodegradation, Denmark (former gas works site/Fredensborg).

6.2.1 Case Study 6-A: Decontamination of Ville Mercier Aquifer for Toxic Organics, Ville Mercier, Québec, Canada.

This case study was chosen for two reasons. Firstly, it is a demonstration of a full scale "pump and treat" system, the first in Canada and perhaps North America, designed to decontaminate an aquifer. Secondly, an evaluation of the treatment technologies employed (a combination of "air stripping" and activated carbon) was being undertaken by Environment Canada.

Site. From 1968 to 1972 some 40,000 m^3 of waste oils and liquid industrial wastes from chemical and petrochemical industries in the vicinity of Montréal, Québec were dumped in a lagoon in an old gravel pit located near Ville Mercier, Québec. The dump site was closed in 1972. Over the next 10 years, as a result of several investigations, it was determined that about 30 km^2 of the aquifer supplying drinking water for several local communities was contaminated.

The gravel pit is located in a sand and gravel esker of fluvio-glacial origin. The sand and gravel extend to a depth of roughly 30 meters and overlie fractured dolomite and sandstone bedrock. The most contaminated zone extends over an area of about 2 km^2 down gradient from the lagoon.

The climate in the area is typically temperate, with snow and rain averaging about 254 cm per year. Cold weather extends generally from mid October through mid April.

Treatment System. The installation became operational in 1984. Three ground water extraction

wells were located down gradient from the lagoon and provided a flow of 65 L/s to the treatment plant. The primary treatment processes involve air stripping to oxidize and precipitate iron and manganese and to remove volatile organic compounds (VOC's); coagulation and flocculation with alum and polymer addition; sedimentation and rapid sand filtration to remove iron and manganese and other suspended solids. Activated carbon is used to remove the remaining organic compounds. More detailed information is provided in the references at the end of this chapter and in Appendix 6-A.

6.2.2 Case Study 6-B: Evaluation of Photo-oxidation Technology (Ultrox® International), Lorentz Barrel and Drum Site, San Jose, California, United States.

This case study was chosen because it was the evaluation of a photo-oxidation process to treat organics in a contaminated ground water. This technology was evaluated under the Superfund Innovative Technology Evaluation (SITE) program of the United States Environmental Protection Agency (U.S. EPA). The demonstration took place in February and March 1989 at a former drum recycling facility in San Jose, California.

Site. In 1947, Lorentz Barrel and Drum began its drum recycling operations. Drums were received from over 800 private companies as well as military bases, research laboratories and county agencies in California and Nevada. The drums generally contained residual aqueous wastes, organic solvents, acids, metal oxides, and oils. Residual wastes from drums and wastewaters were disposed of in an on-site drainage ditch routed to a large sump. Prior to 1968, wastewater from the sump was discharged to the storm drain system. In subsequent years, discharge was to the sanitary sewer. This practice was discontinued between 1983 and 1984. Subsequently, liquid wastes were reportedly reduced in volume by evaporation, put in drums, and disposed of off-site as hazardous wastes. In 1987, the facility ceased operation and the U.S. EPA Regional Office in California assumed lead agency responsibility for site remediation and initiated a remedial investigation/feasibility study. When the company began operations, the site consisted of 25.9 hectares. Since then half has been sold. The highest contamination levels are suspected to be in the remaining 13 hectares.

The surface soils are silt and clay (about 1 meter) underlain by sand and gravel, about 7 meters below which there is a clay aquitard. The water table occurs at a depth of approximately 6 meters. The shallow ground water flow appears to follow the ground surface topography flowing towards a local watercourse, Coyote Creek, about 0.8 km away.

The climate in the area has warm, dry summers and cool, wet winters. Normal average rain fall is 353 mm (13.9 inches) most of which occurs from November through April.

Treatment Process. The Ultrox® technology (a registered trademark of Ultrox International) simultaneously uses ultraviolet radiation, ozone and hydrogen peroxide to oxidize dissolved organic contaminants (including chlorinated hydrocarbons and aromatic compounds) found in ground water or wastewater.

The objectives of the technology demonstration were to:

■ Evaluate the ability of the technology to treat the 44 volatile organic contaminants found in the ground water at the site

■ Evaluate the effects of major process parameters on process performance

■ Evaluate the efficiency of the ozone decomposer unit in treating off-gas from the reactor

■ Develop information useful for evaluating whether this technology is suitable for other hazardous waste sites with similar conditions.

Five variables examined during the 10-day pilot scale test included hydraulic retention time, ozone dose, hydrogen peroxide dose, UV radiation intensity, and influent pH level. To facilitate the test program, three indicator VOC's were selected: trichloroethylene (TCE) 1,1-dichloroethane (1,1-DCA) and 1,1,1-trichloroethane (1,1,1-TCA). At a flow rate of 14 Lpm 3.75 gpm, the reactor retention time was 40 minutes. This was varied between 20 and 60 minutes. Additional details are presented in the references at the end of the chapter and in Appendix 6-B.

6.2.3 Case Study 6-C: Zinc Smelting Wastes and the Lot River, Viviez, Averyron, France

This case study was chosen because it represented an example of a "pump and treat" system and the contaminants of concern were metals (in contrast to organics).

Site. Zinc production in Viviez was started in the 1870's. Until 1930, a thermal process was used to extract the zinc from the ore with the wastes being disposed of on a hillside near the plant. After 1930, an electrometallurgic process was used and again the wastes were deposited near the plant. The total, now, is about 700,000 tonnes. Water percolating through the wastes dissolves cadmium and zinc which reach the ground water and eventually, surface water. In 1987, it was calculated that 37 kg/d of cadmium were reaching the Lot River. Hydrogeological studies were undertaken to better define the hydrodynamic behaviour of the alluvial aquifer, the hydraulic relation-

ship between the waste heap and the aquifer, and the surface water regime in the vicinity of the heap. Additional water analyses were done on various chemical parameters as well.

In 1988, action was taken to cover ponds on the heap, to relocate the smallest storage piles, and collect contaminated surface and ground water. With these actions, the cadmium flux was reduced by 94 percent to 2 kg/d. Several additional actions, such as flushing parts of the heap and diverting surface water, resulted in reduced quantities of contaminated water to be treated.

Treatment Process. The treatment is performed in a batch mode with 320 to 800 m³ of contaminated water collected in any one day. The process involves the addition of lime in several reactors followed by the addition of sodium sulfide. Polymer is added to the clarifier to ensure effective settling of the sludge and to ensure that the effluent objectives are met. The sludge is dewatered on a filter press and sent off-site for metal recovery. The effluent is discharged to a receiving water. Additional work is underway to further reduce the quantity of water (and contaminants) to be treated and, hopefully, reduce the cost of treatment. Additional details are presented in Appendix 6-C.

6.2.4 Case Study 6-D: Separation Pumping, Skrydstrup, Denmark

This case study was chosen because it demonstrated the use of a novel pumping technique, separation pumping, to reduce the volume of ground water and the quantity of contaminants to be treated.

Site. In the period 1963-1974, chemical waste from a refrigerator factory was dumped in a gravel pit near Skrydstrup in western Denmark. The ground water was considerably contaminated by 1,1,1 trichloroethane and organic phosphorus. The waste was excavated in 1986. The drums with chlorinated solvents were sent for destruction and the contaminated soil was placed in a special waste disposal site for treatment. (For more details, refer to Appendix 6-D.) The pollution plume has been found up to 1.5 km downstream and to a depth of 25 meters.

Technique. This technique relies on simultaneous pumping from the top and bottom of a fully penetrating well through the polluted section of the aquifer. The objective is to reduce the volume of water requiring treatment. In a test well, during the period July-October 1989, from 50 to 65 percent of the total water pumped was within acceptable limits of contaminants - obviously a significant reduction in the volume of water that would have to be treated. In the subsequent period, November 1989 to March 1990, the pump ratios had to be changed such that only 10 percent of the total discharge was within acceptable limits; still, however, producing a reduction in the volume to be treated. Additional pilot scale experiments with en-

couraging results were also completed in a limestone aquifer and a chalk aquifer. As these were only pilot scale experiments, no cost data are available yet for full scale application. Additional details are provided in Appendix 6-D.

6.3 Background of the Case Study Sites as a Group

Only three of the four case studies mentioned above will be used to demonstrate the performance of treatment technologies. Before describing the performance results, background information is provided on the sources and types of contaminants, some site characteristics, and the success in remediating one aquifer. The sources of contamination are set out in Table 6-1.

Table 6-1. Sources of contamination at case study sites.

Site	Source
Ville Mercier	Waste dump in a rural area containing primarily organic wastes and oils. Some PCB's detected.
Lorentz Barrel and Drum	Decommissioned industrial site in an urban area.
Lot River	Old industrial site near an urban area.

Table 6-2. Principal contaminants at the Ville Mercier, and the Lorentz Barrel and Drum sites.

A. Ville Mercier	B. Lorentz Barrel and Drum	
Phenols[1]	Benzene[2]	Trans-1,2-dichloroethylene[3]
1,2-Dichloroethane (1,2 DCA)[1]	Benzyl Chloride	Dichloromethane
1,1,1-Trichloroethane (1,1,1-TCA)[1]	Bis (2-chloroisopropyl) ether	1,2-Dichloropropane[3]
1,1,2-Trichloroethane (1,1,2-TCA)	Bromobenzene	1,3-Dichloropropylene
Trichloroethylene (TCE)[1]	Bromodichloromethane	Ethyl benzene
Chloroform	Bromoform	1,1,2,2-Tetrachloroethane
Chlorobenzene	Bromoethane	1,1,1,2-Tetrachloroethane
Trans 1,2 Dichloroethylene	Carbon tetrachloride	Tetrachloroethylene[3]
PCB's[1]	Chloracetaldehyde	Toluene
Iron	Chloral	1,1,1-Trichloroethane[2,3]
Manganese	Chlorobenzene	1,1,2-Trichloroethane
	Chloroethane[3]	Trichloroethylene[2,3]
	Chloroform[3]	Trichlorofluoromethane
	1-Chlorohexane	Trichloropropane
	2-Chloroethyl vinyl ether	Vinyl Chloride
	Chloromethane	Xylenes
	Chloromethyl methyl ether	Arsenic[4]
	Chlorotoluene	Barium[4]
	Dibromochloromethane	Chromium[4]
	Dibromomethane	Cobalt[4]
	1,2-Dichlorobenzene	Iron
	1,3-Dichlorobenzene	Manganese
	1,4-Dichlorobenzene	Molybdenum[4]
	Dichlorodifluoromethane	Nickel[4]
	1,1-Dichloroethane[2,3]	Vanadium[4]
	1,2-Dichloroethane[3]	Zinc[4]
	1,1-Dichloroethylene[3]	

[1]Contaminants selected to evaluate the performance of the technology.
[2]Contaminants selected as "indicator" VOC's to guide the test program at Lorentz.
[3]Principal contaminants measured for test work.
[4]Metals found in wells on-site but not reported in test work.

Table 6-2 identifies the principal contaminants at Ville Mercier and Lorentz Barrel and Drum. Volatile organic compounds (VOC's) and some PCB's were found at both sites. In the case of Lot River, the contaminants of concern are the toxic metals, zinc and cadmium.

The site characteristics of the case studies were significantly different. As the focus of the chapter is primarily on treatment technologies, the type and range of site characteristics are not particularly relevant.

6.4 Performance Results

6.4.1 Effectiveness of Aquifer Remediation at Ville Mercier

It was anticipated that the aquifer would be remediated within a period of five years based upon the predesign hydrogeological investigations. The site investigations that were conducted as part of the 1989 study clearly indicated that this did not occur nor would it likely occur within the foreseeable future. The reason for this was that, when additional monitoring wells were placed and sampled, significant quantities of nonaqueous phase liquids (NAPL) were found throughout the soil and into the fractured bedrock. Thus, although the pumping appeared to be effectively constraining the down gradient movement of contaminants, it was obvious that the aquifer could not be remediated until some means was found to remove the NAPL.

6.4.2 Effectiveness of Treatment Technologies

Each of the treatment systems at the three sites were judged using a similar basis, i.e., that the effluents and emissions had to meet regulatory standards. The specific objectives to be met are presented in Tables 6-3 and 6-4. The effectiveness of the treatment systems at Ville Mercier and Lorentz Barrel and Drum was assessed by how well they removed the contaminants of concern primarily VOC's and if the effluent criteria were met. For the Lot River case study, the process was assessed on its ability to reduce zinc and cadmium.

Ville Mercier. A review of the results of the performance of the treatment plant from 1984 to 1989 (Appendix 6-A) and during the two sampling campaigns undertaken in 1989 reveals that there were a number

Table 6-3. Performance results for Ville Mercier, and Lorentz Barrel and Drum sites.

	Results in μg/L (unless otherwise noted)					
	Ville Mercier			Lorentz Barrel and Drum		
		Results			Results[5]	
Compounds	Objective	1[2]	2[3]	Objective[4]	Run 12[6]	Run 13[6]
Iron (mg/L)	0.30	0.02	0.01		low	low
Manganese (mg/L)	0.05				low	low
PCB's	0.01	nil				
Phenols	2.0					
Benzene	50	78.0	27.0	5.0	0.23	0.45
Chloroform				5.0	0.74	0.81
Chloroethane				5.0	0.00	0.00
1,1-Dichloroethane				5.0	3.80	4.20
1,2-Dichloroethane	50	620	123	1.0	0.92	1.00
1,1-Dichloroethylene				5.0	0.00	0.00
Trans-1,2-Dichloroethylene				5.0	0.00	0.00
1,1,1-Trichloroethane	33	nil	nil	5.0	0.43	0.49
1,1,2-Trichloroethane	50	441	25.0			
Trichloroethylene	4.5	11.0	1.0	5.0	0.55	0.63
1,1,2,2-Tetrachloroethane				5.0	0.045	0.045
Tetrachloroethylene				5.0	0.19	0.091
1,2-Dichloropropane				5.0	2.60	2.90
Vinyl Chloride				0.5	0.11	0.12
Any other VOC	50.00					

[1]Ville Mercier - Oxidation-air stripping followed by suspended solids removal and activated carbon. Lorentz Barrel and Drum - Ultrox® process consisting of the use of hydrogen peroxide, ozone and ultraviolet light.
[2]Campaign conducted 4 months after granulated activated carbon (GAC) replacement; period - two weeks.
[3]Campaign conducted immediately after GAC replacement; period - six weeks.
[4]Regulatory threshold.
[5]Thirteen volatiles identified - only 3 common to both sites.
[6]Mean values; Runs 12 and 13 were replicate runs.

Table 6-4. Performance results for Lot River site.

Effluent	Objective	Results (daily average)
pH	5-9	8.5-9
Suspended solids	<30 mg/L	N/A
Phosphorus	<10 mg/L	N/A
Hydrocarbons (total)	<5 mg/L	N/A
Metals (total) (Zn + Cu + Ni + Al + Fe + Cr + Cd + Pb + Sn)	<15 mg/L	N/A
Zinc	<5 mg/L	0.5 - 3.0 mg/L
Cadmium		
Monthly average	0.2 mg/L	
Maximum daily	0.4 mg/L	0.03 - 0.18 mg/L

N/A = Not available

of problems associated with various unit operations in the treatment train. The initial unit operation, consisting of a packed column, was designed for iron oxidation and, to some extent, stripping of the VOC's. Iron was oxidized effectively; however, the column packing quickly became coated with an iron colored scale. Removing the scale added to maintenance of the system. The packed column had not been designed as an efficient air stripping device and therefore the performance results for VOC's are inferior to those expected from a column designed specifically as an air stripper.

The carbon columns failed to perform as well as required, so effluent quality objectives were not consistently met. For example, 1,2-DCA "broke through" the carbon within two to three weeks after replacement. This may have been due to factors such as competitive adsorption with other VOC's or generally with the other organics present measured as "total organic carbon", or simply because 1,2-DCA is poorly adsorbable.

Significant changes in the influent concentration of VOC's likely impacted on the performance of the treatment train as well. As an example, the concentration of 1,2-DCA increased about ten times over what was expected from the initial pump well tests. Therefore, in summary, a number of factors contributed to the inability of the treatment system to consistently meet the effluent objectives.

Lorentz Barrel and Drum. The Ultrox® process was evaluated for a period of 10 days during which five variables were examined and 13 runs conducted. Given an initial set of conditions based upon a treatability study, the objective of the evaluation was to determine a set of operating parameters under which the process effluent would meet the permit requirements. The objective was met and a set of operating conditions was defined.

The preferred operating conditions, determined in the demonstration are the following:

- Electricity 11 kw/h operation (24 UV lamps operating)
- Ozone 110 mg/L
- H_2O_2 - 13 mg/L
- Influent pH - 7.2 (unadjusted)
- Retention time - 40 minutes
- Flow rate - 14 L/min
- Reactor - 568 liters wet volume
- Cooling water - 13 L/min.

Lot River. Although information on the treatment process was provided, there was no information provided on the long term operation of the treatment process. The data provided indicate that for the metals of concern, zinc and cadmium, the effluent objectives were easily met.

6.4.3 Lessons Learned on How to Improve Effectiveness

Ville Mercier. Because of the unexpected finding of NAPL at the site several years after the treatment system had been operating, the need for comprehensive hydrogeological/geochemical investigations to be undertaken prior to initiating the pump and treat system was clearly underscored.

As noted, a number of factors impacted on the performance of the treatment system. As a result, the following needs have been identified:

- Comprehensive treatability studies should be undertaken prior to design. These should be at bench and pilot scale (preferably at the site to be cleaned up).

- More comprehensive hydrogeologic/geochemical information should be obtained before a remediation scheme is implemented.

- Ground water treatment plants should be designed with flexibility so that the performance can be optimized under variable influent conditions.

As an integral part of the 1989 Ville Mercier study, a pilot plant was constructed and operated to determine if a different combination of unit operations would be appropriate to treat the ground water. The pilot plant study was conducted from January through July 1989.

The unit operations tested and selected as being appropriate for a treatment train were:

- Diffused aeration followed by sand filtration for iron removal

- Optimized, packed, air stripping column for the removal of VOC's

- Activated carbon for polishing purposes (TOC's, phenolics).

Because the air stripping column was optimized on the basis of 1,2-DCA being the limiting contaminant, it was found that the existing discharge objectives could be met using only this unit operation (with pretreatment for iron removal).

Lorentz Barrel and Drum. The period of the technology evaluation was limited to 10 days. Although an appropriate set of operating conditions was defined to meet the objective of the demonstration, these were not necessarily either an optimum set or the most cost effective.

Lot River. It is difficult to draw significant conclusions given the limited information provided. However, it should be noted that the usefulness of minimizing the volume of contaminated water and the quantity of pollutants to be treated appeared to have a significant impact on the treatment system and the receiving water. The treatment process, as designed, effectively removed the metals of concern to acceptable levels.

6.5 Residuals and Emissions

Ville Mercier. From this plant, there were air emissions, sludge from the clarifier and spent activated carbon.

The air emissions were acceptable to the local regulatory authority, the Ministry of the Environment of Québec (MENVIQ). The sludge was analyzed for a variety of chemicals and found acceptable for disposal in a local sanitary landfill. The spent activated carbon was returned to the supplier in the United States for regeneration.

Lorentz Barrel and Drum. A "Decompozon" unit (for which no process or technical details were provided) was employed to destroy residual ozone and residual VOC's that were present in the "air" emission. This unit successfully reduced the contaminants to acceptable levels.

Lot River. The residual from the process was a sludge containing significant concentrations of zinc and cadmium. The sludge was dewatered, using a filter press producing a cake of 20-30 percent solids containing zinc (25 to 35 percent), cadmium (0.2 to 0.5 percent), and calcium (1.5 to 6 percent). The dried sludge was shipped off-site for metal recovery.

6.6 Factors and Limitations to Consider for Determining Applicability of the Technology

6.6.1 Application of Pump and Treat

The nature of the "pump and treat" technology limits its use to situations where a realistic quantity of water can be pumped out of a contaminated aquifer within a reasonable period of time, particularly if the goal is to decontaminate the aquifer.

This technology will only be applicable to situations where the soils are relatively permeable, and where the contaminants in the ground water are well defined, both in terms of the chemical nature of the contaminants and their behaviour in the soil and ground water matrix.

All sources of contamination must be removed in order for the cleanup to be successful. This includes obvious sources such as buried tanks, drums, etc., and also less obvious sources, such as "pockets" of nonaqueous phase liquids.

6.6.2 Application of Ground Water Treatment Technologies

- Comprehensive hydrogeological and geochemical characterization of the site must be completed in order to identify the treatment system design requirements, such as the volume of flow; the quantity, type and nature of contaminants; and probable variability in contaminant concentrations.

Application of Air Stripping and Activated Carbon

- Appropriate treatability studies should be conducted to identify the design parameters for the air stripper and activated carbon adsorbers. At this stage, pretreatment requirements should be identified and appropriate design parameters developed.

- Effective removal of volatile organic compounds and other adsorbable organic compounds will be accomplished when the process train is properly designed.

- Pretreatment will be required for the removal of iron and manganese, oil and grease and suspended solids.

- If metals are present, some form of additional treatment (pre or post) will have to be incorporated into the treatment train.

- Chemicals may need to be added to control microbiological growths in the various units.

- Air emissions may or may not be acceptable to the regulatory authorities; a number of technologies exist to control the emissions from air strippers.

- Means of disposal of activated carbon (and any other process residues) needs careful consideration; the spent carbon may be considered a hazardous waste.

Application of Photo-oxidation Technology

- The chemistry of the process is quite complex when a number of different organics are being treated. Therefore the process cannot be mathematically modelled, nor can oxidant dosage be based on stoichiometric relationships to the organics present. This means that the appropriate operating conditions and oxidant dosages can only be determined through treatability experiments at an appropriate scale.

- Effective for removal of volatile organic compounds and other nonvolatile organic compounds.

- There are no residues generated by the process.

- Electrical power requirements for the process are significant and require careful consideration.

- Hydrogen peroxide is the only chemical required and must be readily available. This is not seen as a significant problem.

- Pretreatment will be required for the removal of iron and manganese, oil and grease, and suspended solids.

- If metals are present, some form of additional treatment (pre or post) will have to be incorporated into the process train.

- Based on the gas chromatography (GC) and gas chromatography/mass spectroscopy analysis performed for VOC's, semivolatile organics and PCB's/pesticides, no new compounds were detected in the treated water. The organics analyzed by GC methods represent less than 2 percent of the total organic carbon (TOC) present. Very low TOC removals occurred, which implies that partial oxidation of organics (and not complete conversion to CO_2 and H_2O) took place in the system.

- Variability in the concentration of influent contaminants to the process must be carefully considered as the operational parameters for the process can only be set for a given set of influent concentrations. Presumably, continuing treatability testing would be required to determine the appropriate level of the operating parameters for a significant change in the influent concentration of organic compounds. Another option to accommodate variability may be the installation of equalization capability.

- Presumably, there is no limit on the concentration of organics that can be successfully treated. The limiting factor will be cost, primarily for oxidants and for power: ultraviolet (UV) lights are relatively inefficient, e.g., 0.1 percent.

Application of Precipitation Technology

- Treatability studies at an appropriate scale are essential.

- Effective for removal of cadmium and zinc and many other heavy metals.

- Variability of the volume of water to be treated will impact on system design, e.g., tank sizes required and must be carefully considered.

- Not all metals can be removed using lime and sodium sulfide and, therefore, the solubility of metals in relation to pH must be carefully considered.

- Residual sludge may present a disposal problem in some jurisdictions. Recovery of the metal values appears to be an attractive option.

- The quantity of lime required for precipitation is relatively insensitive to the concentration of metals to be treated. However, the quantity of sodium sulfide to be used is a direct function of the quantity of metals to be treated.

6.6.3 Availability of the Technologies

All the technologies are commercially available. However, they have to be appropriately designed to suit the site and contaminated ground water characteristics. Technologies and process trains can either be designed by consultants, or proprietary "commercial packages" can be purchased from various suppliers.

6.7 Costs

Ville Mercier. The plant was constructed and became operational in 1984. The total capital cost for the treatment facility including the purge wells was Cdn\$3.1 million (Simard 1987). The operating costs for the plant are set out in Table 6-5. Over the period of operation from 1984 to 1987, it can be seen that the unit operating costs decreased significantly from US\$0.70 to US\$0.39/m^3 and was projected to decrease to US\$0.32/m^3. It should be noted that the relative cost of the activated carbon is a significant expense and, therefore, steps to minimize this cost would be desirable.

Table 6-5. Ville Mercier operating costs, (x 1,000 CDN$).

	1984/85	1985/86	1986/87	1987/88[1]	1988/89[1]
FIXED COSTS[2]	270.0	307.0	283.7	212.9	212.9
VARIABLE COSTS[3]					
Maintenance	11.0	16.5	22.4	22.0	23.2
Electricity	41.1	57.9	59.8	76.0	79.8
Chemicals	60.3	108.0	145.0	168.0	176.4
Activated carbon	222.7	271.0	210.3	290.0	304.4
SUPPLEMENTARY COSTS[4]	172.7	65.6	152.6	133.8	139.1
TOTAL COSTS	777.8	826.0	873.8	902.7	935.8
Volume treated (10^6 gal)	181.8	284.0	369.1	420.0	472.5
Operating time (%)	34.5	54.1	70.3	80.0	90.0
UNIT COSTS (Cdn$/$10^3$ gal)	4.30	2.90	2.37	2.15	1.98
(US$/$m^3$)	0.70	0.48	0.39	0.35	0.32

[1]Projected

[2]Plant management, personnel, maintenance of works and equipment, disposal of sludges and domestic wastes, supply of tools and various materials, drinking water, telephone and alarm services, insurance program, control analytical costs, and upkeep of the access road.

[3]Including those set out in the table plus cleaning of the purge wells.

[4]Including purchase and repair of mechanical equipment, minor modifications, and technical studies needed for sound plant management.

Lorentz Barrel and Drum Site. Table 6-6 was extracted from an "Applications Analysis Report" prepared for the U.S. EPA (U.S. EPA 1990) on the Ultrox® technology. These costs are order-of-magnitude estimates (-30 to +50 percent) as defined by the American Association of Cost Engineers. A more detailed explanation of the derivation of these costs can be obtained from the report. The significance of the utility costs as the size of the units increase should be noted although the relative cost per liter treated decreases.

For the purpose of this economic analysis, it is assumed that the system will be operated in a continuous mode, 24 hours a day, 7 days a week, for one year. During this period, the unit should treat approximately 40 million liters in the 75L/min unit, 200 million liters in the 375 L/min unit, and 500 million liters in the 950 L/min unit. One year was chosen as the period of time for this analysis so that reliable annual operating and maintenance costs could be determined. Based on these data, unit operating costs were calculated and are presented in Table 6-6. Numerous assumptions with respect to the mode of operation of the units were made and these are outlined in greater detail in the U.S. EPA report.

Lot River. No information was provided on the capital costs of the system. However, operating cost data were provided and are set out in Table 6-7.

6.8 Future Status of Case Study Processes and the Technology as a Whole

6.8.1 Air Stripping and Activated Carbon

The design of air stripping and activated carbon processes is highly developed and well understood. Mathematical models exist for both processes. The design of processes to treat the emissions from an air stripper are also well developed. However, the Ville Mercier experience reinforces the need for careful consideration of the types of contaminants to be treated for successful process design and performance.

Both unit operations can be designed by qualified consultants. Proprietary systems are also commercially available. Recently, several novel proprietary air strippers, which supposedly have advantages over packed towers, have come onto the market place.

Areas anticipated for research and development relate to more cost-effective processes for the treatment of air emissions from air strippers. In part, this is expected because of the likelihood that regulatory agencies will not allow untreated air emissions from air strippers in the future.

Future developments may relate to the use of more specific resins for the recovery of organics from liquid or gaseous streams, or to the use of membrane technologies, such as pervaporation to remove the or-

Table 6-6. Estimated capital and operating costs associated with three Ultrox® system units (in US$, 1990).

Item	Treatment Flow Rate		
	75 L/min	375 L/min	950 L/min
CAPITAL COSTS			
Site preparation costs	36,000	55,000	75,000
Permitting and regulatory costs	3,500	7,500	13,000
Capital equipment costs	70,000	150,000	260,000
Startup and fixed costs	32,000	32,000	32,000
Site demobilizing costs	2,000	3,000	4,000
Total One-Time Costs	143,500	247,500	384,000
OPERATING & MAINTENANCE COSTS			
Labor costs	6,600	6,600	6,600
Supply and consumable costs	10,500	16,500	20,800
Utility costs	12,000	58,000	145,000
Effluent monitoring and disposal costs	3,000	3,000	3,000
Residuals and waste shipping, handling, and transporting costs	1,000	5,000	7,000
Analytical costs	24,000	24,000	24,000
Equipment repair and replacement costs	4,000	22,000	33,000
Total Annual Operation and Maintenance Costs	61,100	135,100	239,400
CALCULATED UNIT COST, US$ PER 3750L	5.82	2.57	1.82

ganics, condense them into a small volume, and either purify them or destroy them using other processes.

6.8.2 Photo-oxidation Technologies

The Ultrox® technology is one example of a class of technologies generally called "advanced oxidation processes". A number of competing processes which are a variation of the Ultrox® technology are commercially available. Some of these use only the oxidants H_2O_2 and O_3; others use medium pressure UV lamps in combination with H_2O_2 or O_3.

Advances will come as we increase our understanding of the process and can therefore more readily define optimum process operating conditions.

Other advances are likely to occur in the areas of reducing power consumption, ameliorating the effects of foulants, such as iron and manganese, and combining the process with membrane technologies to treat a broader mix of contaminants.

As there are no residuals from these processes and when operating experience is gained with these processes, the future looks promising as regulations with respect to the treatment of emissions become more stringent. (It should be noted, however, that there may be residuals associated with pretreatment processes.)

Table 6-7. Lot River operating costs (in French francs).

Chemicals	2,460 F/d
Handling	600 F/d
Energy	2,190 F/d
Analyses	260 F/d
Maintenance	1,890 F/d
Personnel	2,830 F/d
TOTAL	10,230 F/d
CALCULATED UNIT COSTS/M³**	12 to 33 F/m³
	US$2 to US$6/m³ (approx.)

*5 French francs = approximately US$1.
**Cost is variable depending upon the flow to the plant which can vary from 20 to 50 m³/h.

6.8.3 Precipitation Technology

This technology is readily available and can either be designed or can be purchased as a "turnkey" package from a number of vendors.

The technology is highly developed. Residuals in effluents may be lowered through the use of "tertiary" processes after clarifiers. These generally consist of either granular media filtration or membrane "filtration". Both processes are commercially available.

If sludge disposal is a serious problem, specific resins or "adsorbents" may be used as an alternative, thus eliminating sludge production. However, the metals must then be removed from the resins or adsorbents and preferably recovered, with any chemicals used being recycled. Obviously if simply another sludge is produced, there is no point in using this alternative.

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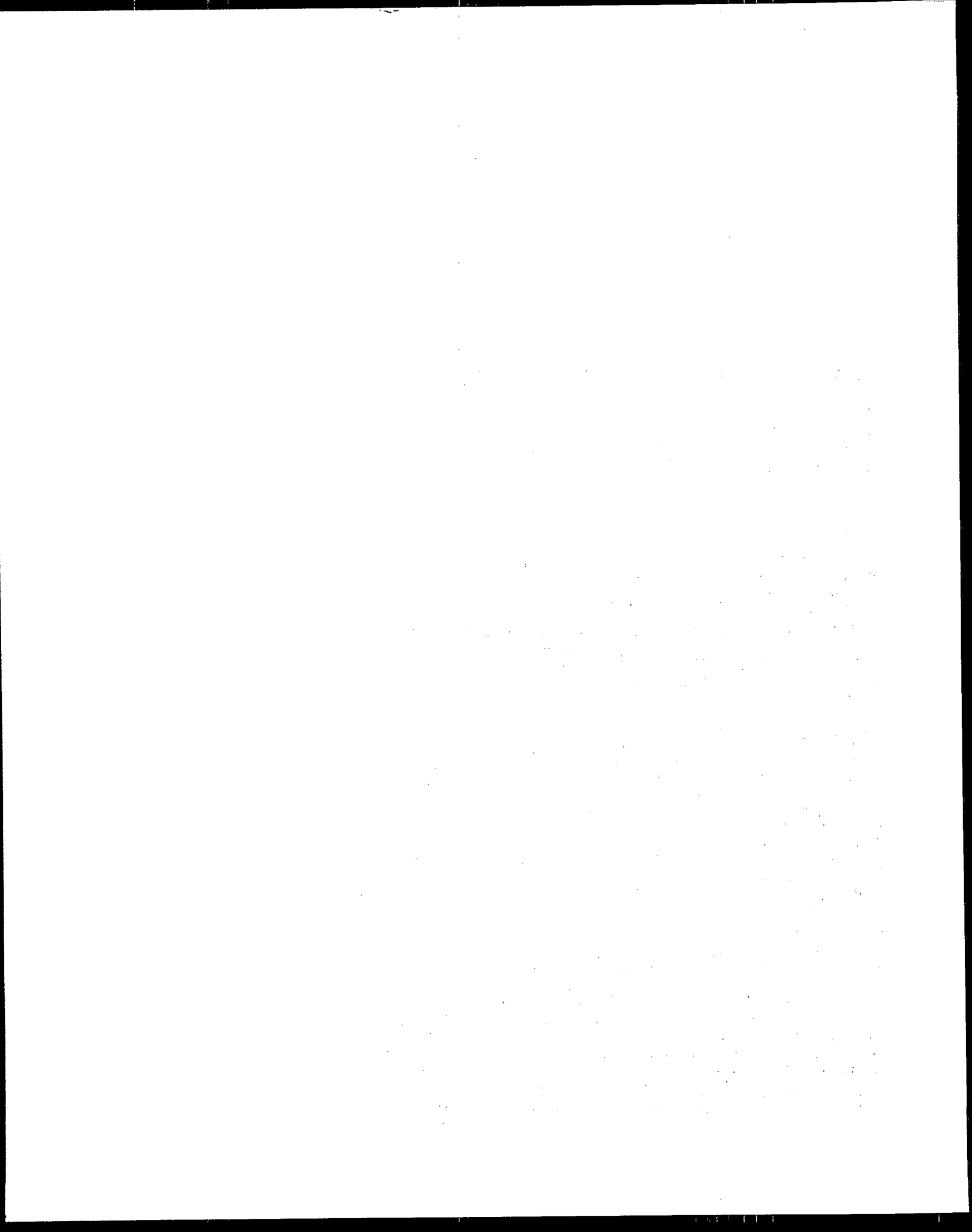
Chemical Treatment of Contaminated Soils: APEG

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ABSTRACT

The conversion of halogenated compounds (particularly PCB's) in contaminated soils into far less harmful products may be carried out using an alkaline metal hydroxide with polyethylene glycol (APEG). Processes of this type are applicable to soils and soil-like materials (after excavation) contaminated with either aromatic or aliphatic chlorinated organic compounds; the latter require more rigorous treatment conditions.

In general terms, the reagent (APEG) dehalogenates the pollutant to form a gylcol ether and/or a hydroxylated compound and an alkali metal chloride which are water soluble. There are many variants of the general process, many covered by patents etc. The most widely used version uses potassium hydroxide in combination with polyethylene glycol to form a polymeric alkoxide anion referred to as KPEG. The end products of the technology are regarded as nontoxic and having minimal environmental impact.

7.1 Introduction

This chapter is about the chemical treatment, or dehalogenation, of soils contaminated with chlorinated organic compounds, using an alkaline metal hydroxide with polyethylene glycol (APEG). A schematic drawing of an APEG application is shown in Figure 7-1. The soil is screened to remove debris and large objects, homogenized, and reduced in size to allow treatment in the reactor without the soil binding to the mixer blades and to permit close contact of the contaminants with the reagents. Because water inhibits the reaction, it may be necessary to dry the soil before treatment.

Typically the reagents are mixed thoroughly with the contaminated soil in a reactor which is heated to 100 to 180 °C (the range 25-150 °C has also been quoted (U.S. EPA 1989b). The reaction proceeds for 1 to 5 hours depending upon the type, quantity and concentration of the contaminants. The treated material goes from the reactor to a separator where the reagent is removed and can be recycled.

During the reaction, water vaporizing from the reactor is condensed and collected for further treatment or recycling through the washing process, if required. Carbon filters are used to trap any volatile organics that are not condensed. The soil is washed with water to remove residual reagents and products, and neutralized by the addition of acid. It is then dewatered before disposal. The treated soil may be returned to beneficial use with appropriate amendment with fertilizers etc.

7.1.1 Applicability

APEG processes are applicable to contaminants in soils, sludges, sediments and oils. These processes are mainly used to treat chlorinated aromatic or aliphatic organics such as polychlorinated biphenyls (PCB's), polychlorinated dibenzo-p-dioxins (PCDD), polychlorinated dibenzofurans (PCDF's), polychlorinated terphenyls (PCTP's), chlorobenzenes, and some halogenated pesticides and herbicides.

The concentrations of PCB's treated are reported to be as high as 45000 mg/kg (4.5 percent); concentrations in this case were reduced to less than 2 mg/kg per individual PCB congener (U.S. EPA 1990). However, there are reported to be limitations to the
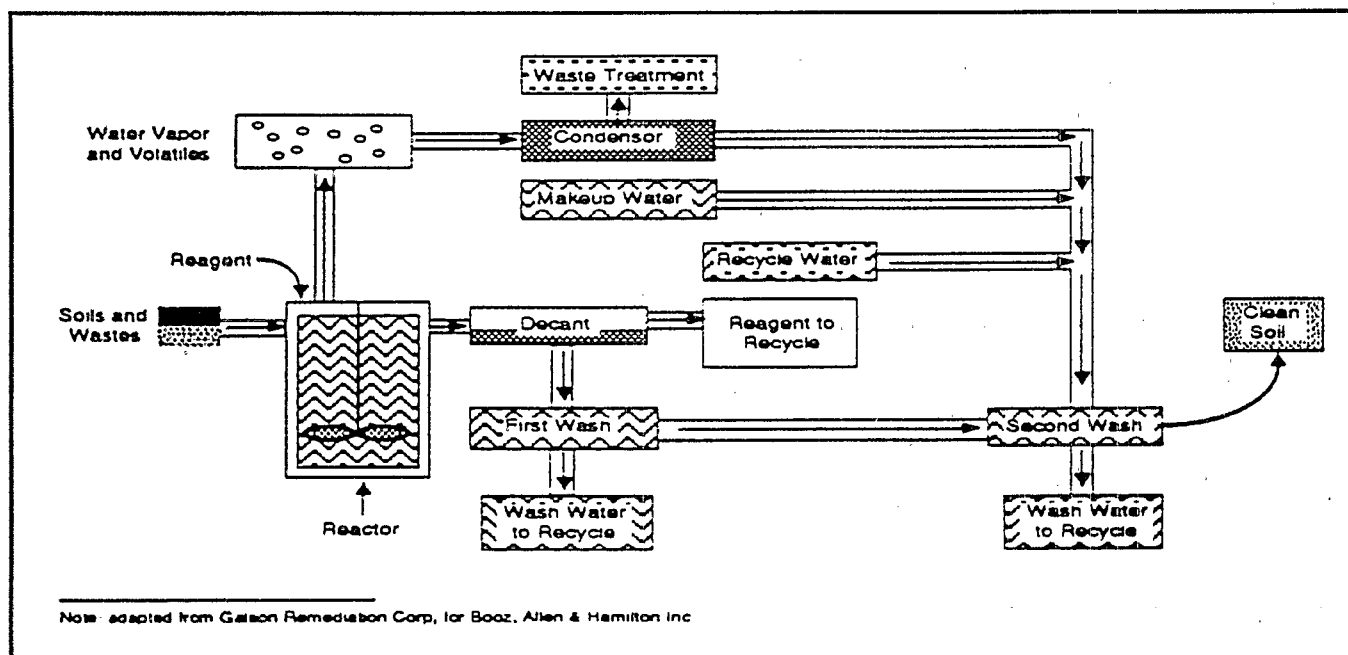
Figure 7-1. Schematic diagram of a typical glycol dehalogenation treatment facility.

process with regards to lower weight Aroclors; DMSO-based processes may not work on Aroclor 1240 for example (see below).Polychlorinated dibenzo-p-dioxins (PCCD's - "dioxins") and polychlorinated dibenzofurans (PCDF's - "furans") have been treated to nondetectable levels at ng/kg (parts per trillion) sensitivity (U.S. EPA 1990).

APEG technology, preferably using the reagent KTEG (potassium tetraethylene glycol), will dehalogenate aliphatic compounds but higher temperatures and longer reaction times are required than for aromatic compounds.

7.1.2 Variations on the APEG Process

The most widely used variant of the process uses potassium hydroxide (KOH) with polyethylene glycol (PEG) to form a polymeric alkoxide anion, referred to as KPEG. This acts as an effective nucleophile and as a phase-transfer catalyst (Kornel and Rogers 1985). The presence of oxygen is an essential requirement of the process. The reactions involved are shown schematically in Figure 7-2.

In some KPEG reagent formulations to treat chlorinated aromatics, dimethyl sulfoxide (DMSO) is added to reduce the reaction time. Sofolane (SFLN - tetrahydrothiophene) may also be used to accelerate the reaction.

Although potassium hydroxide has been the most widely used reagent, sodium hydroxide has been used in the past and may be used increasingly in the future because of lower costs. Other possibilities include

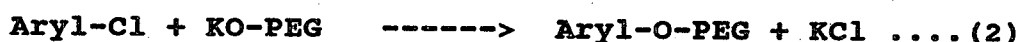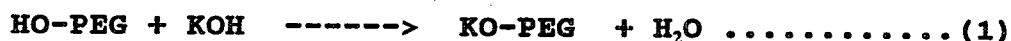combinations of potassium or sodium hydroxides with tetraethylene glycol (ATEG).

Proprietary variations include the "APEG-PLUS" treatment system which uses potassium hydroxide with DMSO marketed by the Galson Remediation Corporation and one offered by SDTX Technologies Inc who own the Fuller Institute patents (e.g. Pytlewski and Krevitz 1983).

The United States Environmental Protection Agency (U.S. EPA) has devoted effort to the development of KTEG (potassium tetraethylene glycol) processes for the treatment of halogenated aliphatic compounds (Kornel and Rogers 1985; Harden and Ramsay 1986; Rogers and Kornel 1987). When KTEG is used, a dehydrohalogenation reaction occurs. Halogenated compounds with one carbon atom react to form carbon dioxide and potassium halide. Compounds containing more than one carbon react to form acetylene (Rogers and Kornel 1987; Harden and Ramsay 1986). KTEG has been shown on a laboratory scale to work with compounds such as ethylene dibromide, carbon tetrachloride, ethylene dichloride, chloroform and dichloromethane (Harden and Ramsay 1986; Rogers and Kornel 1987).

7.1.3 Operational Requirements

Land is required for the operating plant, and for the safe and secure storage of reagents, soil to be treated, oversize material prior to crushing or disposal, and for treated soil pending certification that treatment has been effective.

$$HO-PEG + KOH \quad -----> \quad KO-PEG + H_2O \quad ....(1)$$

$$Aryl-Cl + KO-PEG \quad -----> \quad Aryl-O-PEG + KCl \quad ....(2)$$

$$Aryl-O-PEG \quad -----> \quad Aryl-OH + Vinyl-PEG \quad ....(3)$$

Note: *In reaction (1) the polyethylene glycol (PEG) is reacted with potassium hydroxide to form the reactive KPEG species. This preparative step may be performed directly in the contaminated matrix or externally. Reaction (2) takes place takes place over a wide temperature range from ambient to about 110C. Reaction (3) represents the conversion of the ether linked PEG/Aryl moeity to a phenolic with consequent release of a vinyl terminal polyethylene glycol.*

Equation (4) below represents this overall reaction.

$$R-(Cl)_x + A-PEG \quad --------> \quad R-(Cl)_y-OR' + ACl + R-(Cl)_y-OH \quad ...(4)$$
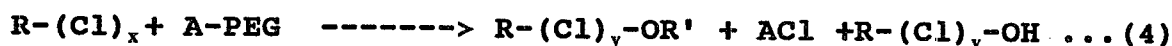
Figure 7-2. APEG reactions.

A supply of water is required. Energy is required to dry the materials to be treated, heat the reaction vessel, and to dry the treated materials. Electric power and a steam generating plant will be required; according to the U.S. EPA (U.S. EPA 1989b), a full-scale dehalogenation plant with a batch capacity of 60 m³ (80 yd³) requires an average of 670 kilowatts, (U.S. EPA 1989b). Such a plant might be expected to treat 120-150 m³ (160-200 yd³) in one working day.

On-site analytical facilities, including extraction equipment and gas chromatography/mass spectrometry, are required to monitor inputs and outputs from the process. Perimeter air monitoring may be required.

Contaminated soils and reagents are hazardous and a safety plan is required to ensure personnel safety, safety in plant operation, and to protect the environment.

7.2 Case Study Chosen

Only one case study was included in the NATO/CCMS Pilot study: the U.S. EPA's SITE (Superfund Innovative Technology Evaluation) Demonstration at Wide Beach, New York (U.S. EPA 1989a; U.S. EPA 1991b; U.S. EPA 1991a). This involved application of a KPEG process to the treatment of PCB-contaminated soils in combination with a complex four-stage "thermal processor".

7.2.1 Background

The Wide Beach site is located in a residential area south of Buffalo, New York. From 1968-1978, PCB (Aroclor 1264) contaminated waste oil was used for dust control on local roads at Wide Beach. About 155,000 liters of oil were applied. Following installation of a sewer in 1980, excavated contaminated soil was used as fill in residential gardens (yards) and a community recreation area.

Soil contamination in the area ranged from 0.18 to 1026 mg/kg in samples collected from residential driveways, roadways and drainage ditches. PCB concentrations in excess of 10 mg/kg were detected at depths of up to 1 meter in the soil in drainage ditches; in general, these concentrations reached only to about 0.15 to 0.3 meters in depth. It was estimated that 21,700 tonnes (15-16,000 m³) of soil were contaminated; about 43,000 tonnes of soil were actually processed.

A cleanup target of not more than 2 mg/kg was set (U.S. EPA 1989a; AOSTRA 1990).

7.2.2 The KPEG Demonstration Project

The remedial action at Wide Beach consisted of:

- Excavating soils with PCB concentrations greater than 10 mg/kg from all areas

- Excavating contaminated asphalt material from roadways for disposal off-site, with uncontaminated material being retained for reuse

- Treating the PCB contaminated soils in a continuous process using an Anaerobic Thermal Processor (ATP) in association with a KPEG process

- Using the cleaned soil as fill in excavated areas

- Repaving the roadways and driveways

- Treating perched water in the sewer trench (this water has been found to contain up to 10 μg/l PCB's).

After the work was completed, the residences were thoroughly cleaned to remove any stray dust, etc. (See Figure 7-3 for the overall flow of materials. See Appendix 7-A for a more detailed discussion of the process.)

7.3 Performance Results

The continuous-processing ATP technology was demonstrated in May 1991. Key findings of the demonstration were:

- The ATP unit removed PCB's in the contaminated soil to levels below the desired cleanup concentration of 2 mg/kg. PCB concentrations were reduced from an average concentration of 28.2 mg/kg in the contaminated feed soil to an average concentration of 0.043 mg/kg in the treated soil.

- The ATP does not appear to create dioxins and/or furans.

- No volatile or semivolatile organic degradation products were detected in the treated soil. There were also no leachable VOC's or SVOC's detected in the treated soil.

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

7.4 Residuals and Emissions

There are three main process streams: the treated soil, the wash water and, possibly, air emissions.

The treated soil will need to be analyzed to determine if it meets treatment objectives and/or regulatory requirements for disposal or re-use. The soil's acidity must be adjusted to a suitable value before disposal or reuse.

Research by the U.S. EPA has shown the by-product compounds to be neither toxic nor otherwise of concern (see for example Kornel and Rogers 1985). However this will only be the case if the process is carried out properly and dechlorination is complete. If full dechlorination is not achieved, toxic residual materials may remain (see Limitations below).

Waste wash water should contain only trace amounts of contaminants and reagents, and should meet appropriate discharge standards enabling it to be disposed to public sewer or surface water, subject to the usual licensing and regulatory requirements.

7.5 Limitations

Factors limiting the effectiveness of glycolate treatment include highly concentrated contaminants (greater than 5 percent), high water content (greater than 15 percent), low pH (less than 2.0), high humic content (soil), and the presence of alkaline-reactive materials (e.g., aluminium or other metals).

7.5.1 Inherent in the Technology

Although shown to be effective for a wide range of chlorinated hydrocarbons in a range of media, there are limitations to its effectiveness with regard to certain compounds such as lighterweight Aroclors (e.g., 1240, 1242) and hexachlorobenzene. This has been attributed, at least in the case of the latter (Rogers et al. 1991), to steric hindrance caused by the bulky nature of the attacking nucleophilic reagent, polyethylene glycoxide.

The apparent lack of information on the long term stability of the resulting products in the soil environment may also be limiting in some applications because it may be considered that the initial nontoxic nature of the reaction products can not be guaranteed to last.

These potential difficulties appear to be overcome in the combined thermal and KPEG treatment used at Wide Beach which appears to result in complete destruction of PCB's through combined chemical and thermal action.

7.5.2 Health and Safety

Treatment of certain chlorinated aliphatics in high concentrations with APEG may produce compounds that are potentially explosive (e.g. chloroacetlylenes) and/or cause a fire hazard. The use of DMSO or similar reagents may result in the formation of highly flammable volatile organics (e.g., methyl sulphide). Alkaline reactive materials such as aluminium can result in formation of hydrogen. Vapors from heating oily soils, which are often the matrix in which PCB's are found, can also create such potential problems as

TACIUK PROCESS SYSTEM BLOCK DIAGRAM
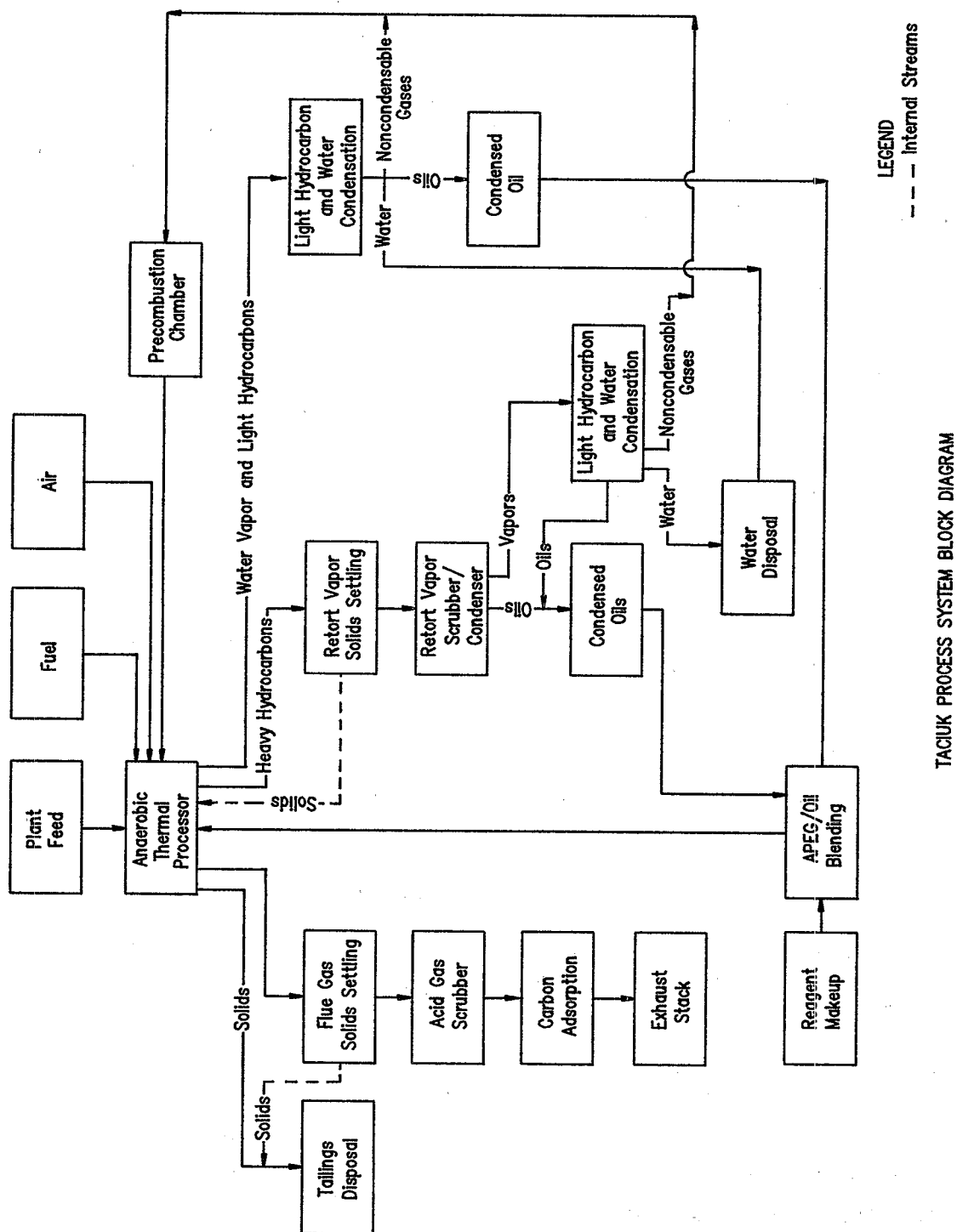
Figure 7-3. Block diagram of internal flow of materials.

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fires and noxious fumes. These potential problems can all be overcome by appropriate process design. The process must also be conducted with care because of the elevated temperatures and production of steam, the use of caustics in the process, and the acids used in neutralization. If DMSO is used, care must be taken to prevent contact of DMSO with skin. It is a powerful solvent and skin penetrant, and enhances transport of PCB's through the skin, thus increasing the risk of exposure. KTEG processes are exothermic and can produce vinyl halides as intermediate compounds. Special considerations will therefore apply in the design of plants to operate these processes (Harden and Ramsay 1986).

7.6 Costs

In September 1990 US$, costs were put at $220-550/tonne ($200-500/short ton).

One vendor quoted the average cost of treatability studies as US$2000-3000 depending on the chemistry of the target contaminant(s). Treatment costs were estimated to be $130-390/m^3 ($100-$300/yd^3) depending on site-specific factors (U.S. EPA 1989b).

Costs at the Wide Beach demonstration site had been estimated (U.S. EPA 1989a) as likely to be about $6,000,000 to treat about 15,000 m^3 (20,000 yd^3) of soil to achieve a level not greater than 2 mg/kg, i.e., about $390/m^3 ($300/yd^3). In practice, the contract value for the work was $15,500,000. Information on the details of this value is not available, nor is information on the cost of treating the larger than expected volume of soil (23,000 m^3) that was actually treated.

7.7 Factors to Consider for Determining Applicability of the Technology

Studies on materials to be treated should include determination of the nature and quantities of individual organic compounds present, and investigation of the presence of moisture, alkaline metals, organic matter content (humic content), clay content, glycol extractables content, presence of "multiple phases" and total organic halides, and other factors that have the potential to affect processing times, effectiveness and costs. The major difficulty is devising means to reduce processing times sufficiently to permit practical treatments to be effected.

Laboratory treatment studies should be carried out to determine optimum operating factors such as type and quantity of reagent to use, temperature and treatment time.

7.8 Future Status of the Technology

The KPEG technology demonstrated in Wide Beach has been selected for application for treatment of soils and sediments containing 500 to 500,000 mg/kg PCB's at Waukegan Harbour north of Chicago (de Percin 1991).

Batch processes of this type have also been shown to be effective in terms of reducing contaminant levels to acceptable concentrations in a number of applications (for example see Peterson 1990).

Variants of the process are available from a number of vendors. It is expected that work will continue to incorporate the dechlorination process with other treatment steps to ensure effective application to a range of contaminants and media. In addition, it is expected that efforts will be made to overcome the limitations to effectiveness mentioned above.

It should be noted however, that competitor technologies are being developed. One process in particular is catalytic transfer hydrogenation (Rogers et al. 1991) in which hydrogen is the reacting nucleophile. It is claimed that this process overcomes the problems of steric hindrance associated with the use polyethylene gylcol, and is thus capable of bringing about total dechlorination with formation of non-toxic reaction products.

In contrast, reports that quick lime might be an effective treatment agent for PCB's have been shown not to be true (U.S. EPA 1991c; Sedlak et al. 1991).

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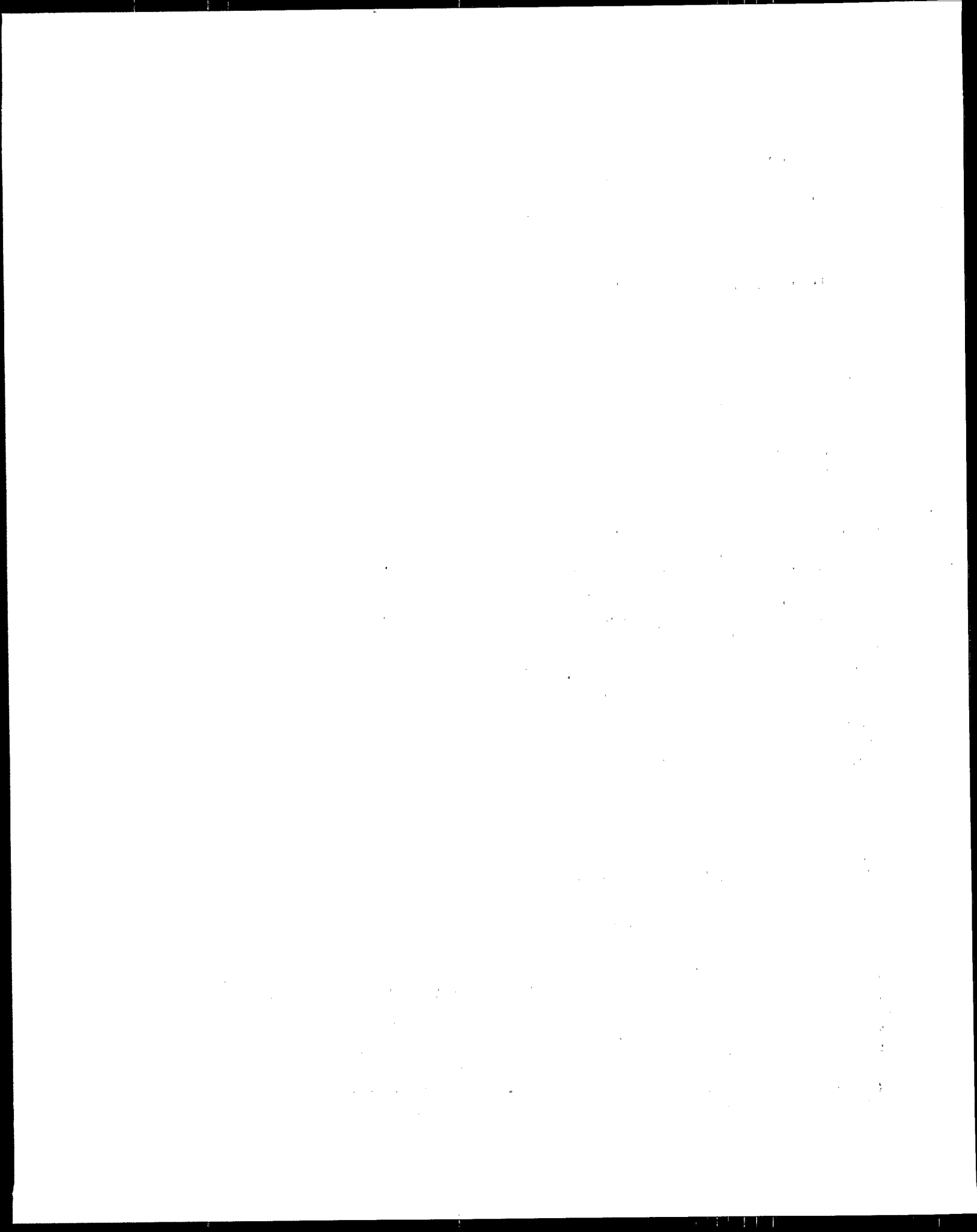
Microbial Treatment Technologies

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ABSTRACT

A large number of organic contaminants can be degraded by microorganisms. The compounds can vary from easily degradable compounds like monocyclic aromatics to more xenobiotic compounds like chlorinated aliphatics.

Basically, biological soil remediation techniques can be divided into three groups: *in situ* biodegradation, landfarming and composting, bioreactors.

An advantage of biological treatment is its cost-effectiveness. On the other hand, the treatment period is relatively long, ranging from a few weeks for composting up to a few weeks to several years for *in situ* biorestoration. Also, when treating soil biologically, it is typical that, depending on the type of soil and contaminant, some residual concentrations will remain after treatment. It has to be determined whether these low residual concentrations can be regarded as safe.

Given the high level of international research in microbial treatment, it is expected that the scope of application will be broadened in the coming years.

This NATO/CCMS Pilot Study included five case study reports regarding microbial treatment. In addition, as a NATO/CCMS Fellowship project, the study "International evaluation of *in situ* biorestoration of contaminated soil and ground water" was conducted. These studies are discussed in this chapter.

8.1 Introduction

A large number of organic contaminants can be degraded by microorganisms. The compounds can vary from easily degradable compounds like monocyclic aromatics (e.g., benzene) to more xenobiotic compounds (e.g., trichloroethylene, a halogenated hydrocarbon).

Biological treatment techniques for contaminated soil and ground water aim at optimizing conditions for promoting biodegradation of organic compounds therein. These factors are related to characteristics of the chemical compound, soil, and the indigenous population of microorganisms.

The chemical compound and its degradation pathway are decisive for the environmental characteristics to be chosen. For example, an aerobic environment should be chosen in the case of nonhalogenated contaminants, and an anaerobic environment should be chosen in most cases of halogenated contaminants, since the fastest degradation occurs under these conditions.

The purpose of biological treatment is the degradation of contaminants to harmless intermediates and end products to such a degree that the remaining concentrations of contaminants and degradation products are below the applicable standard. The ultimate goal is to reach complete mineralization of the contaminants, that is, degradation into CO_2 and H_2O.

Basically, biological soil remediation techniques can be divided into three groups:

- *In situ* biodegradation
- Landfarming and composting

■ Bioreactors.

The first technique is applied *in situ;* the latter two are applied on- or off-site.

In situ biodegradation of soil and ground water aims at the stimulation of the biological degradation of contaminants in the subsurface environment. Usually a recirculation system for ground water is installed. Contaminated ground water is treated above ground, after which oxygen and, if necessary, nutrients are added to the water that infiltrates the soil, in order to stimulate the indigenous microorganisms to degrade contaminants. The ground water treatment can consist of an air stripper for volatile contaminants or a biological treatment for dissolved contaminants.

Also, activated carbon filters are often used. Contaminants in the exhaust air from an air stripper can be removed by means of activated carbon or a biofilter with compost.

In addition to *in situ* biorestoration by means of recirculation of water, venting can be applied in order to stimulate the indigenous microorganisms to degrade contaminants and to remove volatile contaminants in the unsaturated zone.

With landfarming, contaminated soil is spread out over a certain land surface up to a thickness of about 0.40-0.60 meters. If necessary, nutrients are added. Regularly, the soil is mixed by means of agricultural implements in order to increase the biological degradation.

Composting is a treatment similar to landfarming. However, the soil is placed on heaps and materials such as wood chips or compost are usually added to facilitate the oxygen distribution through the heaps.

Bioreactors are used to treat more recalcitrant compounds, such as polynuclear aromatic hydrocarbons (PAH's). A soil-water(-air) system is used, in which several environmental factors can be controlled and maximized for optimal degradation.

8.2 Case Studies Chosen

The NATO/CCMS Pilot Study included five case studies regarding both *in situ* and on- or off-site microbial treatment technologies. In addition to these case studies, a NATO/CCMS Fellowship project under the Pilot Study was conducted: "International evaluation of *in situ* biorestoration of contaminated soil and ground water (Staps 1990)." In this Fellowship project, 21 *in situ* biorestoration projects in The Netherlands, Germany, and the United States were visited and evaluated. Because of the evaluating character of the Fellowship project, its results run through the "*in situ*" part of this chapter as a continuous thread.

A short description of the case studies is given below. Longer discussions are included in Appendix 8.

8.2.1   *In Situ* Projects

8.2.1.1   *Case Study 8-A: Aerobic/Anaerobic In Situ Degradation of Soil and Ground Water, Skrydstrup, Denmark*

The purpose of the project was to verify whether full-scale cleanup of ground water is possible using *in situ* biodegradation of chlorinated solvents.

Four separate research approaches to biorestoration have been initiated:

■ Biodegradation of chlorinated solvents in contaminated soil

■ Aerobic biodegradation of chlorinated solvents by addition of methane

■ Aerobic biodegradation of chlorinated solvents in the unsaturated zone by co-metabolism by oxidation of methane and/or propane gas

■ Anaerobic biodegradation of chlorinated solvents in the contaminated zone by addition of sodium acetate.

8.2.1.2   *Case Study 8-B: In Situ Biorestoration of Soil, Asten, The Netherlands*

The objective of this research and demonstration project is to study the technical and financial feasibility of *in situ* biorestoration of a subsurface soil contaminated with oily substances. The approach of the project started from a literature study (1983) and laboratory research, continued with column studies, and is ending up with a full-scale cleanup (started in 1990). Field data are currently not available. A simplified schematic is shown in Figure 8-1.

8.2.1.3   *Case Study 8-C: In Situ Enhanced Aerobic Restoration of Soil and Ground Water, Eglin Air Force Base (AFB), United States*

The project includes a full-scale biodegradation research project at a JP-4 jet fuel spill site on Eglin AFB near Ft. Walton Beach, Florida, United States. A treatment system was designed to compare the operational benefits and limitations of the following three hydrogen peroxide/nutrient application methods:

■ Injection wells

■ Infiltration galleries

■ Spray irrigation.

Figure 8-2 shows the system flow diagram.

8.2.2   *Ex Situ* Projects

8.2.2.1   *Case Study 8-D: Biological Pre-treatment of Ground Water, Bunschoten, The Netherlands*

The subject of this project is the pretreatment of ground water contaminated with hexachloro-
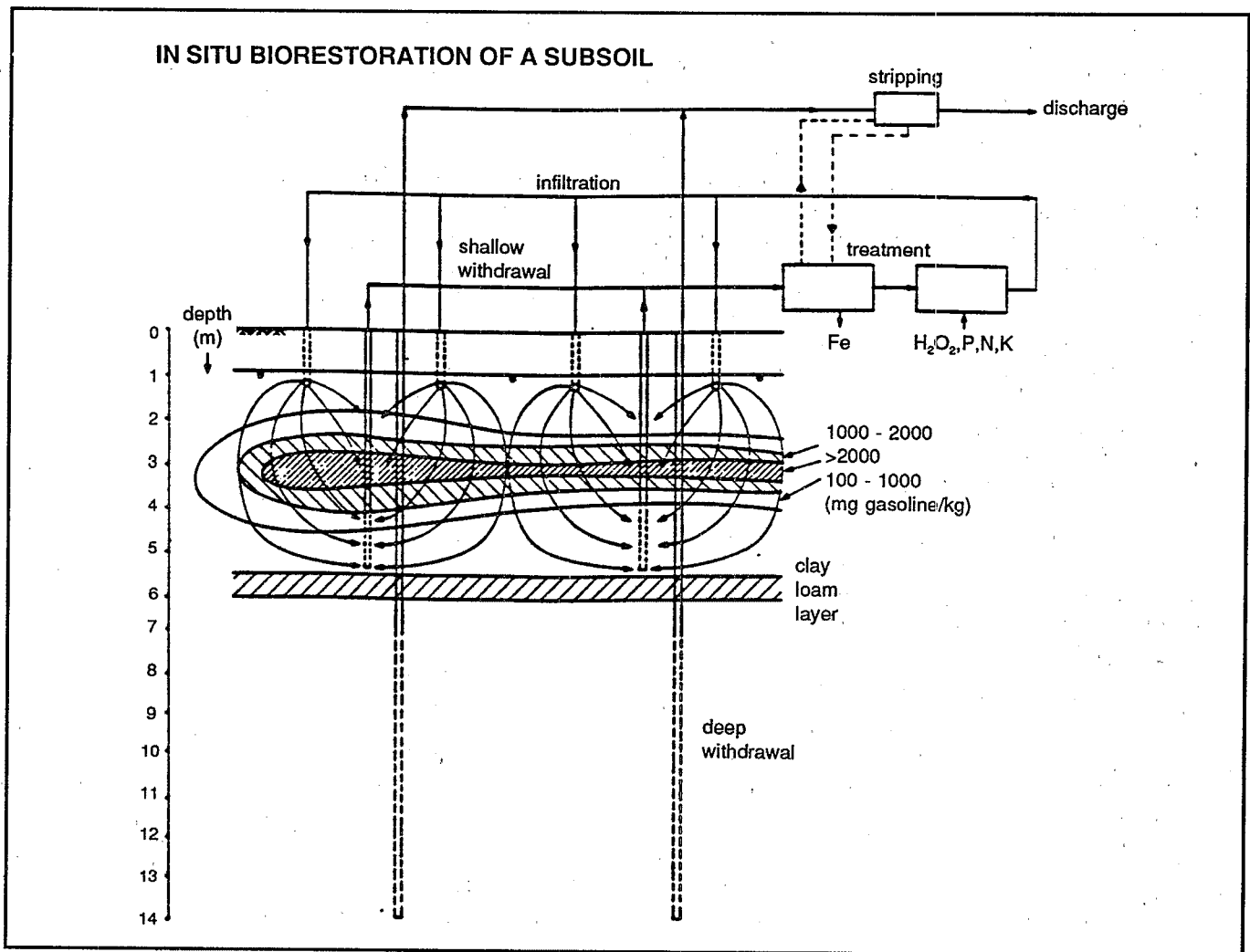
IN SITU BIORESTORATION OF A SUBSOIL

Figure 8-1. Cross-section of the soil with an overview of the restoration process.

cyclohexane (HCH, a pesticide), chlorobenzene, and benzene. The project concerns some small-scale experiments with a trickling filter and a rotating biological contactor. A simplified schematic is shown in Figure 8-3. The applied method is based on the following four main processes:

- Washing of contaminants from the soil by enhanced recirculation of purified water

- Purification of the pumped-up water by reverse osmosis (RO)

- Biological purification of the concentrate of RO (without inoculation)

- *In situ* biodegradation of contaminants in the soil. The present concept will be tested in a large-scale pilot project in The Netherlands.

8.2.2.2 Case Study 8-E: Rotary Composting Reactor for Oily Soils, Soest, The Netherlands

This biological treatment method was developed for off-site decontamination of oil-contaminated soil at field capacity. First, laboratory-scale studies were carried out in order to determine the optimum environmental conditions for oil degradation. Then the (research) project was carried out at a former municipal solid waste composting installation. The soil was treated in the rotating bioreactor, in which the soil temperature, oxygen, moisture, and nutrient levels can be adjusted. A schematic of the biological treatment process in the rotating bioreactor is shown in Figure 8-4.
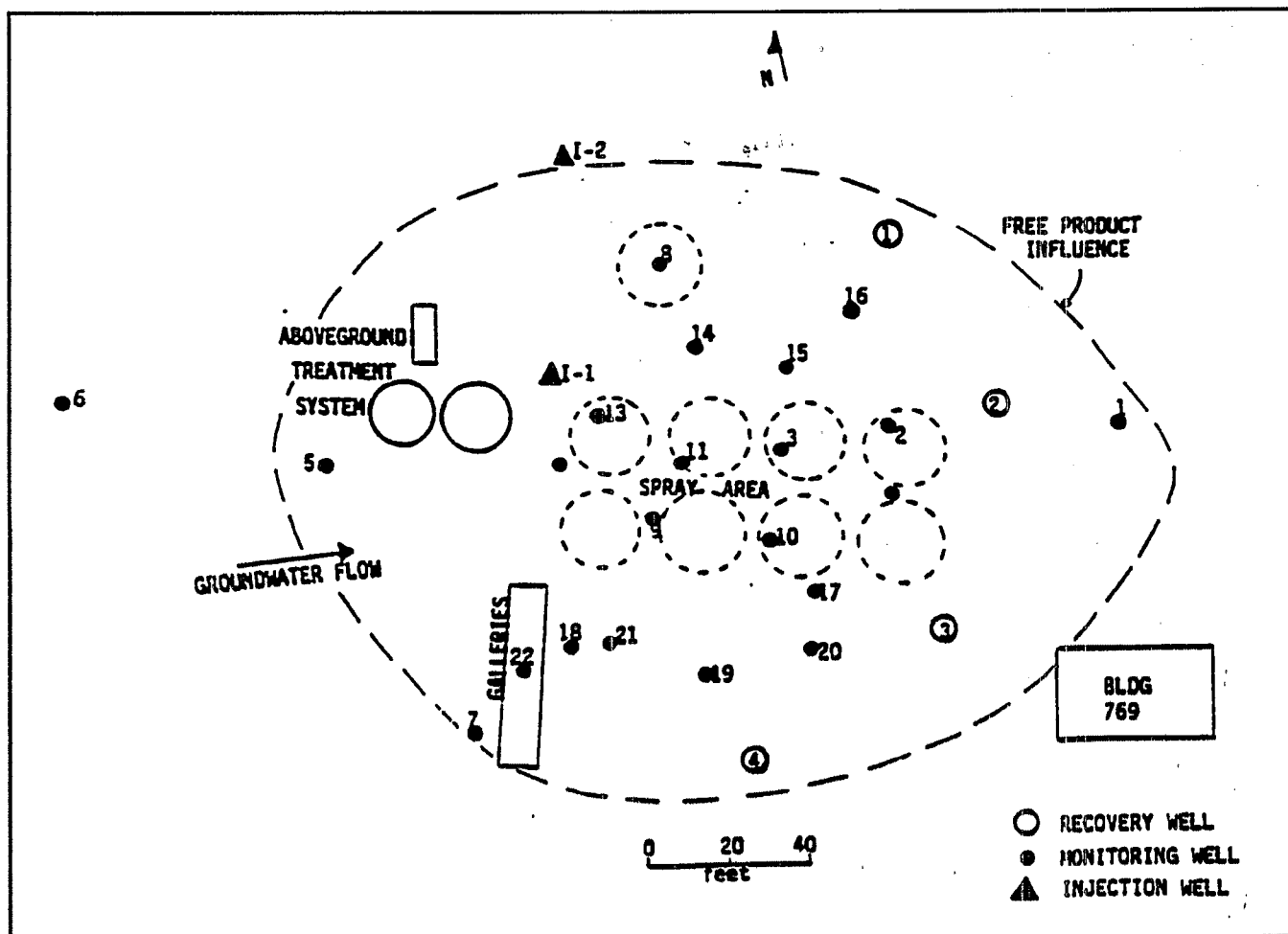
Figure 8-2. Eglin AFB Site profile.

8.3 Background of the Case Study Sites as a Group

When regarding the group of case study sites, it is evident that there is considerable heterogeneity. For example, the contamination sources include a chemical waste disposal site, a (former) gas and kerosene station, and a pesticide production facility. A municipal composting installation was also studied in relation to biodegradation.

These sources were responsible for the following range of contaminants:

- *Chlorinated* solvents
- Petrol
- JP-4 (an aviation fuel)
- Hexachlorocyclohexane (HCH, a pesticide) in different forms
- Diesel oil.

These contaminants are typical of the compounds that generally can be biologically degraded. They range from the easily degradable petrol to the more recalcitrant chlorinated compounds. Typically, the individual projects have to deal with a specific group of contaminants like mono-aromatic hydrocarbons, polynuclear aromatic hydrocarbons, or chlorinated hydrocarbons. Each of these groups has its own requirements for degradation.

Another example of the diversity of the project sites is that some required the treatment of soil, some of ground water, and some of both soil and ground water. Biodegradation was applied within the projects as follows:

- *In situ* treatment of both soil and ground water (in combination with on-site biological and chemical/physical treatment).

- On-site treatment of the ground water (both with and without physical/chemical treatment).

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■ On-site treatment of the soil (after excavation).

In two cases, the treatment was combined with excavation; in one case the waste from a chemical waste disposal site was excavated, after which *in situ* biorestoration of the ground water was applied. In a second case, the soil was biologically treated on site after being excavated.

8.4 Performance Results

In general, degradation results were assessed in relation to the original site concentrations of the contaminants (percent degradation). In order to get insight into the risks of the intermediate or residual concentrations, standards like the Dutch Examination Framework for Soil Pollutants were used in several projects.
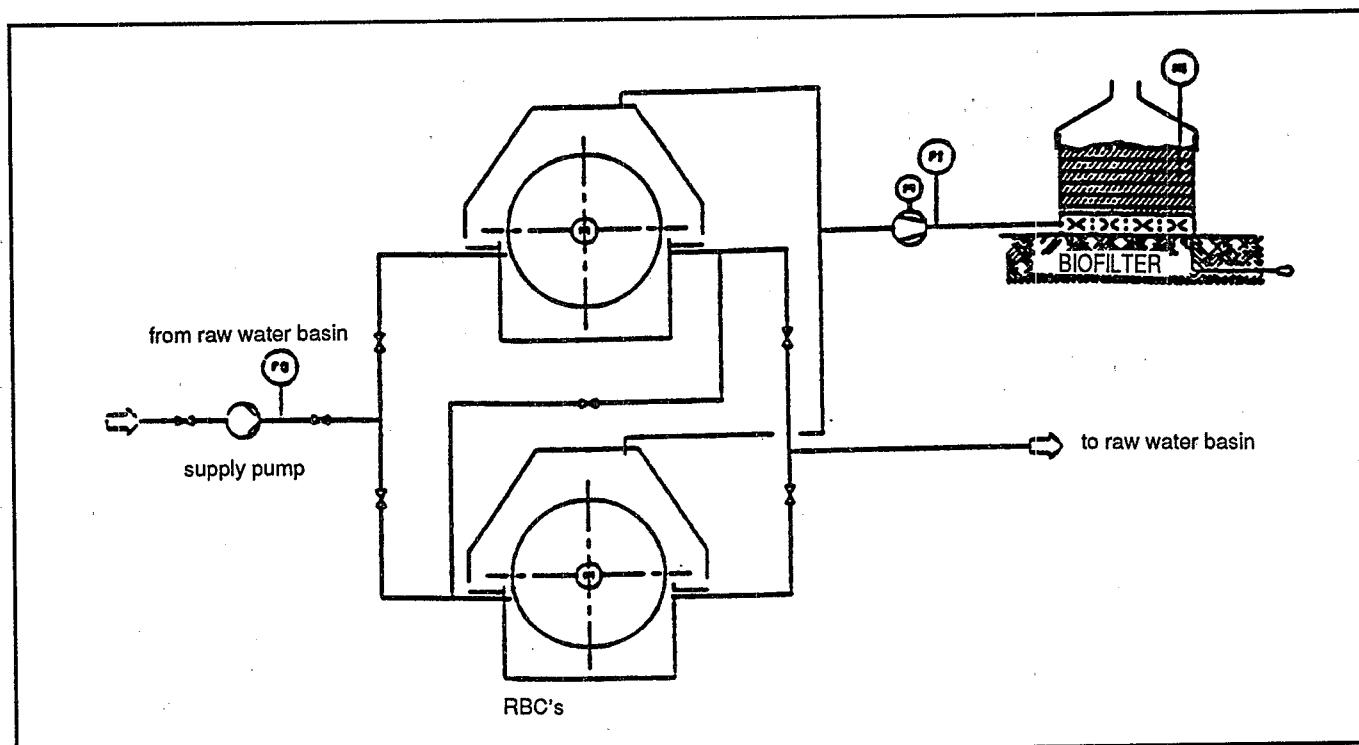

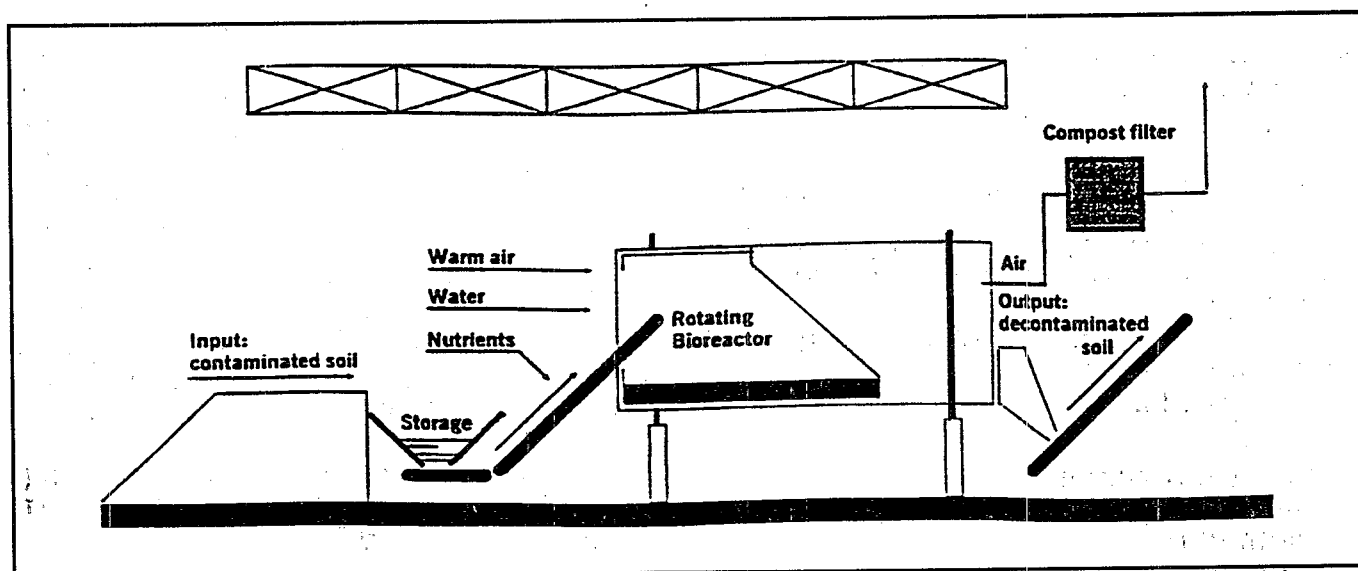Figure 8-3. Flow diagram of the RBCs and compost filters.

Figure 8-4. Biological treatment process in the rotating bioreactor.

Different countries require widely varying clean-up standards. For example, a project in The Netherlands started with a concentration level of mineral oil in the soil that in Germany is regarded to be a sufficient level of reclamation.

8.4.1 Common Effectiveness of Process Units

IN SITU BIORESTORATION

In situ biorestoration can technologically and financially compete with other technologies when it is applied at a suitable location and the process is well run. The remediation time can vary between a couple of months and several years, and is largely dependent on the initial concentrations, the kind of contaminants, the soil structure, and the cleanup requirements.

In The Netherlands, an Examination Framework for soil pollutants has been set up. In this Framework, three different indicative values can be distinguished:

- A - Reference value
- B - Indicative value for further investigation
- C - Indicative value for cleaning up.

In principle, the A-value must be reached when cleaning contaminated soils in The Netherlands. Residual concentrations below B-level, or even undetectable levels, have been reached with *in situ* biorestoration in projects for petrol, kerosene, diesel oil, fuel oil, mineral oil, and certain chlorinated hydrocarbons (e.g., 4-chloro-2-methylphenol) (Staps 1990).

In situ biodegradation of contaminated ground water (Case Study 8-A). Laboratory tests showed that tetra-chloroethylene (PCE), trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA) in sewage sludge can be degraded under anaerobic conditions. Lower chlorinated compounds are formed.

It was not possible to achieve anaerobic degradation of PCE, TCE or TCA in laboratory tests on sediment from the Skrydstrup aquifer. This might be due to the fact that there has not been a restricted anaerobic environment in the upper part of the aquifer. It was possible to build up a methane-oxidizing biomass which was able to degrade TCE and 1,1,1-TCA, but not PCE.

The ground water at Skrydstrup contains high concentrations of chlorinated aliphatics. Therefore, the toxicity of 1,1,1-TCA and TCE towards a mixed culture of methane-oxidizing bacteria was examined in batch experiments. The consumption of methane was inhibited, even by small concentrations of 1,1,1-TCA and TCE. A total inhibition of the methane consumption was observed at a TCE concentration of 13 mg/L, whereas a total inhibition was not observed at a 1,1,1-TCA concentration of 103 mg/L. Experiments also showed that the presence of methane inhibited the degradation of TCE.

Accumulation of dichloroethanes and dichloroethenes was observed in the leachate from the two sites of excavated soil from Skrydstrup, showing that anaerobic biodegradation had occurred at both sites. A significant amount of the contaminants from both sites has been removed, but it could not be determined how much had been removed by biodegradation and how much had been removed by other processes, such as stripping.

A pilot plant for aerobic on-site biodegradation of chlorinated aliphatics in ground water has been established at Skrydstrup. The plant was operated with different hydraulic retention times, in order to optimize the degradation of the chlorinated aliphatics. It was possible to obtain degradation of TCE of 40 percent with a hydraulic residence time of 3.5 hours. At the same time, a methane consumption of 85 percent was observed. Degradation of TCA did not occur. About 10 percent of 1,1,1-TCA and TCE were stripped. The plant was operated with alternating addition of methane to avoid competition between methane and chlorinated aliphatics, but it did not result in an increased degradation of TCE.

EX SITU BIODEGRADATION

Rotating biological contactor for biodegradation of HCH in ground water (Case Study 8-D). Over 90 percent removal of HCH, benzene, and chlorobenzene in the rotating biological contactor (RBC) can be attributed to biodegradation. Volatilization and adsorption onto the sludge are of minor importance to the total removal. αHCH and γHCH show a degradation rate of up to 70 percent. δHCH shows little breakdown, while ϵHCH and βHCH concentrations in the RBC remain constant. The mineralization of contaminants is complete; there were no metabolites found with gas chromatography/mass spectroscopy analysis.

Rotary composting bioreactor (Case Study 8-E). The production-scale trials of the rotary composting bioreactor indicate that, at a soil temperature of approximately 22 °C, the oil can be degraded. This process starts with concentrations up to 6000 mg oil/kg dry soil, and drops within one week to a residual concentration, varying from less than 50 to 350 mg/kg dry soil. In this process, the greatest microbial activity occurs in the first 3-4 days. In processes where other circumstances are present (temperature, oxygen content, humidity), results will be different.

Compost filter. Compost filters can be used to treat off-gas, mainly from air strippers that are used to remove volatile components from ground water on site. The system is based on adsorption of the contaminants on compost material, followed by biodegradation by microorganisms. Generally, performances of compost filters for treatment of air show poor results (i.e., approximately 70 percent for a broad

range of compounds). This is regardless of whether there is a mixture of compounds or an individual compound present.

8.4.2 Effectiveness of the Rotating Composting Bioreactor on Diesel Fuel

The approach in Case Study 8-E of using a composting installation for biological treatment of soil contaminated with diesel fuel is rather unique. Consequently, it has unique effectiveness for a biological system. Relatively low residual concentrations (less than 50-350 mg oil/kg dry soil) can be achieved in a relatively short time period (one week).

8.4.3 Lessons Learned on How to Improve Effectiveness

In situ **biorestoration.** Recirculation of the extracted ground water has positive effects on soil biodegradation. The reason for this is not yet precisely known. It might be due to the fact that surfactants, which are produced by microorganisms, are recirculated through the contaminated soil. Another explanation can be that the recirculating water contains degradation products, which can more easily be broken down than the original contaminants. In this way, there is an extra stimulation of the microbial activity, which influences the total biodegradation.

The positive effect of the addition of surfactants is still questionable. Fundamental research and practical experience indicate that the effect on degradation is negative. Detergents that can be applied need to be biodegradable (the original contamination should not be replaced by contamination with surfactants). However, in several research projects microorganisms preferred these surfactants as a food source and degraded the original contamination less than before surfactant addition.

When applying surfactants, clogging problems also occurred, due to complex interactions between soil surfactants, soil particles, contaminants, and microorganisms.

Addition of microorganisms to the subsoil, with the aim of enhancing the biodegradation, is being used by a few companies on a field scale. These microorganisms can either be selected in the laboratory or can be cultured at the laboratory after being sampled from the contaminated site. Although this approach has some potentially beneficial effect, it has not been proved to date. Cost-benefit calculations are unavailable.

The experiences with hydrogen peroxide (H_2O_2) as a supplemental oxygen source are not consistent with respect to effectiveness. While in the Asten project hydrogen peroxide was chosen as the most promising oxygen source after laboratory research, the results with H_2O_2 in the Eglin project are very disappointing. Currently, there is no explanation for this difference in

results. The differences may be due to enzymatic breakdown of H_2O_2 or due to abiotic degradation.

Another cause could be the different temperatures in Florida and The Netherlands. As long as the efficiency of hydrogen peroxide cannot be predicted, preliminary (field) treatability testing is necessary when considering its application.

Venting of volatile contaminating compounds in the unsaturated zone and treatment of these components above ground can be a cost-effective method for removal compared to *in situ* biorestoration by means of recirculation of water. Apart from the volatilization of contaminants, venting will enhance biodegradation because of the extra oxygen supply. Also combinations of venting in the unsaturated zone and the application of a water recirculation system can be cost-effective.

Off-site biorestoration. The application of an off-site rotating bioreactor for degrading oily contaminants (Case Study 8-E) is one way of improving the effectiveness of off-site biological soil treatment compared to other biological techniques like landfarming and *in situ* biorestoration.

8.4.4 Lessons Learned in Site Preparation and Testing

The success of *in situ* biorestoration, as all *in situ* technologies, largely depends on the permeability of the soil. Since the soil itself is used as a bioreactor, the permeability is the gate to the degradation. When permeability is limited, *in situ* biorestoration is adversely affected.

If the permeability of the soil allows *in situ* biorestoration, the most important limitation (for oily contaminants) is usually oxygen supply. In fact, in demonstration projects, oxygen is always the limiting factor. Understanding the behavior of oxygen in the subsoil and the possibilities for enhancing oxygen supply are the prime technological challenges to improving *in situ* biorestoration effectiveness.

Because of the general complexity of soils, the degradation process can never be predicted completely. Therefore, preliminary testing and evaluation, both in the laboratory and in field tests, will always be necessary. The field tests should include oxygen utilization rates and potential clogging problems. These clogging problems can occur as a result of the reaction of oxygen with iron or manganese present in the soil. Clogging can also be caused by excessive bacterial growth, due to the stimulation of microbial activity.

Biodegradation is necessarily limited to those organic compounds that can be degraded biologically. To date, there is a broad range of compounds that have been proved in principle to be biologically degradable. As research continues, more and more compounds can be added. Continued research and

demonstration will be needed to achieve biodegradation in the field.

Some contaminants seem to be only biodegradable in the presence of other, easily degradable contaminants. This degradation is called co-metabolism. For example, chlorinated alkenes can be degraded in the presence of oxygen and methane, while methane-oxidizing bacteria (methanotrophs) obtain energy from the oxidation of methane. The enzyme monooxygenase, which then is formed, brings about the degradation of chlorinated alkenes (McCarty et al. 1989; Janssen et al. 1987).

Inoculation with (selected) microorganisms has not been shown to improve degradation results. In most cases, the indigenous population, which has been adapted to the specific contamination present, can be stimulated in order to reach comparable degradation results. It is expected that the strategy and technology of isolating and selecting microorganisms will be most beneficial for very specific contaminants.

8.5 Residuals and Emissions

The residuals and emissions from biological treatment can be divided into the following categories:

- Residual concentrations of contaminants and intermediates in soil and ground water

- Emissions of contaminants and intermediates with the ground water being discharged

- Emissions of contaminants and intermediates into the air.

When treating soil biologically, it is typical that, depending on the type of soil and contaminant, some residual concentrations will remain after treatment. It has to be determined whether these low residual concentrations can be regarded as safe. Attention should also be paid to compounds that can be formed by biodegradation and in certain cases appear to be resistent to further degradation.

A similar problem is the presence of residual concentrations in the ground water; site-specific characteristics determine whether or not low concentrations of contaminants should be accepted as safe in the ground water to be discharged.

The above mentioned subjects of concern are also applicable to the exhaust air from either soil venting, (biological) ground water treatment, or composting. Petrol-contaminated soils should not be treated in a rotating bioreactor without provisions to reduce emissions of volatile aromatics into the air. At the Soest project no significant emissions of aromatics from diesel-polluted soils were measured. However, at the beginning of the incubation, hydrocarbon emissions of up to a few hundred mg/m^3 may sometimes occur.

The use of activated carbon to treat air emissions is a relatively expensive treatment method; consequently, a compost filter is potentially very welcome. However, the effectiveness of compost filters generally is rather poor. Catalytic oxidation can be a good alternative for larger amounts of contaminants in air to be treated.

8.6 Factors and Limitations to Consider for Determining Applicability of the Technology

A general advantage of biorestoration is the fact that it is an "environmentally sound" technology; there is very little or no generation of waste products. Attention should be paid, however, to the formation of intermediates, which in some cases, can be more harmful than the original contaminant (for example tetrachloroethylene degrading to vinyl chloride).

Another advantage of biological treatment is its cost-effectiveness. Off-site landfarming will generally be cheaper than alternative techniques like thermal treatment or soil washing after excavation. On the other hand, the treatment period is relatively long, ranging from a few weeks for composting up to one or two seasons for landfarming.

In situ biorestoration is often more cost-effective than *in situ* soil washing, largely due to the shorter time period that is needed for cleanup.

As mentioned earlier, it is typical that biological treatment will leave some residual concentrations of contaminants in the soil. This is caused by limitations in the "bio-availability" of contaminants at low concentration levels. The problem of bio-availability is not fully understood. Several factors might play a role. The concentrations may be too low to be favorable as an energy source for the microorganisms, or the concentrations can be too low to induce the production of certain enzymes necessary for biodegradation.

In certain countries, such as The Netherlands, the limited capability of microbial treatment to reach low residual concentrations may lead to limited or no possibilities for application. For example, the relatively low residual concentration of less than 50-350 mg/kg dry soil achieved in the Soest project is still higher than the A-level defined in the Interim Soil Clean-up Act (50 mg/kg dry soil for soil containing 10 percent organic matter).

As regards *in situ* biorestoration, the permeability of the soil is a very important parameter. Generally, a K$_f$-value of 10^{-5} m/s is regarded as being the minimum permeability required for successful application.

When considering the use of biological treatment, the following should be considered:

Biological treatment in general
- Biodegradability of contaminant(s)

- Microbial parameters (total cell count, nitrifiers, denitrifiers, hydrocarbon degraders)
- Inoculation
- Oxygen and redox conditions
- Oxygen demand (TOC, DOC, BOD)
- N_{total}, NH_4+, NO_3, NO_2 concentrations
- Phosphate concentration
- Nutrient demand
- Contaminant degradation rate
- Bio-availability
- pH
- Temperature
- Concentration of potential toxic components
- Mass balance (contribution of biodegradation versus vaporization)
- Formation and fate of intermediates
- Residual concentrations of contaminant and intermediates.

In situ biorestoration

- Partition of contaminants in soil and ground water
- Soil permeability
- (Geohydrological) isolation
- Fe and Mn concentrations
- Heterogeneity of the soil
- Behavior of the oxygen source in the subsoil and effectiveness of providing oxygen to microorganisms.

Biological treatment of ground water

- Partition of contaminants in soil and ground water
- Soil permeability.

Ex situ biological soil treatment

- Consequences for excavation and transport
- Partition of contaminants in soil and ground water.

When cleaning up contamination of both the soil and ground water, the partition of contaminants between soil and ground water is important. Most contaminants will be present both in an adsorbed form on soil particles and in a dissolved form in the ground water. The monitoring of the cleanup process can at first be based on the concentrations of contaminants in the ground water. When low concentrations in the ground water have been reached and there is a very slow decline in concentrations, the recirculation process should be stopped for a while in order to allow the concentrations in soil and ground water to reach a new equilibrium. This must be repeated several times. Only when the concentrations in the ground water do not rise after a period of rest and the concentrations in the soil are sufficiently low, can termination of the remedial action be considered.

8.7 Costs

In situ biorestoration. A wide range of site- and system-characteristics and remedial objectives influences the total costs for *in situ* biorestoration projects. Included are:

- Geology and soil structure
- Type and concentrations of contamination
- Distribution of contaminants in the subsoil
- Total surface and volume of the contaminated area
- System characteristics: recirculation, water and gas treatment, etc.

In the case of the Asten site (Case Study 8-B), total costs for *in situ* biorestoration of a sandy soil and ground water contaminated with petrol are estimated to be about 70-80 percent of the costs for excavation and treatment off-site. As regards total costs, a great advantage of *in situ* biorestoration for industrial sites is the fact that commercial activities can be continued during the cleanup period; because the process occurs largely in the soil itself, there is no need for stopping industrial activities.

For smaller sites, like petrol stations, costs vary between 40 and 250 US$/m^3 (1990). For larger sites, costs are estimated up to 150 US$/m^3. Of these costs, operating and maintenance costs account for about two-thirds of the total costs. Generally, approximately one-third of the cost is due to preliminary research and installation costs, which occur in about equal amounts (Staps 1990).

If applicable, *in situ* biorestoration will in many cases be more cost-effective than other techniques, such as incineration, or soil washing of the excavated soil plus treatment of the ground water (approximately 70-170 US$/m^3 excluding excavation and transport costs).

On-site biological treatment of ground water. The on-site treatment of HCH-contaminated ground water with the rotating biological contactor (RBC) is estimated to lead to a cost reduction of at least 30 percent (with costs ranging from US$102,000 to US$130,000) compared to using activated carbon plus physical/chemical treatment alone (costing US$175,000). In Table 8-1, treatment costs are given in relation to treatment techniques and removal efficiencies. For a combined biological/physical/chemical treatment, costs have been calculated for three different biological removal efficiencies. Also costs for a one-stage physical/chemical treatment without biological pretreatment are given.

Table 8-1. Costs of control techniques by levels of pollutant removal efficiency (in US$).

| Removal efficiency, RBC | | Costs | | | |
HCH	Benzene/ Chlorobenzene	RBC	Activated carbon	Physical/ chemical installation	Total
70%	95%	55,000	7,500	40,000	102,500
60%	95%	45,000	10,000	50,000	105,000
20%	60%	17,500	50,000	62,500	130,000
0	0	-	100,000	75,000	175,000

8.8 Future Status of Case Study Processes and Microbial Treatment as a Whole

8.8.1 Future Status of Case Studies

Results of demonstration tests on applying biological treatment as a substitute to airstripping at the Skrydstrup site (Case Study 8-A) are promising. Therefore, additional experiments will be carried out and full-scale treatment is likely to be applied. As the operation of the airstripping unit brings along high energy costs, biological methods are regarded as a very relevant alternative to bring down operation costs. The monitoring of soil will continue with additional microbiological investigations in the two compartments.

The laboratory and column studies related to the Asten site (Case Study 8-B) were finished in 1989. The full-scale cleanup was started in 1990 and is expected to be finished in 1992.

Because of the poor results obtained in using hydrogen peroxide at the Eglin site (Case Study 8-C) and cost estimates that were very high for cleanup, the Air Force decided not to cleanup the site with *in situ* biorestoration.

The research project related to RBC-application for on-site ground water treatment at Bunschoten (Case Study 8-D) was finished. Because of the project results, it was recommended that more biological techniques like RBC's should be applied in ground water remedial action, especially for (chlorinated) aromatic contaminants.

Based on the results of the rotating bioreactor at Soest (Case Study 8-E), it cannot be guaranteed that the A-level for mineral oil, required by The Netherlands, will be achieved by soil treatment in the bioreactor. Therefore, there are no practical applications for this kind of biological cleaning of oil-contaminated soil in The Netherlands.

8.8.2 Future Status of Microbial Treatment In General

Given the level of international research in the area of microbial treatment, it is expected that the scope of application will be broadened in the coming years. More compounds will be proven to be susceptible to microbial degradation. Thus, the importance of microbial treatment might improve in the future. However, the status of microbial treatment will depend on the residual concentrations that can be reached and the standards that have been set by the authorities. For example, in The Netherlands, the applicability of microbial degradation is limited because of the relative severely standards.

Available research indicates that there is a factor called "bio-availability", which refers to limits on the availability of the contaminants in the soil to the water. In order to be available for microorganisms, the contaminants must be dissolved in the water. Bio-availability is of major concern for compounds with a low water solubility. This is one of the current obstacles for broadening the field to the further application of microbial treatment.

As regards the range of compounds that can be degraded by means of microbial treatment, there can be a further extension of applicability to other compounds like PAHs or other chlorinated compounds. The permeability of the soil will remain a specific limitation for the application of *in situ* biorestoration.

The status of microbial treatment for ground water is expected to have more possibilities for growth, because here the microbial treatment is often followed by a polishing step, for example, with activated carbon. The philosophy here is that every bit of biological degradation that can happen first helps reduce total treatment costs when alternative and more expensive technologies must be added at the end.

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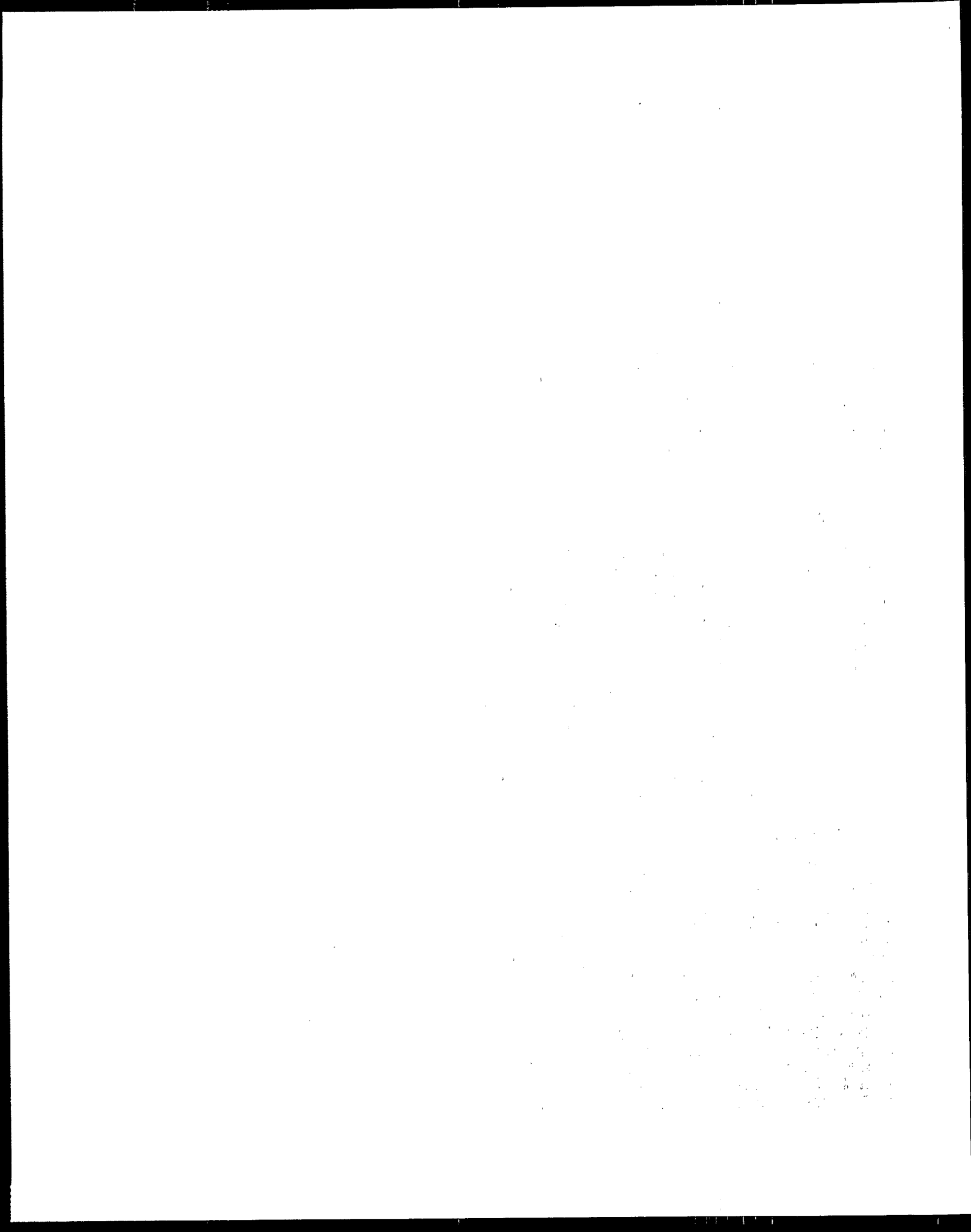
Selecting Remedies at a Complex Hazardous Waste Site

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ABSTRACT

Selecting remedies at a complex hazardous waste site is a difficult but necessary process. Countries use a variety of approaches. This chapter uses the Stringfellow Site in California, United States (U.S.) as a case study to describe the process used by the United States Environmental Protection Agency (U.S. EPA) and examine remedial selection problems of mutual concern to many countries. The environmental problem at the Stringfellow Site and the remedy selection process are described. Major conclusions include:

- Selecting remedies at a complex site requires a methodical approach to move from uncertainty to rational decisions.

- Flexibility within the process must be maintained to address inevitable unforeseen circumstances.

- Conducting treatability studies as early as possible and arriving at conclusions from interim remedies are important in effective remedy selection.

- Constructing remedies is not the final chapter in cleaning up complex sites; long term monitoring is required to validate remedial hypotheses and to determine success.

9.1 Introduction

Selecting remedies at a complex hazardous waste site is a difficult, but necessary process. A variety of approaches are used by countries. The process selected by a given country is driven by such variables as sense of urgency, philosophical approach, degree of experience and funds available. To illustrate the process used by the U.S. and to highlight areas of mutual concern for many countries, a case study is included below. This case study describes the remedy selection process at a U.S. site.

During the 1950's, southern California was undergoing rapid post-war industrial growth. One unfortunate outcome was the generation of increasing amounts of hazardous waste. Consequently, the State of California began seeking safe disposal sites for these waste products. This search led to Pyrite Canyon, a box canyon on the southern slopes of the Jurupa Mountains, approximately 80 kilometers (50 miles) east of Los Angeles, California (see Figure 9-1).

nderlying the shallow alluvium in Pyrite Canyon is bedrock of metamorphic and igneous origin. It was reasoned that the combination of the bedrock floor, a cemented alluvial cone, and the construction of a concrete barrier dam across the surface drainage channel could provide a suitable location for a disposal site.

In 1955, the Stringfellow Quarry Company received a permit to operate a hazardous waste disposal facility in the canyon. The 6.9 hectares (17 acres) disposal site was operated from 1956-1972 and consisted of as many as 20 surface impoundments (see Figure 9-2). About 200 industries sent 130 million liters (34 million gallons) of liquid industrial process wastes containing
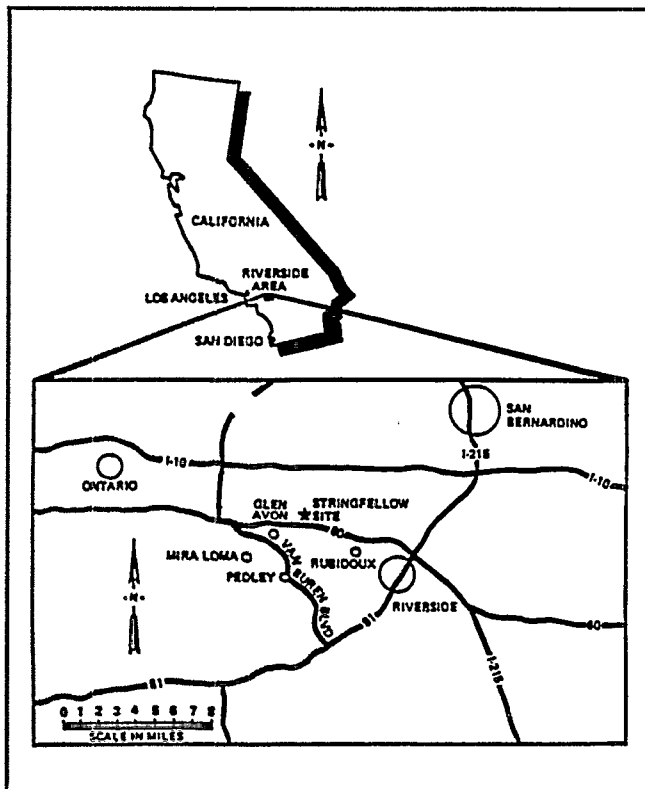
Figure 9-1. Location of the Stringfellow Waste Disposal Site.

Figure 9-2. General site configuration by 1972 for disposal operations.

spent acids and caustics, solvents, pesticide by-products, metals, and other inorganic and organic contaminants to the site by trucks which discharged the wastes into the ponds.

In 1968, site operators noted soil discoloration on the downgradient side of the concrete barrier dam. Over the next several years, the site had an increasing number of problems. These problems included surface water overflow during heavy rains, and the appearance of inorganics in ground water at the site monitoring well which was over 1,000 meters (3,400 feet) downgradient from the site. These events culminated in November 1972 with the voluntary closing of the site and, despite subsequent efforts to reopen it, the site's land use permit was revoked in 1974. Subsequently, the site reverted to the State of California because the owners had not paid taxes.

9.2 Interim Studies/Remedies

Between 1975 and 1982 the State of California conducted studies and implemented interim remedies at the site, though with limited budgets. The studies determined that:

- The cemented alluvial cone was underlain by an alluvial, permeable stream channel extending to about 27 meters (90 feet) below grade.
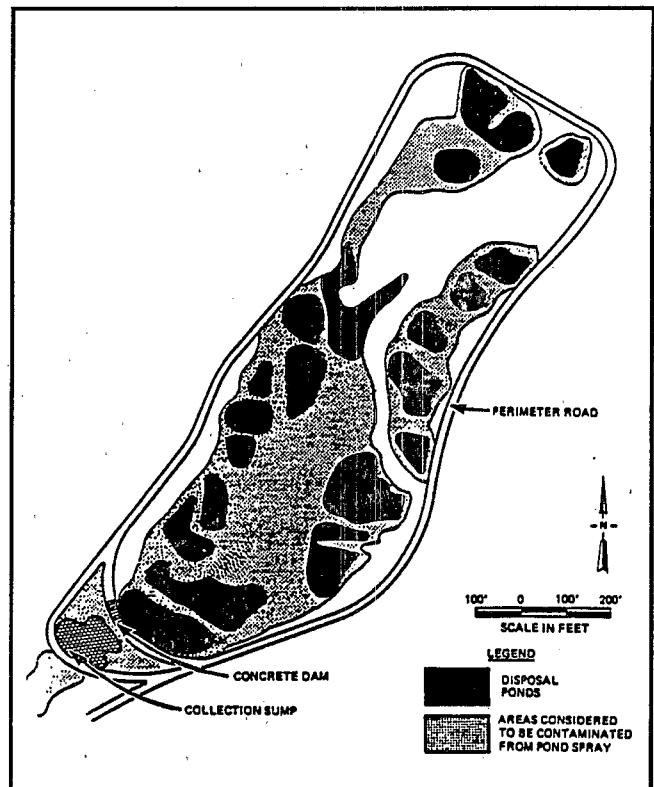
- The bedrock underlying the downgradient end of the site and the concrete barrier dam were fractured, providing potential pathways for off-site contaminant migration.

- Ground waters were entering the site from upgradient springs.

- Permeable, alluvial materials existed next to both ends of the concrete barrier dam, providing additional potential pathways of contaminant migration.

- Site-related contaminants, including metals and chlorinated organics, were found in ground waters at and downgradient from the site.

Interim remedial actions conducted during this period included:

- Millions of liters of on-site pond liquids were hauled off-site for disposal.

- Pond bottoms and soils from the northern half of the disposal site were excavated down to bedrock and moved to the southern half of the site.

- Lime kiln dust was disked into surface materials of the southern half of the site; kiln dust was placed over the entire disposal site. These ac-

tions were taken in an unsuccessful effort to neutralize the highly acidic wastes.

■ French drains were placed along bedrock lows in the northern half of the site to carry subsurface liquids to a sump from which they could be pumped to off-site storage and disposal.

■ An east-west clay-core barrier dam approximately 240 meters (800 feet) long was constructed near the old concrete dam, from canyon wall to canyon wall and from surface to bedrock.

■ A french drain was placed at the upgradient base of the clay core barrier dam to take hydraulic pressure off the dam and carry liquid to two sumps for pumping to off-site storage and disposal.

■ Silica gel was injected into fractured bedrock underlying the clay core dam in an effort to seal fractures.

■ The disposal site was covered with an approximately 0.3 meter (1 foot) layer of clayey material, and then a 0.3 meter (1 foot) layer of topsoil.

■ A surface drainage system was installed on the sides of the disposal site to carry uncontaminated runoff around the site.

■ A 14-well monitoring network was installed downgradient from the site.

■ Approximately 760 cubic meters (1,000 cubic yards) of DDT-contaminated soil were removed from the site and disposed of offsite.

■ Two mid-canyon extraction wells were constructed approximately 600 meters (2,000 feet) downgradient from the barrier dam.

In 1980, things changed in many ways when the U.S. passed the Comprehensive Environmental Response, Cleanup and Liability Act (referred to as "Superfund") to deal with abandoned hazardous waste sites such as Stringfellow. In 1982 the site was placed on the U.S. EPA's National Priority List (NPL) as California's highest ranked site. Including the site on the NPL made it eligible for Superfund remedial action money.

9.3 Litigation

Work done at the Stringfellow site up to 1982 was significant but not sufficient to fully define the areal and vertical extent of contamination or to mitigate all contamination. By the fall of 1982, U.S. EPA had identified approximately 200 industries that had sent wastes to the site. Under Superfund, U.S. EPA notified these industries, as well as former owners/operators/transporters, that they had been identified as Potentially Responsible Parties (PRP's) and tried to have them accept responsibility for necessary studies and remedies.

Efforts toward a PRP-led cleanup failed, and in April 1983 the U.S. and State of California filed suit against 31 of the PRP's in U.S. District Court. The industries involved represented over 80 percent of the liquid volume that had been disposed at the site. These litigation efforts continue in one of the most heavily litigated cases in the U.S. While these efforts continue, U.S. EPA pays for the necessary studies/remedies with the intent of recovering costs from the responsible parties. In addition, the U.S. EPA and the State of California meet regularly with a technical committee of PRP companies to discuss site developments and to encourage PRP participation in necessary studies/remedies.

9.4 The Remedial Investigation/Feasibility Study (RI/FS) Process

In 1983, the U.S. and State of California decided to conduct a Remedial Investigation/Feasibility Study (RI/FS) at the Stringfellow site to determine the areal and vertical extent of contamination, assess risks, and select remedies.

The process which U.S. EPA uses to select remedies is specified in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) and is shown in Figure 9-3; the process seeks to gather progressively more and more detailed information. Once the agency receives information that there may be a problem, it conducts a Preliminary Assessment, which makes use of readily available information to see if further action is necessary. If it is, a Site Inspection is conducted which gathers more extensive information, perhaps including some sampling.

Data collected during the Preliminary Assessment/Site Inspection phases are put into a site scoring model. If the numeric score is high enough, the site is placed on the National Priorities List and a RI/FS is conducted. Throughout the process, investigators must be aware of the need for short term actions (e.g., removal of leaking drums, construction of a security fence, etc.); these are termed "Removal Actions" by the U.S. EPA. Similarly, if it becomes apparent during the often lengthy RI/FS process that interim remedial actions are called for (e.g., construction of a leachate treatment plant), they should be started rather than waiting for the whole process to be completed.

Once a decision has been made to conduct a RI/FS, a planning or Scoping phase is begun. This phase includes activities such as:

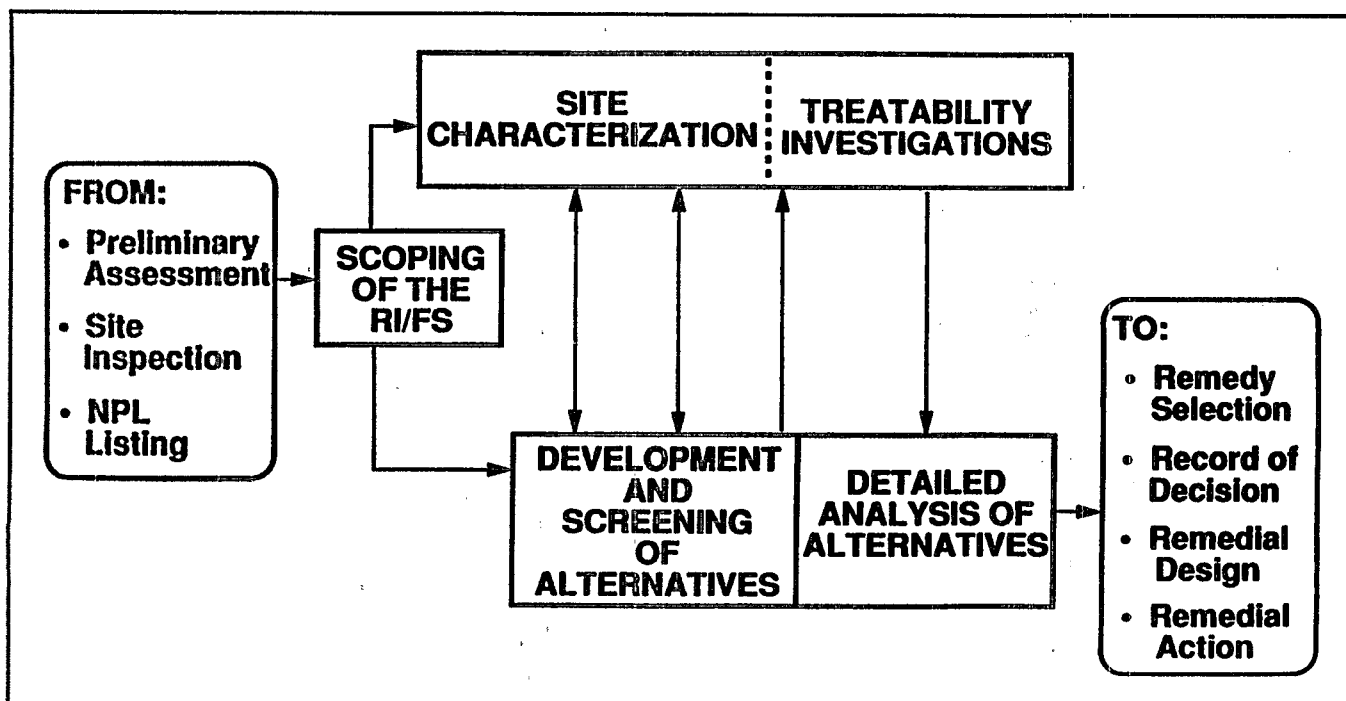■ Meeting with study participants to discuss important issues and assign responsibilities.

Figure 9-3. U.S. Superfund remedy selection process.

- Evaluating existing data to develop a conceptual site model to assess the problem as it is understood at the time and to identify potential exposure pathways and health and/or environmental receptors.

- Beginning limited field investigations, if existing data are not adequate to scope the project.

- Identifying preliminary remedial action objectives for each contaminated medium, and likely remedial actions. These will change with time as more information becomes available, but conceptualizing early is extremely useful.

- Identifying the preliminary criteria that will apply to site characterization and remediation. There can be many of these, particularly if several regulatory agencies exist; if criteria can be identified early, the site investigators can use them as work goes on.

- Determining data needs and the level of analytical and sampling certainty required for additional data collection. For example, initial data may show that a problem exists but may not be enough to define actual risks or select remedies.

- Evaluating the need and setting the schedule for treatability studies to better evaluate potential remedial alternatives.

- Designing a data collection program that describes sampling and analytical requirements. Often it is difficult to balance between a concern for controlling costs and perfection. However, one must not forget that the resulting process must yield conclusions that can be defended and from which the site can be characterized and the problem solved.

- Developing a work plan that documents the scoping process and outlines anticipated future tasks.

- Identifying health and safety protocols required during field investigations and preparing a site health and safety plan. As one learns more about the problem, these may have to change to reflect greater or lesser threats.

- Meeting with the community and developing a community relations plan. The studies and remedy implementation may take much time; and it is extremely important to establish a program that both keeps the public well informed and asks for its input.

Once the scoping phase of the RI/FS process is completed, a Site Characterization phase is begun. This consists of:

- Conducting field investigations. Some of the primary effort includes defining the areal and vertical extent of contamination and degree of threat

to health and the environment. Determining how much data to collect is always a difficult task, and as mentioned earlier requires a balance between a concern for controlling cost and perfection.

■ Analyzing field samples. Many analytical techniques, some at high cost, are available to the investigator. Again there must be a balance which gets the job done without spending too much of the available funds on the analyses and leaving too little for the remedies. Much attention must also be given to quality assurance/quality control methods to assure that the investigator can draw conclusions that can be defended.

■ Evaluating the results of the data analysis to characterize the site and develop a baseline risk assessment. The baseline risk assessment is designed to provide an evaluation of the potential threat to human health and the environment if there was no remedial action. It provides the basis for determining whether or not remedial action is necessary and for justifying the remedial actions. The assessments include contaminant identification, exposure and toxicity assessments, and risk characterization. Where possible, assumptions (such as dose/response relationships, standard ingestion rates for receptors, etc.) should be standardized to remove variables from this difficult analysis.

■ Determining if data are sufficient for developing and evaluating potential remedial alternatives. As field investigations continue and data are analyzed, new concerns often arise beyond those which were identified at the beginning. For example, additional contaminants may be identified which are not treatable by the same technologies (e.g., extractable versus volatile organics). Therefore, it is not uncommon to have to rescope investigative approaches to address these concerns. The use and acceptance of such a dynamic process is very important. If the process is rigid, the result may be a well conducted, but entirely inadequate investigation.

The Development and Screening of Alternatives phase of the RI/FS process is one which can be described as iterative, but in fact is part of the necessary thought process which begins at the time of Scoping. It includes:

■ Identifying remedial action objectives. As discussed above, the earlier these can be identified the better so that the investigations can be designed to address them.

■ Identifying potential technologies that will address these objectives. Often there will be a variety of technologies that are potentially applicable. For example, if there is a volatile organics comtamina-

tion problem, both activated carbon and air stripping are potentially applicable technologies. Later evaluations may demonstrate that one is more appropriate for use than the other (e.g., because of cost, presence of other organics, etc.).

■ Screening the technologies. Various criteria are possible; the U.S. EPA uses effectiveness, implementability, and cost. In general, one should use a set of criteria that eliminates technologies that are not applicable. For example, if the presence of a particular contaminant makes a technology ineffective, or if the necessary depths of application are not achievable, those technologies should be screened out. The screening mechanism selected should attempt to balance the desire to reduce options as quickly as possible against the desire to leave options open for finally selecting the "right" remedial option.

■ Assembling technologies into remedial alternatives that address the problem. Again the U.S. EPA uses the criteria of effectiveness, implementability, and cost. Effectiveness focuses primarily on whether the alternative protects human health and the environment. Implementability focuses on the technical aspects (i.e., the ability to construct and successfully operate) and administrative aspects (e.g., the ability to obtain approvals for using the alternative). Cost focuses on relative comparisons between alternatives, recognizing that a high degree of accuracy is not possible at this stage. There is a wide range of alternatives which can be developed. The U.S. EPA develops a range which has as its upper end an alternative which prevents, as much as possible, the need for any long term management of residuals and untreated wastes. The lower end of the range is a "no action" alternative. The best approach is to find a cost-effective alternative that satisfies the upper end of the range. However, this is not always possible for any number of reasons, including the important variables of high costs and technical uncertainty.

If available data are insufficient to evaluate the remedial alternatives, Treatability Investigations (bench and/or pilot scale) may be necessary. The point at which these can be conducted varies; they should be conducted as early as possible within the process. In some cases the need can't be predicted until the screening process has begun. For example, as studies continue and more data become available, it may become clear that a certain technology seems to be promising (i.e., anticipated cost or performance). In these cases, extra time will be required to perform the necessary treatability studies and then resume the remedial selection process.

The next step in the RI/FS process is the Detailed Analysis of Alternatives. The criteria which are used by U.S. EPA for this analysis are:

- Overall protection of human health and the environment

- Compliance with "applicable or relevant and appropriate requirements" (ARAR's)

- Long term effectiveness and permanence

- Reduction of toxicity, mobility, or volume through treatment

- Short term effectiveness

- Implementability

- Cost

- State acceptance

- Community acceptance.

Each alternative is analyzed against each criterion and then compared against one another. This identifies strengths and weaknesses so that U.S. EPA can evaluate the alternatives and prepare a Proposed Plan. This plan, which summarizes the remedial alternatives and identifies a preferred alternative, is presented to the public for comment. After considering the comments received, U.S. EPA documents the remedial alternative chosen in a Record of Decision. Then the selected alternative is designed and constructed.

Successful construction of facilities is not the end of the process. It is extremely important that a comprehensive monitoring system be designed and implemented. Since there is not enough long term experience with remedies, it is a good idea to start with a system that errs on the high side for monitoring points, parameter coverage, and frequency of sampling. As experience is gained, these can be diminished or modified to reflect new information. It is also important to select and use statistical techniques to characterize cleanup over time. Apparent changes may be subtle or misleading, and statistical significance is necessary for decisions over time. Initial predictions of cleanup times should be viewed with caution, as considerable uncertainty often accompanies the necessary calculations.

9.5 Stringfellow Site RI/FS

Beginning in 1984, a large number of technical site studies (see Table 9-1) and treatability studies (see Table 9-2) were conducted at and near the Stringfellow Site as part of the RI/FS process. Most of these were conducted under the direction of the State of California and the U.S. EPA. Several were conducted for companies that had originally sent wastes to the site. Be-

Table 9-1. Stringfellow Site technical studies.

Environmental (soil, air, water) sampling

Geology/hydrology

Fault/fracture survey

Geophysical
  - Electromagnetic conductivity
  - Resistivity
  - Seismic

Soil gas sampling

Hydraulic testing

Ground water modeling

Air modeling

Risk assessments

cause it was increasingly clear that completion of the RI/FS process for this complex problem would take much time, numerous additional interim remedies were implemented. To date, these have included:

Table 9-2. Stringfellow Site treatability studies.

Reverse osmosis

Carbon adsorption optimization

Carbon regeneration

Incineration

Metals precipitation

Air stripping

Ultraviolet oxidation

Dewatering tunnel (conceptual study)

Ion exchange

Stabilization/solidification

Rotating biological contactor

Ultrafiltration

Additional technology evaluations (ongoing)

- Provision of an alternate drinking water supply to approximately 500 residents of nearby Glen Avon, California to protect them from potential hazard exposure.

- Diversion of surface waters around and from the on-site area to prevent contamination.

■ Interception and diversion of shallow uncontaminated ground water upgradient of the site.

■ Improvement of surface drainage patterns.

■ Construction of a pretreatment plant in the mid-canyon area to remove metals and organics from on-site, mid-canyon and lower canyon extracted ground waters. Treatment includes lime and sodium hydroxide additions for metals removal and activated carbon for organics removals. Treated waters are taken to a sewer drop station and then discharged offshore in the Pacific Ocean. The plant began operation in late 1985, and by January 1992 had successfully treated about 170 million liters (45 million gallons) of contaminated ground water.

■ Installation of a subsurface french drain downgradient from the barrier dam to intercept shallow, contaminated ground water for later treatment at the pretreatment plant.

■ Installation of additional mid-canyon extraction wells to improve the efficiency of the capture system. The intercepted water is sent to the pretreatment plant.

■ Establishment of a systematic ground water monitoring program to detect any encroachment of site-related contaminants.

■ Installation of a lower canyon extraction well system approximately 1,200 meters (4,000 feet) downgradient from the barrier dam to capture ground water contaminants that otherwise would flow into the community (PRP companies implemented this interim remedy).

In 1987 the Remedial Investigation (RI) report was released to the public; some of the major conclusions included:

On-site Conditions

■ Approximately 83 million liters (22 million gallons) of contaminated ground water are held in unconsolidated soil and rock material on-site. An undetermined amount of contaminated ground water is in the fractured bedrock underlying the site. Contaminated ground water was found as deep as 60 meters (200 feet) below land surface in bedrock wells.

■ Most contaminants on-site were found in the ground water; the on-site soil (alluvium/fill) is not a primary source of mobile contaminants (solvents, metals, etc.). Mobile contaminants were found almost exclusively in the ground water.

■ Contaminated ground water is moving downgradient from the site, leaving the site al-

most entirely through the fractured bedrock under the subsurface barrier wall. Sulfates were found in percentage concentrations, heavy metals in 100's of mg/L, and volatile and extractable organics in mg/L ranges.

■ The site contains over 600,000 cubic meters (800,000 cubic yards) of unconsolidated soil and rock (alluvium, decomposed rock and metamorphic rock) that contains contamination.

■ The on-site barrier/extraction system intercepts and recovers over 80 percent of the potential ground water leakage from the site.

■ The composition and distribution of on-site contaminated soils, rocks, and ground water are extremely heterogeneous.

■ Soils beneath the low permeability site cover but above the water table are principally contaminated with pesticides, polychlorinated biphenyls (PCB's), parachlorobenzene sulfonic acid (p-CBSA), a DDT by-product, and traces of slightly water soluble organic compounds. These soils are also acidic and contain several heavy metals at levels above natural background.

■ The pesticides and PCB's in the unsaturated soil/fill on-site are immobile. The remaining low levels of soluble organics and metals can be mobilized by leaching through ground water infiltration.

■ The on-site soil/fill below the water table has many of the same insoluble organic compounds in it as the unsaturated zone; however, levels of water soluble organics and heavy metals are much higher and appear to be associated with the ground water.

Downgradient Conditions

■ A plume of contaminated ground water extends over 3 kilometers (2 miles) downgradient from the site and ranges from 60 meters (200 feet) to about 270 meters (900 feet) wide (Figure 9-4).

■ The Stringfellow-related contaminants found in this plume under the community of Glen Avon include several organic solvents (trichloroethylene, chloroform, chlorobenzene, dichlorobenzene), sulfate, and p-CBSA.

■ Heavy metals in the ground water extend about 600 meters (2,000 feet) downgradient from the site; they have been tied up or precipitated out in the aquifer materials upgradient of this point.

■ Under 1985/86 water level conditions, which are affected by significant mid-canyon extraction, ground water flux past canyon cross sections is
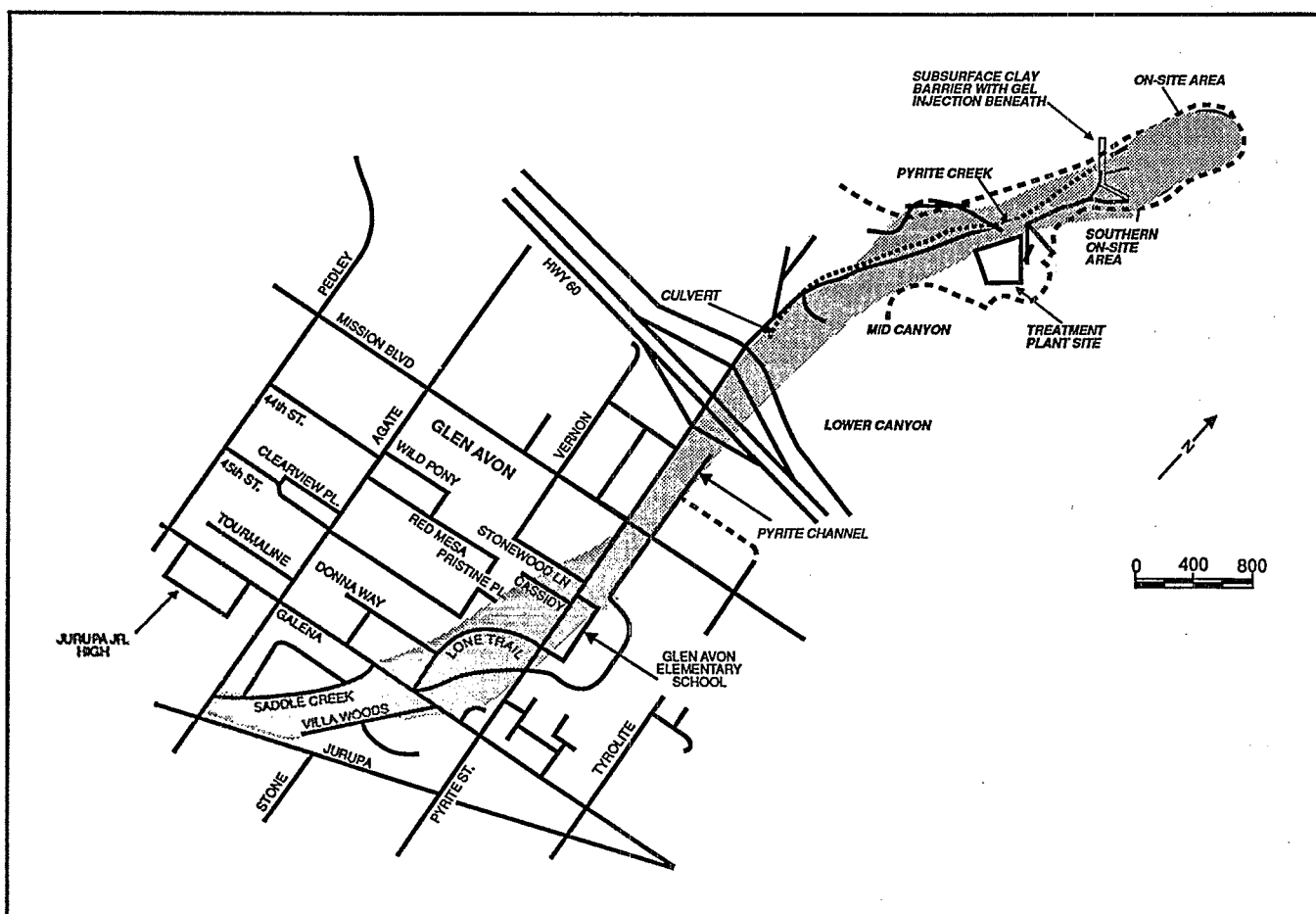
Figure 9-4. Approximate location of TCE contaminated ground water that extends from the Stringfellow Site into Glen Avon.

estimated to increase from about 45 to 57 liters per minute (12 to 15 gallons per minute) in the upper portion of Pyrite Canyon below the site, to about 110 liters per minute (28 gpm) just north of Highway 60 (1,500 meters or 5,000 feet downgradient of the site).

■ The two original mid-canyon extraction wells are estimated to extract about 50 to 60 percent of the total ground water flow through the mid-canyon. The addition of five more interception wells in the mid-canyon in late 1986 increased this fraction.

■ Contaminated surface runoff can discharge from the site during sustained rainfall. Under present conditions, no measurable amounts of surface water contamination have been found further than 600 meters (2,000 feet) downgradient of the site.

■ Surface soils within 300 meters (1,000 feet) south of the site have been contaminated at concentrations above existing environmental standards.

■ Within the zone extending about 300 meters (1,000 feet) downgradient of the barrier, measurable contamination by site-related contaminants was also found in subsurface soils.

Public Health Evaluation

■ Before starting interim abatement actions in 1980, the pathways for exposure to the contaminants included air, surface water, soils, and ground water; now, the primary exposure pathway of concern is migrating contaminated ground water.

■ The combined maximum lifetime risk from exposure to ground water contaminated with trichloroethylene (TCE) and chloroform in the community area, if used for drinking water, exceeds the U.S. EPA's risk guidelines (i.e., a carcinogenic risk ranging from 1 in a million to 1 in 10,000 cancer occurrences).

■ Without site remediation and ground water cleanup, the contaminants which have already

migrated below the mid-canyon extraction system will continue to migrate downgradient, adding to the risk of exposure for the local community.

■ Air emissions modeling indicates that, even if the on-site cap/cover were removed to excavate the underlying contaminated materials, there would be only a minimum threat to the residents of Glen Avon.

■ Contaminated surface soils in the first 300 meters (1,000 feet) downgradient from the site's subsurface barrier system are a potential risk to individuals in Pyrite Canyon by breathing in air-suspended dust under severe wind conditions. Continual airborne dust from this zone will not reach the community area, and the levels of soil contamination in this zone are not an ingestion or skin contact health risk.

■ Subsurface soils within 600 meters (2,000 feet) downgradient of the site are accumulating precipitated and adsorbed contaminants from migrating ground water. While there is no human health threat now, this zone must be considered a secondary contamination source during remediation planning.

9.6 Remedy Selection at Stringfellow

The data compiled during the technical and treatability studies were evaluated to determine appropriate remedies. As part of the Feasibility Study released in 1988, 86 technologies were screened for potential application; 30 were retained for remedial alternatives selection. Seven remedial alternatives were chosen from these technologies and were analyzed in detail using the nine criteria discussed earlier.

The seven remedial alternatives ranged from the no action alternative to one which included incineration of on-site contaminants (Table 9-3). As one would expect, these alternatives spanned a wide range of anticipated costs. A "low cost" alternative, the on-site natural flushing and downgradient plume cleanup option, was estimated to have a 30-year present worth cost (assuming a 7 percent discount rate) of approximately US$131 million (1989 $). A "high cost" alternative, the on-site soil incineration and downgradient plume cleanup option, was estimated to cost about US$742 million (Table 9-4).

A Preferred Alternative was selected which included:

■ Dewatering the on-site area with extraction wells

■ Implementation of soil-gas extraction for volatile organics removal in the on-site area, if field tests prove favorable

■ Diversion of surface drainage away from the site

Table 9-3. Summary of remedial alternatives resulting from the Stringfellow Site feasibility study.

Remedial Alternative 1

The no action alternative, would involve discontinuing on-site (Stream A) and mid-canyon (Stream B) ground water extraction and treatment that is presently performed. Also, there would be no effort to minimize the generation of contaminated leachate from the on-site area; or to clean up or stop the further migration of the downgradient plume.

Remedial Alternative 2

Natural flushing of the on-site area, and downgradient plume cleanup.

Remedial Alternative 3

On-site dewatering, extraction and treatment of on-site leachate, and downgradient plume cleanup.

Remedial Alternative 4A

On-site dewatering, extraction and treatment of on-site leachate, in situ soil-gas extraction, in situ soil flushing, and downgradient plume cleanup.

Remedial Alternative 4B

On-site dewatering, extraction and treatment of on-site leachate, in situ soil-gas extraction, selective soil excavation of higher contamination areas, soil treatment and redisposal on-site, in situ soil flushing, and downgradient plume cleanup.

Remedial Alternative 5

On-site dewatering, extraction and treatment of on-site leachate, full excavation of all diggable soil, soil treatment followed by redisposal on-site into the excavation, and downgradient plume cleanup.

Remedial Alternative 6

On-site dewatering with extraction and treatment of on-site leachate, in situ soil-gas extraction, additional treatability studies of on-site soil contamination, and downgradient plume cleanup.

■ Continued extraction, treatment and sewering of contaminated ground water from the on-site, mid-canyon and lower canyon areas,

■ Extraction, treatment and reinjection of ground water back into the community area

■ Additional studies to determine whether there is a feasible method for further addressing on-site soil and bedrock contamination

■ Installation of a multilayered cap in the on-site area.

Table 9-4. Estimated cost comparison of revised remedial alternatives - overall site remedy.

		RA No. 2	RA No. 3	RA No. 4A	RA No. 4B	RA No. 5	RA* No. 6
Approximate time until ground water cleanup is achieved (years)	Zone 1	448	Never	65	60	63	**
	Zone 2	162	162	46	46	46	46
	Zone 3	40	40	40	40	40	40
	Zone 4	25	25	25	25	25	25
Total estimated capital costs (million US$)		$40.7	$44.2	$55.5	$253.3	$630.9	$64.7**
Total estimated present worth costs 7% discount rate (million US$)		$131.2	$156.2	$197.8	$392.3	$741.7	$186.0**

*RA No. 6 is the DHS/EPA Preferred Alternative.

**Estimated time and costs for cleaning up Zone 1 are not clear at this time. The results of on-going pilot tests of soil treatment processes and evaluations based on EPA's nine Superfund criteria may affect what future on-site actions are taken.

The selection of ground water treatment and disposal methods will address heavy metals, organics and inorganics, depending upon levels of contamination, and desired end uses for the treated water.

Treatability studies and experience with operating the interim pretreatment plant which began operation in late 1985 provided valuable information on how to effectively treat the ground waters and what problems to anticipate. When trying to deal with a complex site such as the Stringfellow Site, numerous interactions and interferences may occur. For example, on-site ground waters at Stringfellow contain percent levels of sulfates. When these waters are treated for metals removal by lime addition, a large amount of gypsum sludge is also generated. These metals/inorganics-laden sludges in turn are disposed of off-site as hazardous wastes.

Another example of potentially hidden costs results from the large percentages of organics that cannot be identified by conventional gas chromatography/mass spectroscopy (GC/MS) methods. Only about 5 percent of the organic carbon in on-site ground waters at Stringfellow is identifiable by the GC/MS methods; therefore, more activated carbon is necessary for treatment than would be predicted by using the GC/MS results. It was also discovered that some ground waters that appeared to be treatable by air stripping from the standpoint of the volatiles were, in fact, not since other compounds caused frothing which prevented effective stripping. Making these types of discoveries early in the remedial process is invaluable in scoping potential remedies and selecting effective remedies.

To date, the U.S. and State of California governments have spent approximately US$110 million on the site. The estimated present worth cost of the Preferred Alternative, not including implementation of additional technologies following the planned treatability studies, is an additional approximately US$186 million. Cost estimates are assumed to potentially vary by -30 to +50%.

In September 1990, the U.S. EPA signed a Record of Decision (ROD) to implement some of the items contained in the Preferred Alternative. Another Record of Decision will be necessary in the future to reflect the treatability study outcome and to make final cleanup goals/remedy decisions. To implement the September 1990 ROD, the U.S. EPA convinced PRP companies to come forward, negotiate and take over implementation of the ROD elements. Obligations undertaken by the PRP's will require work into the late 1990's. Once a final ROD is issued by U.S. EPA, additional negotiations will commence regarding remedial work that could last for the foreseeable future.

9.7 Conclusions

Selecting remedies at a complex hazardous waste site requires a methodical approach to successfully move from uncertainty to rational decisions. It is also necessary to keep the investigative process flexible in order to deal with inevitable unforeseen circumstances. As noted in this chapter as well as in others in this report, applying lessons learned from interim remedies and conducting treatability studies as early as possible are also important to effective remedy selection.

The remedial efforts conducted over the past 15 years at the Stringfellow Site have been extremely time-consuming and costly but are, nonetheless, representative of what can happen when there is the combination of a complex problem, an aggressive

environmental regulation, a litigation atmosphere, and an aroused public. Cleanup of Stringfellow site-related contamination is, at best, many years away. The construction of remedies is not the final chapter in cleaning up complex sites such as this; long term monitoring is required to validate remedial hypotheses and determine success. Hopefully, lessons have been and will continue to be learned from sites such as Stringfellow that will be helpful to others in solving hazardous waste site problems.

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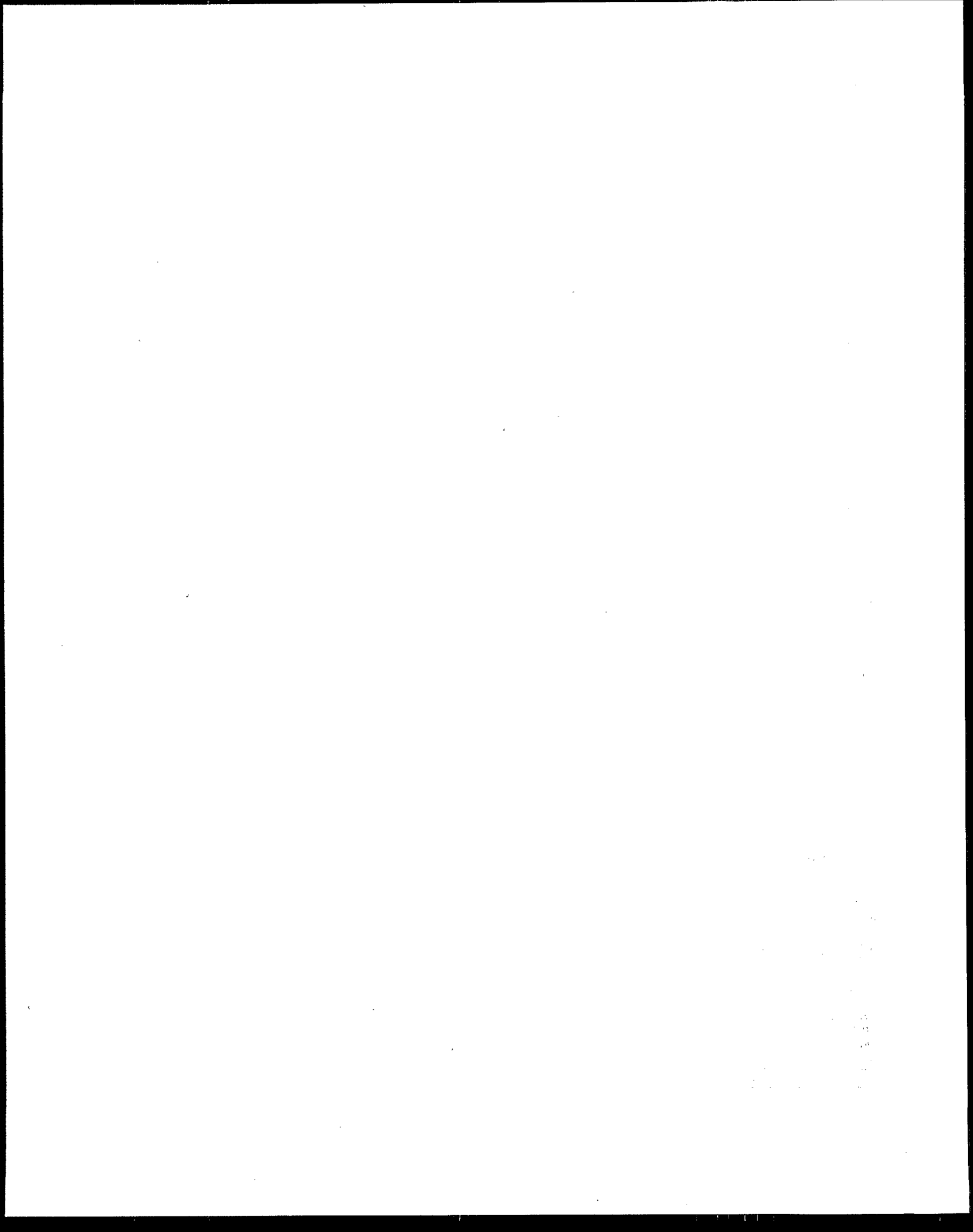
Conclusions and Recommendations

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10.1 Introduction

One of the major accomplishments of this Pilot Study was that it demonstrated the need to exchange technical and economic information on contaminated land and ground water remediation technologies. The conclusions are first presented by the specific technology chapters in this report, followed by general observations on remediation, technology transfer and research needs. The conclusions are based on the case studies, expert speaker presentations, and special studies carried out by Fellows of the Pilot Study.

In addition to the conclusions, a number of recommendations were made by the participants in this Pilot Study to the North Atlantic Treaty Organization's Committee on the Challenges of Modern Society (NATO/CCMS) in a separate Summary Report to this final report. They address potential actions that could be taken to increase technology development and technology transfer for site remediation.

10.2 Specific Technology Chapter Conclusions

The following conclusions were reached on the basis of the case studies included in the Pilot Study, as well as related experiences and observations of the Study's participants. They include specific technology needs that could be met through research, development and demonstration activities.

10.2.1 Chapter 2: Thermal Technologies

10.2.1.1 Existing high temperature incineration (on- and off-site) successfully destroys organic contamination; however, not all nations allow its use for chlorinated compounds.

High temperature incineration is a successfully documented remediation technology that can be applied for treatment of sludges, soils, liquids and air effluents contaminated with various organic constituents. This technology has been successfully applied in many NATO countries, although the thermal treatment of chlorinated organics is not allowed in at least one country, The Netherlands, because of concern for formation of dioxins and/or furans. The technology is currently offered by several vendors in many countries and extensive documentation exists on its costs and performance.

10.2.1.2 Low temperature thermal desorption is a successful technology for treating volatile and semivolatile wastes.

This technology, which generally operates at temperatures below 800 °C, allows for the desorption of volatile and semivolatile constituents from solid and semi-solid waste. The removed constituents, entrained in an air stream, are then processed through a secondary treatment unit, usually a secondary combustion chamber. Metal and other nonvolatile waste components come out in the residual ash stream and

can be further processed, if necessary, for final disposal.

10.2.2 Chapter 3: Stabilization/Solidification (S/S) Technologies

10.2.2.1 S/S has been proven for the immobilization of most inorganics.

S/S technologies, used as an isolation technology, have been shown to be effective with many inorganic contaminants, but not with materials containing organic chemicals.

10.2.2.2 Long term effectiveness data is not available.

The long term effectiveness of these processes has not been proven, especially when they are applied under field conditions (weathering, leaching, structural durability, etc.).

10.2.2.3 Scientifically based S/S leaching tests would provide a more easily comparable data base than is available today.

A variety of S/S leaching tests exist today, most of which do not have a common technical basis nor a readily understood knowledge of their physico/chemical processes. It is, therefore, rarely possible to compare S/S leaching results due to the lack of data on the physiochemical forms of the waste treated, the chemical basis of the S/S mix, the process design used, and the final product pH. It would be helpful, therefore, if current leaching tests had a more fundamental and uniformily understood basis.

10.2.3 Chapter 4: Soil Vapor Extraction (SVE) Technologies

10.2.3.1 SVE is a viable technology for unsaturated zone remediation of volatile and semi-volatile contaminants.

The SVE technology has been demonstrated to be viable for the removal of volatile and some semivolatile organic compounds from vadose (unsaturated) zone soils that have sufficient air conductivity. These soil types typically include porous soils such as fine- to coarse-grained sands. The presence of water in the pore spaces impedes the vapor transport into the gaseous phase. This can be overcome by lowering the ground water level in the area of contamination.

10.2.3.2 Off-gases can be treated by conventional technologies.

There are a wide variety of technology options available for the treatment of off-gases. These include activated carbon, condensation, and thermal destruction processes. A number of new technologies are currently under development which may provide a wider range of cost-effective alternatives for treating the extracted vapors.

10.2.4 Chapter 5: Physical/Chemical Extraction Technologies

10.2.4.1 Conventional extractive techniques have limited in situ applications.

In situ extraction techniques will probably play only a marginal role in the cleanup of contaminated sites due to their limited applicability to soils with high permeability.

10.2.4.2 Above ground extraction methods are powerful techniques.

Conventional above ground extraction methods are powerful techniques for a large range of soils containing heavy metals as well as organic contaminants, but are limited in the soil size fraction they can effectively clean. One of the major drawbacks of ex situ extraction techniques is, however, the production of sludge.

10.2.4.3 Electroreclamation deserves to be extensively investigated.

Electroreclamation is a promising new technology for the in situ cleanup of clayey soils contaminated with heavy metals. There currently is no other technique that shows the same possibilities.

10.2.5 Chapter 6: Pump and Treat Ground Water

10.2.5.1 Pump and treat is a limited technology for remediating aquifers.

The pump and treat operation that started out in 1984, as described in this chapter, was intended to remediate the aquifer within 5 years. Although remediation has been limited, the pump and treat operation continues to perform as a barrier technology for inhibiting the further migration of contaminants. The case reflects other remediation industry pump and treat experiences that shows, in general, that ground water extraction and treatment is not an effective approach by itself for the ultimate remediation of aquifers to health-based cleanup concentrations.

10.2.5.2 Air stripping and activated carbon, as illustrated in the case study Ville Mercier, were only partially effective treatment processes.

The air stripping unit, described in this case study, was one of the earliest designed systems for treating both ferrous iron and volatile organic contaminants in ground water. Activated carbon was used with the unit to capture nonvolatile organics and residual volatile organics. However, this approach was found to be only partially successful in treating contaminated ground water. Subsequently, a pilot-scale study at this site using an alternative iron removal process involving diffused air combined with sand filtration, effectively removed the iron to acceptable levels. This approach, combined with an alternative air stripping system designed to remove the most difficult contaminant,

rather than volatile contaminants generally, effectively reduced the organics to acceptable levels.

10.2.5.3 An ultraviolet radiation/oxidation process (Ultrox™) was effective in reducing the concentration of volatile organics in ground water to acceptable levels.

10.2.5.4 A precipitation process involving the use of lime and sodium sulfide was effective in reducing the concentrations of zinc and cadmium to acceptable levels.

10.2.6   Chapter 7: Chemical Treatment of Contaminated Soils: APEG

10.2.6.1 The long term stability and behavior of the products of partial dechlorination in APEG processes require investigation.

10.2.6.2 The combination of thermal pyrolysis and APEG treatment applied at Wide Beach, New York, USA, was successful in reducing PCB concentrations to below target cleanup levels.

10.2.7   Chapter 8: Microbial Treatment Technologies

10.2.7.1 Bioremediation process scale-up from laboratory to the field is difficult.

The complex physical, chemical and biological nature of the subsurface environment makes both laboratory testing and pilot-scale field evaluations (treatability studies) essential elements of a successful approach to remediation.   Generally, either bench and/or pilot-scale studies in the laboratory need to be followed by pilot and/or full-scale testing in the field.

10.2.7.2 There is a need for both data on oxygen behavior in the subsurface and improved methods of providing it for in situ bioremediation.

Since oxygen is both the limiting and most expensive factor in most applications of *in situ* bioremediation, it is important to gain insight into oxygen supply and behavior in the subsurface. Further experimentation with oxygen delivery techniques is needed. One promising technique is the use of soil vapor extraction methods. The combined effect of vapor extraction and biodegradation appears to provide a method for achieving remediation of a wide range of organic contaminants.

10.2.7.3 There is a need for further research on bioavailability and achievable residual concentrations.

To date, bioremediation of contaminated soil always leaves some residual concentrations of contaminants which may be acceptable, depending on site-specific remediation objectives.   These residual concentrations can be higher or lower than what is allowed, depending on a number of possible factors, particularly the apparent nonavailability of the contaminants to indigenous microorganisms. This can be a restriction for application of biological techniques. Since bioremediation is often a relative cheap alternative to other remediation technologies, there exists a need for further research on bioavailability and overcoming its impediment to complete site remediation.

10.2.7.4 Soil inoculation has not been proven to enhance in situ bioremediation.

Although artificially supplied microorganisms are expected to have some beneficial effect, this has not been proven. A major obstruction is that soil microorganisms tend to adsorb onto (soil) particles, and consequently cannot be transported over long distances in the subsoil. Another impediment may be the inability of artifically supplied microorganisms to tolerate real-world subsurface conditions and/or compete with indigenous populations.

10.2.7.5 Permeability is a key factor in applying in situ bioremediation.

Apart from the biodegradability of typical contaminants, permeability is the key parameter which determines the applicability of *in situ* biorestoration. Permeability affects the contact of the microorganisms, contaminants and the oxygen being supplied to support the biodegradation process.

10.2.8   Chapter 9: Selecting Remedies at a Complex Hazardous Waste Site

10.2.8.1 Remediation should strive to be a complete solution.

Once a remediation site has been identified, an assessment of critical problems must be made. Impacts from the site on the environment and health need to be addressed and relevant cleanup goals established. Remediation efforts can be phased and monitored so that problems are solved in a timely fashion. Once the planned remediation actions have been completed, long term monitoring may be needed to determine if the remedial actions have been successful over time.

10.2.8.2 Treatability studies must be conducted as early as possible for effective remedy selection, and technologies should be judged by their overall performance.

Conducting treatability studies as early as possible is essential to effective selection of remedies. The consequence of not doing them until late in the selection process may be unnecessary delays in constructing remedies. The consequence of not doing them at all may be ineffective remedies. In addition, technologies should be judged by their overall performance, including generation of new waste streams

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and long term performance, and not by cleaning results only.

10.2.9 Appendix: *In Situ* Vitrification

10.2.9.1 *Vitrification is a promising technique for treating mixed organic and inorganic wastes.*

Heavy metals combined with organic contaminants still pose problems in the present treatment schemes and treatment trains may be needed to address this problem. It is not expected that this will change in the future. Vitrification combines the advantages of a thermal process (destroying the organic contaminants) with immobilization of the inorganics. Furthermore, it leads to a final product showing a considerable resistance to leaching.

10.3 General Conclusions

In addition to the specific technology area conclusions discussed in Section 10.2, the participants of the Pilot Study reached the following conclusions that apply to most if not all of the case studies, as well as conclusions derived from special studies of the Fellows and guest expert speakers to the Pilot Study.

10.3.1 Remediation

10.3.1.1 *Energy efficiency practices influence plant design and, therefore, processing costs in different countries.*

Energy costs in the United States (U.S.) are very much lower than those in Europe. This may have influenced plant design, since one might expect more attention to have been paid to energy efficiency in plants designed in, for example, Germany, than those designed in the U.S. Thus, simply multiplying energy costs for a plant operating in the U.S. to give an energy cost for a similar plant in Europe may be misleading (leading to a high estimate of operating costs) because the European designer would take care not to use so much energy (but possibly have a higher capital cost, in consequence). Similar considerations might apply to attitudes to how labor-intensive operation of a plant is.

Therefore, care should be taken when comparing costs of different technologies, and when considering the application of a technology in a country other than that in which it was developed. Allowance must be taken of variable factors such as energy and labor costs, which will not only influence operating costs directly, but also plant design and associated capital costs.

10.3.1.2 *Treatment and permanent solutions are preferred.*

Remediations based on technologically permanent solutions are preferred. Successful remediation requires treatment of the waste source. Containment

technologies may only provide temporary solutions leading to the potential need for additional remediation at a future date.

10.3.1.3 *Integrated technology treatment systems are needed for site remediation.*

The complexity of contaminated sites and multiple pollutants requires a multidisciplinary use of engineers and scientists to solve the problems. Similarly, multi-technology solutions offer the potential to be more effective in cleaning up sites than the historical use of single technology systems. A combination of technologies can facilitate the preprocessing and treatment of contaminated soils and ground water, as well the postprocessing of residuals.

Modular designed integrated treatment trains can provide system flexibility in optimizing specific process units to treat different contaminants of varying concentrations within various media. This modular arrangement also allows the addition or withdrawal of processing units within the system, as needed, as well as allowing users the opportunity to insert and evaluate new/upgraded technologies as they become available. Modular design requires additional up-front design but may result in lower capital and operating costs than conventional one-technology designs.

This integrated systems approach also applies to situations where there are multiple areas of contamination on a given "site" and where it makes more sense to use specific technologies on each area, rather than trying to make one technology solve all of the contamination problems. The challenge is to get away from the traditional idea of one technology "fits all."

10.3.1.4 *Field treatability/pilot studies should be conducted for each technology under consideration, under the range of potentially applicable site field conditions.*

This conclusion of the first NATO/CCMS study on contaminated land is reaffirmed by this NATO/CCMS Pilot Study. The complex physical and chemical nature of the subsurface environment makes both laboratory testing and pilot-scale field evaluations (treatability studies) essential elements of a successful approach to remediation. Generally, either bench and/or pilot-scale studies in the laboratory need to be followed by pilot and/or full-scale testing in the field. These treatability studies should indicate if the technology is applicable to the waste and provide information on the optimal level of treatment effectiveness that the technololgy can achieve. Bench- and pilot-scale reactor evaluations must be tailored to each specific application in order to obtain the maximum amount of credible data at minimum costs and establish the basis for follow-on field evaluations.

10.3.1.5 Technology scale problems need to be addressed in design and testing.

Care must be taken in translating technologies from bench to pilot to demonstration or full-scale so that all aspects of the scale up are taken into account (e.g, reactor design, materials and residuals handling).

The scale up of pilot-scale systems to full-scale operating systems can often result in unforeseen difficulties which need to be addressed in the design. Careful consideration is needed of how design variables (e.g., wall effects, mixing efficiencies, flow patterns, fugitive emissions, retention times) can change as a result of system scale up. To overcome some of these problems, particularly for technologies which have not yet been widely used, operating flexibility can be built into the system by modular design, by providing the ability to vary feed rates and by providing surge capacity at various points throughout the system. It is important that adequate design attention be paid to all unit operations and that vendors of similar equipment are contacted to obtain information on scale up problems. However, care must be exercised when using vendor information because frequently their scale up procedures are based more on experience and testing of a particular waste using procedures/protocols that they have developed. Although these testing procedures may work, the design principles involved may not be fully developed or understood.

10.3.1.6 A mass balance approach to remediation is desirable.

For all projects, remediation design should be based on a firm understanding of the mass and types of pollutants involved, the current location of all of the mass remaining in the subsurface, and the chemical, physical and biological processes controlling the movement and fate of the mass from the subsurface. Usually, however, knowing any one of these is rare for in situ remediation, let alone all of them. While it is desirable to conduct all remediation from a mass balance perspective, experience shows that it will be practically impossible to obtain a true mass balance in either in situ or above ground processes because of the heterogeneity of the subsurface environment, limitations of investigation tools and current technology to accurately determine and/or predict the fate and behavior of the contaminants, such as their direction and rate of movement, spacial distribution and concentration.

Nevertheless, all technology application evaluations should be planned and conducted on a mass balance basis since it provides a rational and fundamental structure for asking specific questions and obtaining specific information that is necessary for determining contaminant fate and behavior, for evaluating and selecting treatment options, and for monitoring treatment effectiveness at both laboratory and field scale sized operations.

10.3.1.7 Technology remedies that transfer contaminants from one media to another should be avoided, if possible.

Remediation activities sometimes transfer contamination from one media, such as contaminated soil, to another media (e.g., air). Therefore, it is advisable to review all the pollutant emission pathways which could result from remediation activity. If any emission is possible, its impact on treatment effectiveness and surrounding media should be evaluated. Under such scrutiny, some technologies may be rejected because emission control and/or the additional treatment needed to lessen its impact on other media may change the feasibility of the overall planned remediation effort.

10.3.1.8 All remediations require proper operation and management.

Implementing technologies that have been proven using field demonstration-scale treatability studies is not enough to ensure success of the remediation activities. The overall effectiveness of a remediation scheme, which may include many interrelated elements of civil engineering works and soil and/or ground water cleanup technologies, will depend heavily on the care with which the individual processes are operated in the field; site and operating conditions may change over time and skilled people are needed to adjust technologies to these changes and/or remove them from operation if they don't meet expectations. Similarly, a strong quality assurance program needs to be in place and activities carried out by a dedicated, effective management team.

10.3.1.9 Long-term monitoring of permanent remediation may be necessary to ensure that cleanup goals are met.

Construction of soil and ground water remedies is not the endpoint for determining whether environmental protection concerns have been satisfied. Comprehensive, long term monitoring is essential to assure that the required remedies are implemented, operated and maintained, and ultimately are successful. This, in turn, requires that long term oversight be conducted by well trained personnel.

10.3.1.10 Basic records should be preserved.

A major challenge in evaluating current and emerging technology effectiveness to that used in the past is that there is usually insufficient data available on which to base an evaluation, particularly for in situ remediation activities. Therefore, it will be advantageous to future remediation planners if records of site investigations and associated remediation activities are preserved for future reference and evaluation.

10.3.2 Technology Transfer

10.3.2.1 Uniform data collection is needed.

There is a critical need for the establishment/use of a uniform data reporting methodology that can be universally applied. Various data base systems are available and in use. However, input of consistent data into these systems and easy access to them will benefit all users. One particularly critical area of information needed in these data bases is the cleanup standards used at each site since these provide the basis (remediation goal) upon which technologies have been shown to be effective or not. The cleanup standards are also important since there are no current internationally agreed on standards and those applicable in one nation or state may not be pertinent in another.

10.3.2.2 Independent technology evaluations are needed for effective technology transfer.

Since reporting systems and data bases are only as good as the data in them, a major challenge to the remediation community is obtaining reliable, credible data in a timely fashion. Projects in the field of remediation techniques for contaminated soil are so different in approach, execution and demands for cleanup, that comparison of technology and results is difficult if not impossible without organized, consistent preplanned evaluations.

To overcome these difficulties, demonstrations of technologies are needed that are well designed from a mass balance point of view and objectively monitored, analyzed and reported on by those who do not have a vested interest in the technology itself. When properly designed, executed and documented, such field trials and demonstrations on a variety of site and ground water matrices will not only verify the strengths and limitations of technology but also provide a credible basis for technology transfer and application. These actions require a serious commitment of support by governments to do so because no private organizations will have the capability to do this in a concerted, consistent manner.

This NATO/CCMS Pilot Study has shown the benefits to be gained from such well designed, supported, and independently monitored field scale demonstrations for the evaluation of soil and ground water treatment technologies. The participants of future NATO/CCMS Pilot Studies of a similar character would further enhance the utility of future candidate demonstrations by providing guidance on project design and information needs which would maximize their value as case studies.

10.3.2.3 The NATO/CCMS network is an important source of information.

In order to share the successes and failures of technologies used within the hazardous waste treatment arena, continued, positive interactions between NATO members are needed. Often successful applications of technologies are addressed in public forums and the literature with little attention paid to those efforts which were not totally successful or that were outright failures. It is more likely that the free exchange of information and technology developments will encourage all aspects of environmental research and development when there are avenues available which promote interaction and communication such as the NATO/CCMS Pilot Study Group. It has provided a valuable network for information exchange that otherwise would not have been available.

10.3.3 Research

10.3.3.1 There is a continuing need for development of new technologies and use of common research protocols.

The technical limitations and or cost of present technologies indicate that ongoing research and development (R & D) is needed to improve the effectiveness of current technologies and provide new treatment alternatives. There is also a need for the development of guidance to aid in the design and conduct of research, pilot-scale, and demonstration studies in order to maximize their value to potential users.

As in the case of remediation, it is essential in all research studies on treatment or contaminant technologies that all materials used are fully characterized, in terms of their chemical, physical, mineralogical and microbial composition.

10.3.3.2 Scientific understanding of processes is essential in order to ensure against formation of harmful end products.

As in the case of remediation activities, processes can be shown to be "effective" by relatively simple testing (e.g., showing that the targeted contaminant detected in the feed material is no longer present in the treated material), but it is not a sufficient basis for acceptance of a treatment technology since toxic intermediates, byproducts and residuals may be formed. Therefore, a thorough understanding of the treatment process mechanisms involved is required in order to avoid such undesirable occurrences.

10.3.3.3 Standardization of analytical methods is needed.

There is a lack of standardization of analytical methods used within the worldwide hazardous waste community and, in fact, within each country. As a result, there can be confusion about what the data means and the conditions under which the data was obtained and analyzed. Under such circumstances, data can be misinterpreted or appear inconclusive. A level of confidence in the interpretation of data can be established under world wide acceptable standardized

analytical methods. Concurrently, greater attention is needed in the area of experimental design and in establishing the hypotheses which define what data are needed and the quality of that data, which in turn establishes the analytical methods. Then data collected can and should be interpreted in view of the questions it was set out to answer as defined by the experimental design. In addition, it would be beneficial to the hazardous waste community if qualified organizations had ongoing programs to both evaluate new analytical techniques and update the analytical standards corresponding to use of those techniques.

10.3.3.4 Techniques are needed to remove contamination beneath urban structures without significant disturbance to ongoing activities.

The remediation of contaminated sites in urban areas raises a particular need for *in situ* technologies that can be applied around and beneath buildings, infrastructure and services, with minimal disturbance to artifacts or to the environment.

10.4 Recommendations

The following recommendations were made by the participating members to the NATO/CCMS.

10.4.1 CCMS is invited by the Pilot Study Director to commend this report to NATO Council for approval.

All of the participants in this phase of the study need to be commended for their professionalism, technical expertise and cooperation. The Pilot Study Director particularly thanks the two Co-pilot Countries, Germany and The Netherlands for their assistance. All of the Fellows need to be complimented on their technical quality and input to the study. The Expert Speaker activities within the study were a stellar success in providing an intellectual stimulus to all of their participating Countries. Over and above the technical successes of the study, a camaraderie was established between the participating country representatives that led to many spinoff activities between different Countries and in different areas of environmental technologies. Professional enhancement and recognition increased for many of the participants. Conference participation and publications resulting from this Study were numerous throughout both Western Europe and North America and these proved to be valuable technology transfer activities that provided information being generated within the Study to the rest of the environmental community in a timely manner.

Therefore, the NATO/CCMS is invited to commend this Final Report to member governments and draw their attention to the technical information and the Conclusions and Recommendations contained herein.

10.4.2 Continue the NATO/CCMS Pilot Study to include reporting on the field demonstration of technologies and on new/emerging technologies.

Ongoing problems with waste management practices in all countries continue the need for advancing the state-of-the-art in remediation technologies. The current phase of the NATO/CCMS Pilot Study on this topic provided an excellent forum for technology exposure and technology transfer among countries. Therefore, it is recommended that this Study continue into a second phase. Since *in situ* and on-site remediation usually takes time, this second phase will enable member countries to see how well the technologies perform during complete remediation activities. It will also enable current members, and additional countries that have expressed an interest in the Study, to take advantage of data from new field demonstrations. In addition, it will provide them the opportunity to report on developments in national legislation and regulations, as well as exchange technical information on ongoing work in the development of new technologies, and potentially avoid duplication of research projects.

10.4.3 Continuation of the current NATO/CCMS Pilot Study should also include cleanup criteria, project design methodologies, and documentation of completed remediations.

The continuation of this NATO/CCMS Pilot Study can advance the state-of-the-art in remediation technologies by including related areas of interest to decisionmakers. These include an examination of cleanup criteria used by various countries, methodologies used in the design of research, pilot and field demonstration projects, and documentation of completed remediations that examines success/failure, costs, field problems, etc.

10.4.4 Encourage participation of NATO and nonNATO countries in the continuation study.

Past participation has been a two-way reward for participating Pilot Study members. Not only have participants learned but have also shared their experiences with others. The sharing of knowledge from the current Pilot Study, coupled with an increased exchange of information with new participants, can enhance technology transfer and remedial action progress.

10.4.5 NATO/CCMS should encourage more active participation by all member countries.

The NATO/CCMS should encourage membership within Pilot Studies, whether as full participants or as observers, by as many countries as possible. It should draw the attention of member countries to the way in which membership can open the doors for researchers and regulators, within and outside central government,

and to high quality technology exchange programs. It should, therefore, encourage member countries to adopt formal observer status, even if the country itself wishes to have only minimal active participation at the official level. The NATO/CCMS is also requested to encourage member countries to give greater publicity to the activities of Pilot Study Groups and to the related Fellowship program.

10.4.6 *Encourage participation under the NATO Science Committee to establish a scientific program and advance study institute for soil and ground water contamination issues.*

There are significant deficiencies in our fundamental understanding of subsurface soil and ground water systems and the complicated interactive processes which control contaminant behavior and fate within those systems. Without profound scientific advances in our understanding of these phenomena, site investigation and treatment technologies will likely be slow, risky, expensive, and poorly effective.

Therefore, the NATO Scientific Committee is encouraged to establish a special scientific program for addressing fundamental gaps in understanding these phenomena. Such a program should include a Science Fellowships Programme, an Advanced Study Institute, Advanced Research Workshop(s), as well as collaborative research grants, including both NATO and nonNato researchers.

10.4.7 *NATO/CCMS should support the transfer/application of results of current study through workshops and seminars within NATO and nonNATO countries.*

Mindful of the contaminated land problems known to exist in certain nonparticipant NATO countries, and in many nonNATO countries, including those in Eastern and Central Europe, the Pilot Study Group recommends that NATO arrange a series of workshops and seminars specifically in those places, in order to aid in the dissemination of the results of the present study.

10.4.8 *The NATO/CCMS should encourage annual technology transfer reports from each of its individual pilot studies.*

This Pilot Study showed the value to member countries of frequent publications and verbal presentations on the status and results of the its activities. Therefore, all Pilot Study Directors and technical participants are encouraged to publish an annual report on the progress of their Study in either international conferences or journals, or both. Publication in both Europe and North America is encouraged.

10.4.9 *Create a more formal interface of the continued pilot study with OECD, EC and other international groups.*

Throughout the first phase of the pilot study there was minimum involvement/representation from other international groups such as OECD and EC at the meetings. On two occasions the Pilot Study Director visited OECD and conducted a briefing for Waste Policy Management officials. The EC attended and presented at one meeting over the five year period. It is recommended that the NATO/CCMS lend its support to the various interested Pilot Studies to formalize and increase the participation of other international groups.

10.4.10 *A budget for writing the final report should be established to encourage final report preparation.*

Researchers generally have a limited budget for activities not directly involving their regular work. At present, the preparation of final reports is a spare time activity. Furthermore, not all studies provide the information necessary for a detailed final report and additional information acquisition is needed in some cases. Because contributions to the NATO/CCMS study are not directly profitable to the institution in which the researchers are employed, it is desirable that NATO provide a financial incentive to employers to give contributors time to work on NATO/CCMS reports during regular working hours. This would also make the acquisition of additional information (telephoning, writing letters) easier.