

**CURRENT AND INNOVATIVE EXCAVATE AND TREAT TECHNOLOGIES
FOR THE REMEDIATION OF CONTAMINATED SOILS**

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April 1991

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**FINAL REPORT ON CURRENT AND
INNOVATIVE EXCAVATE AND TREAT
TECHNOLOGIES FOR THE REMEDIATION
OF CONTAMINATED SOILS**

Prepared for

THE NATIONAL GROUNDWATER AND SOIL REMEDIATION PROGRAM (GASReP)
Excavate and Treat Technical Sub-Committee

Prepared by

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Financial support for this project was provided by the Environmental Research Advisory Council of the Canadian Petroleum Association (CPA), and the Federal Panel for Energy Research and Development (PERD) of Environment Canada.

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EXECUTIVE SUMMARY

A total of 45 separate technologies were investigated for the clean-up of excavated soil contaminated with petroleum hydrocarbons, wood preserving chemicals and chlorinated solvents. The purpose of the study was to describe current and emerging technologies, and to identify those promising technologies that should be supported in terms of research funding.

The investigation was conducted through a review of the available literature and telephone and letter interviews with key researchers, government environmental agency personnel, and technology vendors in Canada, the United States, the Netherlands, West Germany, the United Kingdom and Denmark. The individual technologies were grouped into treatment technologies according to thermal, physical, chemical and biological processes, and further subdivision into the following key technology types:

- thermal treatment
- stabilization/solidification
- soil washing
- flotation
- solvent extraction
- substitution and reduction-oxidation
- biological treatment

Each technology was described in terms of the system process, the types of wastes that the technology could treat, examples of demonstrations of the technology, and areas where additional research was required. Included within this description was the extent to which the technology was mobile, the efficiency of contaminant destruction or removal and the cost of treatment per tonne of waste.

Thermal treatment technologies include destructive incineration technologies and non-destructive separation and concentration technologies. Incineration technologies are capable of treating a range of organic compounds in solids, sludge and liquid waste feed. Commercially mobile technologies include rotary kiln, circulating bed combustors, and infrared. Processes

involving plasma arc/torch, heat soaking furnace, advanced electric reactor and molten salt are in the developmental stage while high temperature slagging is a very high cost, non-transportable technology. Incineration processes are generally well known, have been well demonstrated and are rated as having a low to medium research priority.

Non-destructive thermal technologies include the Taciuk process and low temperature thermal process technologies which serve to separate contaminants from the soil matrix through the application of heat. These technologies have the advantage of being able to treat high volumes of contaminated soil at significantly lower costs than incineration technologies but further research is required to prevent the generation of hazardous by-products. These technologies have been given a medium to high research priority rating.

Stabilization/solidification technologies are non-destructive, immobilization technologies which involve the mixing of contaminated soil with reagents to form a low permeability and often solid material. Technologies include Portland cement and lime-based solidification, and clay stabilization. The processes are generally well understood and utilize machinery and equipment currently in use in the aggregate and construction industries. These technologies often involve an increase in the volume of treated material compared to the original contaminated waste because of the addition of reagents. The effectiveness of these technologies is adversely affected by fine grained (clay) material in the waste feed and high concentrations of organic compounds. Long term leachability of organic compounds and effects of freeze/thaw cycles have not been fully evaluated. Generally, research priority ratings for these technologies are low with the exception of clay stabilization which is a potentially suitable technology for the stabilization of organic compounds. This particular technology has been given a medium research priority rating.

Soil washing is an emerging technology in North America but is well developed in West Germany and the Netherlands where fixed and transportable systems have been operational for almost a decade. Soil washing is a non-destructive physical transfer process whereby contaminants are separated from the soil by dissolution and dispersion processes resulting in a significant reduction in the amount of treatable waste. The process works best on soils which contain

a high proportion of sand, and results in a cleaned coarse fraction which can be backfilled on site and a fine grained residue containing the contaminants which require further treatment prior to disposal.

Soil washing techniques which involve the use of water alone as the washing agent can be improved by using water under pressure, heated water, or ultrasonic techniques. Chemical additives such as surfactants, can be used to solubilize organic compounds and enhance particle/contaminant separation. Soil washing has been used to treat soils contaminated with fuel, oils and some chlorinated compounds. Demonstrations of this technology are being undertaken in the United States and commercial, mobile units are available in Canada. Soil washing has been given a medium to high research priority rating.

Flotation techniques which utilize principles of particle surface chemistry and electric double layer theory are well known processes and have been used by the mining industry for the separation of ore metals from waste rock. The techniques have been recently applied to the clean-up of contaminated soils. The technique is non-destructive and serves to separate the contaminant from the soil. Established flotation techniques have been operating in the Netherlands since 1983, but more information on wastes treated, efficiency and costs are required before the technique can be evaluated. In Canada, a pilot-scale facility is currently operating in Alberta. The process uses slurried coal fines to adsorb contaminants. The fines are then removed by flotation caused by bubbling air through the slurry. The process has been effective in the treatment of coal tar wastes and heavy oils from the petroleum industry and has the advantage of being able to treat large volumes of material at low costs. In some instances a saleable byproduct is produced which can offset the cost of treatment. Flotation techniques have been given a low-to high research priority rating.

Solvent extraction technologies are non-destructive separation techniques which utilize organic solvents to solubilize organic contaminants from soil. Several of the technologies are commercially available and have been demonstrated at Superfund sites in the United States, while other technologies are still at the pilot-scale or laboratory-scale. These technologies have been used to treat soils contaminated with fuels, oils and PCB's. The technologies

have the advantage of treating a variety of waste types including soils and sludges. Solvent extraction techniques have generally been given a medium to high research priority rating.

Substitution and reduction-oxidation technologies are discussed under separate processes of dechlorination and oxidation. Dechlorination is an important technique for the treatment of PCB contaminated soils. Dechlorination technologies include the addition of chemical reagents at ambient temperatures or the addition of hydrogen at elevated temperatures to dechlorinate toxic compounds.

Dechlorination using chemical reagents at ambient temperatures has been used to treat PCB contaminated soil and chlorinated phenol contaminated sludge, and has been demonstrated at Superfund sites in the United States. More research is required to evaluate the inhibitory effect of clays and organic materials in various waste feeds, and the identification and toxicity of various transformation compounds. This technology has been given a low research priority rating. Dechlorination by hydrogen addition at elevated temperatures has been tested at the bench-scale. Limited technical literature indicates that the process can treat PCB's and other chlorinated compounds in a variety of solid and liquid matrices. The technique is scheduled for demonstration to the Canadian Department of National Defense in 1990. The technology has been given a high research priority rating.

Oxidation processes utilizing oxidants such as ozone and hydrogen peroxide are in various stages of development. Commercially available techniques have been described for the clean-up of gasoline contaminated soil but a field demonstration and critical review of the technology is required. A medium research priority rating has been given to this technology.

Biological treatment technologies have been used for decades to treat oil refinery wastes and work most effectively on light aliphatic and aromatic hydrocarbons. Heavier molecular weight PAH compounds and chlorinated organic compounds are more recalcitrant. Under optimum conditions, biological treatment is a destructive technology. The simplest technologies are landfarming techniques in which the waste is spread over the ground and aerated using



standard agricultural and construction equipment. Biological breakdown is enhanced by the addition of nutrients to the soil. The concern with airborne emissions from landfarming operations makes this technology environmentally less sound than other biological treatment technologies, and consequently landfarming has been given a low priority research rating.

Enhanced landfarming techniques involve piling the soil into mounds or windrows and enhancing biological activity through the use of soil amendments, forced aeration, heating and nutrient addition. Leaching of contaminants can be controlled by underdrains, and airborne emissions can be controlled by covering the soil. This technology has been given a medium priority research rating.

Bioreactors provide maximum control of environmental conditions since biological degradation occurs within an enclosed reactor vessel. The volume of soil that can be treated in each reactor batch is less than the volume that can be treated using enhanced landfarming techniques, but degradation rates are considerably faster. As well, bioreactors have the potential to treat more recalcitrant, organic compounds. Bioreactors are available commercially although a considerable amount of research continues to be conducted on this technology. This technology was given a high research priority rating.

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1. INTRODUCTION

The National Groundwater and Soil Remediation Program (GASReP) has recently funded a number of literature review and priority research, development and demonstration (RDD) scoping studies in the areas of new in-situ bioremediation, pump and treatment technology, in-situ volatilization and offgas treatment, and excavation and treatment technologies required for the treatment of contaminated groundwater and soils.

The study presented herein provides a review and evaluation of current and emerging technologies used to treat contaminated soil following excavation.

1.1 STUDY OBJECTIVES

In light of the high cost of soil clean-up and the proliferation in the application of current and emerging technologies to the remediation of soil contamination, the following objectives for this study were established:

- (i) Identify and describe current and emerging technologies that would be suitable to the cleanup of soils contaminated with petroleum hydrocarbons, chlorinated solvents and wood preserving chemicals, evaluate them in terms of their suitability to Canadian conditions and state of development.
- (ii) Identify the most pressing research and development needs related to the technology reviewed.
- (iii) Provide GASReP with an up-to-date listing of key references on soil cleanup technologies as well as a listing of key researchers and vendors.

It was understood that the results of this study would assist GASReP in the appropriation of support for contaminated soil remediation through RDD projects.

1.2 SCOPE OF THE STUDY AND WORK PROGRAM DESCRIPTION

The scope of the work program for this study was vast because of the large number of technologies that had to be assessed. As well, application of soil cleanup technologies are well advanced in the United States, West Germany and The Netherlands and considerable time was spent in identifying and contacting government agencies, researchers and vendors by telephone and letter to obtain information. A large body of literature exists in the German and Dutch languages that was not used for this project.

The following methodology was used during the work program to identify and acquire information:

- a search of relevant databases
- acquisition of information through:
 - library searches
 - publication clearinghouses
 - letter interviews
 - telephone interviews

1.2.1 Database Search

A large number of technical and scientific databases are available to provide reference listings relevant to this study. However, since there is a considerable overlap in listings, a few well chosen databases can provide a majority of the most appropriate references. The following four databases were selected:

- | | |
|-----------------------|----------------|
| • Pollution Abstracts | 1970 - present |
| • Engineering Index | 1970 - present |
| • NTIS | 1985 - present |
| • WASTEINFO | 1985 - present |

The listings from these databases were screened and selected references were reviewed on microfilm before obtaining copies.

As well, the database of reference listings of treatment technologies at the Wastewater Technology Centre in Burlington, Ontario was reviewed, and appropriate references were chosen.

The NATO/CCMS International Conference Proceedings for 1987, 1988, and 1989 on the Demonstration of Remedial Action Technologies for Contaminated Land and Groundwater provided a useful source of information on treatment technologies in Europe and North America, and identified some key researchers and government agencies.

1.2.2 Acquisition of Information

Selected references were searched in libraries at the Canadian Institute for Scientific and Technological Information (CISTI), and the Geological Survey of Canada in Ottawa, and the Wastewater Technology Centre in Burlington, Ontario.

Publications clearinghouses such as the United States Environmental Protection Agency's (U.S. EPA) publication offices in Cincinnati, Ohio, and Washington, D.C. and the National Technical Information Service in Springfield, Virginia, were contacted for specific publications.

Letter interviews were conducted with key government agency personnel, researchers and technology vendors. The interview sheet was kept as simple and as short as possible to avoid discouraging potential respondents and was sent under a covering letter. A copy of the interview sheet is given as Figure 1.1.

An initial mailing of forty letters was made to individuals in the United States, The Netherlands, West Germany, United Kingdom, France, Denmark and Switzerland. Those individuals were selected on the basis of their participation in the NATO/CCMS Conferences. The response from the initial mailing identified key researchers and vendors, and a second mailing of the interview sheet was conducted. Forty-two letters were sent to West Germany and twenty-eight were sent to The Netherlands.

Figure 1.1

INTERVIEW SHEET - EXCAVATE AND TREAT

1. IDENTIFICATION OF INVESTIGATOR
 - name, address, telephone no., affiliation
2. SITE CHARACTERISTICS
 - general site conditions:
 - soil type, soil chemistry
 - depth to water table, porosity, permeability
3. CONTAMINANT
 - name of contaminant, class
 - cause of contamination, extent of contamination
4. EXCAVATE AND TREAT TECHNOLOGY SYSTEM DESIGN
 - brief description of the system process
 - treatment train configuration
 - treatment train capacity
 - treatment train capital and operating costs
5. EFFECTIVENESS OF TECHNOLOGY
 - how completely are contaminants broken down?
 - nature of process byproducts
 - is technology stand alone or must it be combined with other technologies?
6. DEVELOPMENT STAGE OF THE TECHNOLOGY
 - problem with process, research areas
 - scaling effects - from bench to operating scale?
 - mobility of system, mobilization time
7. PUBLISHED INFORMATION

Responses to the letter interview seldom addressed specific items on the interview sheet and responses were generally of three types:

- (i) government agencies provided lists of key researchers and vendors
- (ii) researchers provided scientific papers
- (iii) vendors provided company technical information

Telephone interviews were conducted with government agency personnel, researchers, and vendors as an initial contact, to request information and also as a follow up for more information, or to clarify areas of concern flagged during a review of the references.

1.2.3 Report Organization

The results of this study are provided in Sections 2, 3 and 4 and Appendices A and B. The various technologies are broken down according to type under the following general headings:

- Thermal Treatment
- Physical Treatment
- Chemical Treatment
- Biological Treatment

Under each general heading, specific technologies are identified, and a brief description of the technology and its application are provided under the following subject headings:

- i) Process Description
- ii) Wastes Treated
- iii) Applications/Demonstrations
- iv) Need for Further Research

Treatment costs are given in Canadian dollars on a per tonne basis, assuming an 0.85 conversion factor to United States funds, and an annual inflation rate of 5%.

Section 3 provides a summary of the treatment technologies in terms of treatability of specific contaminant groups, and cost, while Section 4 provides a summary of research and development needs.

References are listed in Section 5 according to technology type.

Appendix A provides a listing of key government agency personnel, researchers and research institutions, and vendors involved with each technology.

Appendix B provides case study examples where appropriate information was available, and gives a more detailed description of the application of specific technologies under general headings which include:

- vendor identification and stage of development of technology
- characteristics of the site
- type of contaminants and extent of contamination
- operational information including
 - process description
 - treatment rate
 - treatment costs
 - system mobilization
- treatment effectiveness
- key contacts
- references

1.3 CONTAMINANTS OF INTEREST

Treatment technologies applicable to soils contaminated with petroleum hydrocarbons, wood preserving chemicals and chlorinated solvents were reviewed during the course of this study. These contaminants fall within six of the thirteen contaminant treatability groups identified by the U.S. EPA (1989a), and include:

- Halogenated non-polar aromatics
- PCB's, halogenated dioxins, furans and their precursors

- Halogenated phenols, cresols, amines, thiols and other polar aromatics
- Halogenated aliphatic compounds
- Heterocyclics and simple non-halogenated aromatics
- Polynuclear aromatics

Contaminant treatability groups and sources of contamination are given in Table 1.1.

Table 1.2 lists individual contaminants within each treatability group.

TABLE 1.1 CONTAMINANT TREATABILITY GROUP AND SOURCES OF CONTAMINATION

Treatability Group	Sources of Contamination
• Halogenated non-polar aromatics	- solvents; lubricants; insecticides
• PCB's, halogenated dioxins, furans and their precursors	- insulator fluid; high pressure lubricant; plasticizers; additives to varnish, fiberglass; products of incomplete combustion of PCB's
• Halogenated phenols, cresols, amines, thiols, and other polar aromatics	- disinfectants; polyester fiber solvents; additives for rubber and plastic compounds, dyes, pharmaceuticals and agricultural chemicals; pesticides; wood preservatives
• Halogenated aliphatic compounds	- industrial solvents; degreasers; paint and varnish removers; refrigerants; pesticides; transformers and hydraulic fluid; plastic adhesive
• Heterocyclics and simple non-halogenated aromatics	- additives for pesticides, explosives, fuels, resins, perfume, dyes; paint removers; rubber cement; solvents; lubricants
• Polynuclear aromatics	- manufacture of dye intermediates, pharmaceuticals, pesticides, plastics

Table 1.2 Summary of Contaminants Sorted by Contaminant Treatability Group

W01 - HALOGENATED NON-POLAR AROMATIC COMPOUNDS

Chemical Name	CAS Number*
1,2,4,5-TETRACHLOROBENZENE	95-94-3
1,2,4-TRICHLOROBENZENE	120-82-1
1,2-DICHLOROBENZENE	95-50-1
1,3-DICHLOROBENZENE	541-73-1
1,4-DICHLOROBENZENE	106-46-7
2-CHLORONAPHTHALENE	91-58-7
4,4'-DDD	72-54-8
4,4'-DDE	72-55-9
4,4'-DDT	50-29-3
BENZYL CHLORIDE	100-44-7
CHLOROBENZENE	108-90-7
CHLOROBENZILATE	570-15-6
HEXACHLOROBENZENE	118-74-1
PENTACHLOROBENZENE	608-93-5
TOTAL CHLOROBENZENES	T108-90-7
TOTAL TRICHLOROBENZENES	TOT-TCB

W02 - DIOXINS/FURANS/PCBS & THEIR PRECURSORS

Chemical Name	CAS Number*
1,2,3,4-TETRACHLORODIBENZO-P-DIOXIN	30746-58-8
2,3,7,8-TETRACHLORODIBENZO-P-DIOXIN	1746-01-6
2,3,7,8-TETRACHLORODIBENZOFURAN	F1746-01-6
2,4,5-TRICHLOROPHENOXYACETIC ACID	93-76-5
2,4-DICHLOROPHENOXYACETIC ACID (2,4-D)	94-75-7
2-(2,4,5-TRICHLOROPHENOXY)PROPIONIC ACID	93-72-1
DECACHLOROBIPHENYLS	JPCB
DICHLOROBIPHENYLS	BPCB
HEPTACHLOROBIPHENYLS	GPCB
HEPTACHLORODIBENZODIOXINS	HEPCDD
HEPTACHLORODIBENZOFURANS	HEPCDF
HEXACHLOROBIPHENYLS	FPCB
HEXACHLORODIBENZODIOXINS	HEXCDD
HEXACHLORODIBENZOFURANS	HEXCDF
MONOCHLOROBIPHENYL	APCB
NONACHLOROBIPHENYLS	IPCB
OCTACHLOROBIPHENYLS	HPCB
OCTACHLORODIBENZODIOXINS	OCDD
OCTACHLORODIBENZOFURANS	OCDF
PCB-1016	12674-11-2
PCB-1221	11104-28-2
PCB-1232	11141-16-5
PCB-1242	53469-21-9
PCB-1248	12672-29-6
PCB-1254	11097-69-1
PCB-1260	11096-82-5
PENTACHLOROBIPHENYLS	EPCB
PENTACHLORODIBENZODIOXINS	PCDD
PENTACHLORODIBENZOFURANS	PCDF
TETRACHLOROBIPHENYLS	DPCB
TETRACHLORODIBENZODIOXINS	TCDD
TETRACHLORODIBENZOFURANS	TCDF
TOTAL DIOXINS AND FURANS	TOT-DF
TOTAL FURANS	TOT-FUR
TOTAL PCB'S	1336-36-3
TRICHLOROBIPHENYLS	CPCB

Table 1.2 Summary of Contaminants Sorted by Contaminant Treatability Group cont'd

W03 - HAL PHENOLS, CRESOLS, ETHERS, & THIOLS

Chemical Name	CAS Number*
2,3,4,6-TETRACHLOROPHENOL	58-90-2
2,4,5-TRICHLOROPHENOL	95-95-4
2,4,6-TRICHLOROPHENOL	88-06-2
2,4-DICHLOROPHENOL	120-83-2
2,6-DICHLOROPHENOL	87-65-0
2-CHLOROPHENOL	95-57-8
3,3'-DICHLOROBENZIDINE	91-94-1
3,4-DICHLOROPHENOL	34DCP
4-BROMOPHENYL PHENYL ETHER	101-55-3
4-CHLORO-3-METHYLPHENOL	59-50-7
4-CHLOROANILINE	106-47-8
4-CHLOROPHENYL PHENYL ETHER	7005-72-3
METHOXYCHLOR	72-43-5
P-CHLOROBENZENESULFONIC ACID	PCBSA
P-CHLOROPHENYLMETHYL SULFIDE	CPMS
P-CHLOROPHENYLMETHYL SULFONE	CPMSO2
P-CHLOROPHENYLMETHYL SULFOXIDE	CPMSO
PENTACHLOROPHENOL	87-86-5
SUPONA	470-90-6

W04 - HALOGENATED ALIPHATIC COMPOUNDS

Chemical Name	CAS Number*
1,1,1,2-TETRACHLOROETHANE	630-20-6
1,1,1-TRICHLOROETHANE	71-55-6
1,1,2,2-TETRACHLOROETHANE	79-34-5
1,1,2-TRICHLORO-1,2,2-TRIFLUOROETHANE	76-13-1
1,1,2-TRICHLOROETHANE	79-00-5
1,1-DICHLOROETHANE	75-34-3
1,1-DICHLOROETHENE	75-35-4
1,2-DIBROMO-3-CHLOROPROPANE	96-12-8
1,2-DICHLOROETHANE	107-06-2
1,2-DICHLOROPROPANE	78-87-5
2-CHLORO-1,3-BUTADIENE	126-99-8
BROMODICHLOROMETHANE	75-27-4
BROMOFORM	75-25-2
BROMOMETHANE (METHYL BROMIDE)	74-83-9
CARBON TETRACHLORIDE	56-23-5
CHLOROETHANE	75-00-3
CHLOROFORM	67-66-3
CHLOROMETHANE (METHYL CHLORIDE)	74-87-3
CIS-1,2-DICHLOROETHENE	156-59-2
CIS-1,3-DICHLOROPROPENE	10061-01-5
DIBROMOCHLOROMETHANE	124-48-1
DICHLORODIFLUOROMETHANE	75-71-8
ETHYLENE DIBROMIDE	106-93-4
HEXACHLOROBUTADIENE	87-68-3
HEXACHLOROETHANE	67-72-1
METHYLENE CHLORIDE (DICHLOROMETHANE)	75-09-2
PENTACHLOROETHANE	76-01-7
TETRACHLOROETHENE	127-18-4
TRANS-1,2-DICHLOROETHENE	156-60-5
TRANS-1,3-DICHLOROPROPENE	10061-02-6
TRICHLOROETHENE	79-01-6
TRICHLOROFLUOROMETHANE	75-69-4
VINYL CHLORIDE	75-01-4

Table 1.2 Summary of Contaminants Sorted by Contaminant Treatability Group cont'd

W07 - HETEROCYCLICS & SIMPLE NON-HAL AROMATICS

Chemical Name	CAS Number*
1-ETHYL-2-METHYL-BENZENE	611-14-3
ALKYL BENZENE	ABC
AROMATIC HYDROCARBONS	TOT-AR
BENZENE	71-43-2
BENZENE, TOLUENE, ETHYLBENZENE, XYLENES	BTEX
ETHYLBENZENE	100-41-4
ISOPROPYLBENZENE	98-82-8
M-XYLENE	108-38-3
O&P XYLENE	95-47-6
O-XYLENE	97-47-6
P-XYLENE	106-42-3
PYRIDINE	110-86-1
STYRENE	100-42-5
TOLUENE	108-88-3
XYLENES (TOTAL)	1330-20-7

W08 - POLYNUCLEAR AROMATICS

Chemical Name	CAS Number*
1-METHYLNAPHTHALENE	90-12-0
2-METHYLNAPHTHALENE	91-57-6
ACENAPHTHENE	83-32-9
ACENAPHTHYLENE	208-96-8
ANTHRACENE	120-12-7
BENZO(A)ANTHRACENE	56-55-3
BENZO(A)PYRENE	50-32-8
BENZO(B)FLUORANTHENE	205-99-2
BENZO(G,H,I)PERYLENE	191-24-2
BENZO(K)FLUORANTHENE	207-08-9
BIPHENYL	92-52-4
CHRYSENE	218-01-9
DIBENZO(A,H)ANTHRACENE	53-70-3
DIBENZOFURAN	132-64-9
FLUORANTHENE	206-44-0
FLUORENE	86-73-7
INDENO(1,2,3-CD)PYRENE	193-39-5
NAPHTHALENE	91-20-3
PHENANTHRENE	85-01-8
PYRENE	129-00-0
TOTAL POLYCYCLIC AROMATIC HYDROCARBONS	TOT-PAH

source: U.S. EPA (1989a)

2. TREATMENT TECHNOLOGIES

Treatment technologies discussed in this report have been reviewed on the basis of the following four broad categories of treatment type, each containing a number of sub-categories:

1. Thermal treatment
 - thermal destruction technologies
 - non-destructive thermal processes
2. Physical treatment
 - stabilization/solidification
 - soil washing
 - flotation
3. Chemical treatment
 - solvent extraction using non-critical fluid solvents
 - solvent extraction using critical fluid solvents
 - substitution and reduction-oxidation
4. Biological treatment
 - landfarming
 - enhanced landfarming
 - bioreactors

The treatment technologies can also be grouped according to the final disposition of the waste as:

- separation processes
- destructive processes
- immobilization processes

Separation processes do not destroy the waste but are used to reduce the volume of treatable waste by separating the waste from the soil matrix. They include: non-destructive thermal techniques, flotation processes, soil washing and solvent extraction.

Destructive technologies result in the chemical breakdown of the contaminant and include: destructive thermal technologies, substitution and reduction-oxidation technologies, and biological treatment.

Immobilization technologies are non-destructive and serve to immobilize contaminants in a relatively inert material so that contaminants will have a minimal impact on the environment. These technologies include stabilization and solidification.

For the purpose of this report, the detailed discussions of individual processes in this section will be made based on the four broad categories of thermal, physical, chemical and biological treatment technologies.

In Section 3, which provides a summary of treatment technologies, the various sub-categories of treatment technologies are discussed generally according to how they process the waste as separation, destructive or immobilization processes.

2.1 THERMAL TREATMENT

Thermal treatment technologies for contaminated soil may be broadly classified as either destructive or non-destructive. Destructive technologies include those systems that use thermal energy to destroy the organics present in the waste feed (e.g., incineration technologies). Non-destructive technologies typically use thermal energy to separate and concentrate the contaminant (e.g., distillation).

Incineration technologies have been in existence for some time (although hazardous waste incineration may be a relatively recent application) and the factors controlling incineration are well understood. For a particular waste feed the thoroughness of any combustion process will be determined by four parameters:

- temperature;
- residence time (both solid and gas);

- degree of turbulence/oxygen availability;
- homogeneity of the waste feed.

Within a certain range, changes in one parameter can be offset by changes in another. For example, a decrease in temperature can be compensated by increasing the residence time. The concentration of oxygen is another factor which has a significant impact on the combustion process. An oxygen enriched environment can result in a hotter combustion temperature whereas an oxygen depleted (pyrolytic) environment may be used as a separation (distillation) process.

When incinerating hazardous organic waste it is important that the combustion efficiency is maintained at a very high level to prevent the formation of products of incomplete combustion (PIC). Such PIC's may be much more toxic than the original waste, as the generation of dioxins from the incomplete combustion of PCB's would indicate.

Combustion efficiency is generally evaluated in terms of a destruction and removal efficiency (DRE) which is calculated as:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

where: W_{in} = mass of waste in feed
 W_{out} = mass of waste in exhaust gas.

In the United States under the Resource Conservation Recovery Act (RCRA), the incineration of hazardous material must obtain a DRE of 99.99% and under the Toxic Substances Control Act (TSCA) the incineration of toxic waste must obtain a DRE of 99.9999%. While the DRE is regulated in the United States by specific legislation, the achievable DRE is determined by the initial level of principal organic hazardous constituents (POHC's) and the analytical detection limit for that POHC. For example, for a POHC with an analytical detection limit of 0.001 ppm, the concentration of the POHC in the waste feed must exceed 1000

ppm to attain a DRE of 99.9999%.

Waste feed characteristics will also impact the efficiency of the incineration process. The density, moisture content, organic content and particle size of the feed material will influence the combustion process. Generally lighter weight, dryer and smaller feed material having high organic (i.e., heat content) concentrations are easier to incinerate.

Other waste feed characteristics that may adversely affect the incineration process are the presence of substances that may give rise to acid gases (i.e., high sulfur, chlorine and nitrogen contents).

Non-destructive thermal technologies are governed by many of the same factors and problems as destructive waste technologies. Major differences exist in the fact that there is less potential to generate PIC's and additional expense is required to dispose of concentrated contaminants.

2.1.1 Thermal Destruction Technologies

2.1.1.1 Rotary Kilns

i) Process Description

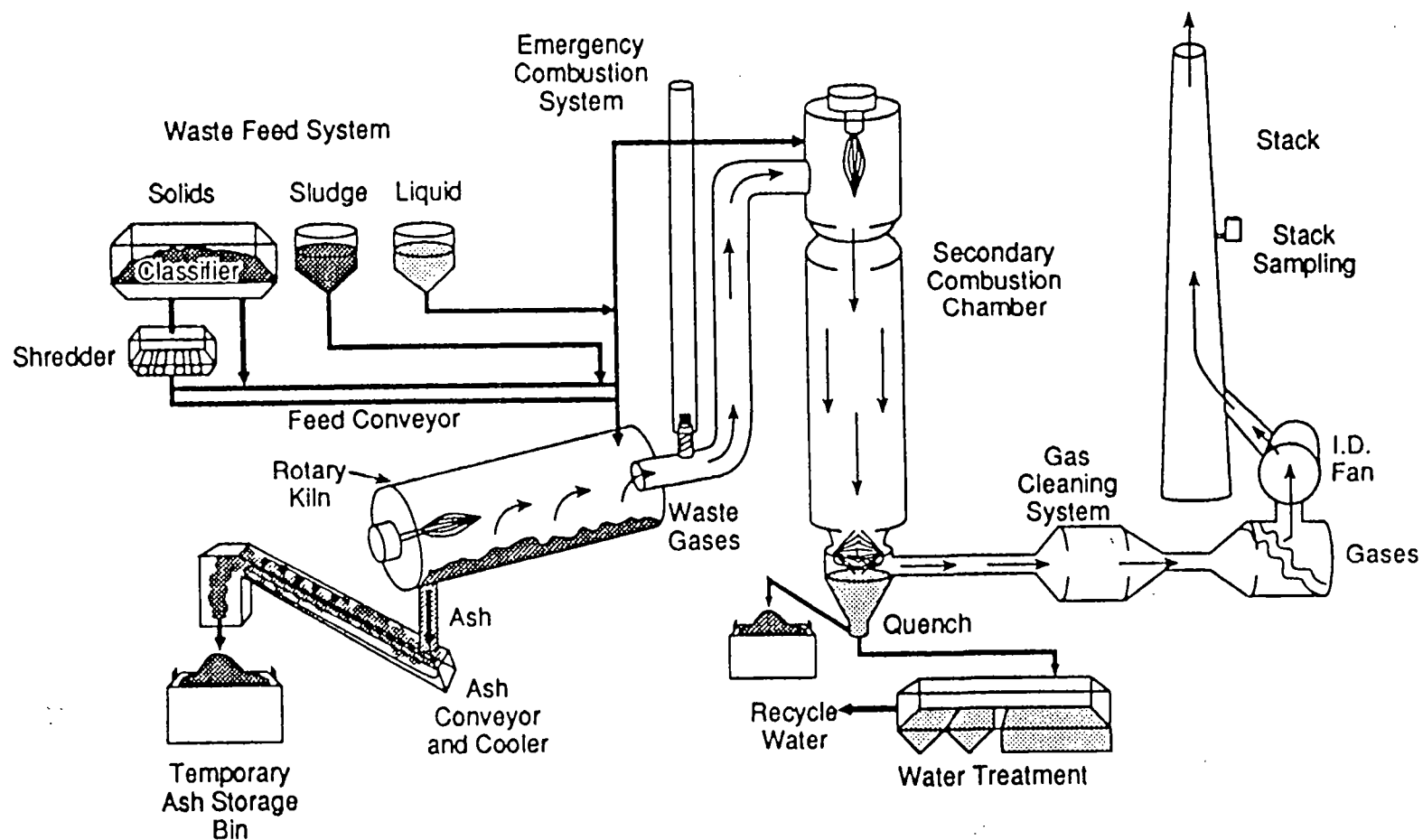
Rotary kilns are one of the oldest and most widely used incineration technologies. These incinerators are very versatile and historically have been used to incinerate solid wastes such as sewage treatment plant sludges, municipal wastes, slurries, etc. Because of this versatility in treating a wide range of feed materials, rotary kilns were one of the first incinerators to be used to incinerate hazardous solid wastes.

A typical rotary kiln consists of a refractory lined steel cylindrical shell mounted at a slight inclination to the horizontal. The kiln rotates about its axis causing mixing of the waste material with the combustion air. Waste and auxiliary fuel are added to the high end of the kiln while ashes are collected from the bottom. Operating temperatures of rotary kiln incinerators can vary

significantly, from 1500°F to 3000°F (815°C to 1650°C), but generally most kilns operate at temperatures less than 2000°F (1093°C). Kilns operating within the cooler range generally require a secondary combustion chamber to ensure the destruction of organic wastes. These units also generally require a pre-cooler, scrubber system and carbon adsorption column for treatment of exhaust gases. Although the hotter burning kilns do not always require secondary combustion chambers and the associated air pollution control systems, they suffer from other drawbacks such as slag formation, higher fuel costs and higher refractory maintenance. A typical rotary kiln system is depicted in Figure 2.1.

A number of companies have developed mobile or transportable rotary kiln incinerators for the incineration of hazardous solid material. In the United States the USEPA has developed its own mobile incineration system (MIS) which is based on rotary kiln technology. Other major vendors/users of this technology for hazardous waste incineration include (in the United States) Weston Services Inc., ENSCO, IT Corp., Haztox, VESTA and OH Materials. In Europe numerous companies have been using both fixed and transportable systems. Some of the more prominent companies include Von Roll Inc., Deutsche Babcock, Ed Zublin, Ecol Tech and WE Environmental. In Canada no companies are currently using mobile rotary kilns for hazardous waste incineration. At Swan Hills, Chem Security currently uses fixed rocking kilns designed by Von Roll Inc. for incineration of Alberta's hazardous waste. Selenco/Sanivan is currently applying to the Ontario provincial government to obtain a permit to operate an ENSCO MWP - 2000 rotary kiln for PCB destruction. Several other Canadian Companies are in the process of developing or evaluating rotary kiln designs, including Aqua-Guard Technologies of B.C., PPM Canada Inc. and Ecological Services.

Because of the wide range of designs available on the market, operating parameters for existing rotary kilns vary significantly. Treatments for mobile units can vary from 1 tonne/hr (VESTA's low capacity unit) to 25 tonne/hr (IT Corp.'s high capacity unit). These treatment rates are generally specified for ideal waste feed conditions. If the moisture content is too high, for example, residence times must be increased (resulting in a corresponding decrease in



treatment rate). McCormick and Duke (1989) indicate that an increase in moisture content from 10% to 40% can necessitate a doubling in solid residence time (i.e., halving of treatment rate). Treatment rates are also a function of the heat content of the waste. Generally excessively high heat contents reduce incinerator throughput since it causes more refractory damage (necessitating more maintenance), slagging and excessive carry over of solids to the after burner.

Setup times also vary significantly. Smaller mobile units may generally be setup in under one week, whereas large transportable systems may require months for setup.

High heat content wastes may, however, be beneficial from an economic standpoint because it may allow for fuel substitution by the waste. Johnson and Cosmos (1989) estimate the cost of incinerating a tonne of contaminated soil (at 20% moisture content) using Weston's transportable incineration system at \$295/tonne. Mortensen et al. (1987) estimate that USEPA's MIS had capital and operating costs of between \$850/tonne and \$1700/tonne for contaminated soil. These costs were anticipated to be reduced by 50% with modifications to the burner system. Lanier (1988) indicates that costs for incineration using ENSCO MWP-2000 incinerator vary from \$235/tonne for relatively dry soil to \$1176/tonne for high water content sludges.

ii) Wastes Treated

One of the major advantages of rotary kiln technology is its ability to incinerate virtually any sort of contaminated material with minimal preprocessing. Rotary kilns have been used to treat virtually all kinds of soil (clay, silt, sand, gravel, topsoil), sludges, solid material (drums, shredded capacitors) and liquid wastes. Generally treatment rates decrease with increasing moisture content and increasing heat content of the waste. However, this decrease in throughput does not affect the final combustion efficiencies. Other feed characteristics that may affect the operation of rotary kiln incinerators are acid gas constituents such as chloride, sulphur and nitrogen which may cause overloading of the pollution control system. The presence of metals in the feed material can also affect the incineration process. Alkali

metals (e.g., sodium) can cause refractory erosion, fouling problems and particulate emissions. Toxic metals are also prone to excessive particulate emissions.

Rotary kilns have been used to incinerate a wide variety of hydrocarbon and chlorinated hydrocarbon wastes. These wastes have included PCB's (up to 120,000 ppm), 2,3,7,8 TCDD (1.0 ppm), BTX (8,200 ppm), and PCP (1,000 ppm).

iii) Applications/Demonstrations

There have been numerous applications of rotary kiln incinerators to hazardous waste problems. In North America virtually all of these hazardous waste applications have been performed using mobile or transportable systems. In Europe a combination of mobile and fixed systems has been used. Table 2.1 summarizes some of the better documented applications of mobile/transportable incineration projects.

USEPA has acquired its own rotary kiln mobile incineration system (MIS). Between October 1981 and August 1987 this system underwent a series of trial burns on material contaminated with a variety of organic contaminants including benzene, carbon tetrachloride, PCB, and dioxins. Since 1985 the MIS has decontaminated over 4,000 tonnes of contaminated material from eight superfund sites in Missouri. The largest of these sites was the Denney Farm site in McDowell, Mo. at which 900 tonnes of dioxin contaminated soil was incinerated.

A number of test burns have been made to evaluate the performance of various rotary kiln systems. The ENSCO MWP-2000 was tested on a variety of PCB contaminated materials at El Dorado, Ar. DRE's of 99.999999% were obtained for PCB's and 99.9999% were obtained for a variety of organic and processing wastes. Dioxin levels were below detection limits.

The USEPA's combustion research facility (Pine Bluff, Ar) was the site of additional test burns conducted on PCB contaminated soil. A total of 14 test runs were performed primarily for the purpose of evaluating destruction efficiencies as a function of operating parameters. It was found that high

Table 2.1 Summary of On-site Rotary Kiln Incineration Projects

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	DRE (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1983	Sydney Mines	--	ENSCO	BTX	--	--	--	Frank et al., 1987
1985-1987	Denney Farms, Mo.	USEPA	IT Corp.	2,3,7,8 TCDD	<0.56	--	900	Mortensen et al., 1987 Freestone et al., 1987
1986	El Dorado, Ar.	USEPA	ENSCO	PCB	55,000	99.999999	<1 test burns	Lanier, 1988 Acharya, 1987
1986	Pine Bluff Ar	--	USEPA US Army	PCB	<286	99.9999	<1 test burns	Tessitore et al., 1987
1986	Stuttgart, FRG	--	Ed. Zublin	PAH	3,150 (total)	99.99	--	Glaser, 1988
1986	Tyndall AFB, FL.	USAF	USAF	2,3,7,8 TCDD	<0.5	99.9999	<10 test burns	Stoddart & Short, 1988 USEPA, 1989a
1987	Aberdeen, NC.	USEPA	VESTA	DDT BHC	131 29	99.993 99.998	<1.5 test burns	USEPA, 1989a
1987	CAAP	USARMY	IT Corp.	explosives	--	--	22,000	Shu, 1989

Table 2.1 Summary of On-site Rotary Kiln Incineration Projects (Cont'd)

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	DRE (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1987	John Zinc Co. test site	--	USEPA	volatile & semi-volatile	<8,200 xylene <6,500 anthracene <1,000 PCP	99.99	2 test burns	Esposito et al., 1988 USEPA, 1989a Esposito et al., 1989
1987	Lenz Oil	Illinois EPA	ENSCO	BTX	<2,000	99.9999	7,000	Frank et al., 1987 (see Case Study 1)
1987	Oak Creek, Wi.	Dupont	OH Materials	naphthylamines	<150	--	50,000	Sulzer et al., 1988
1987	Switzerland	--	Von Roll, Dentag-Mischwerke	PAH PCB	1.5 125	99.9	test burn	Wirth & Haint, 1988
1988	Beardstown, Il.	USEPA	Weston	PCB	<120,000	>99.99998	8,500	Johnston & Cosmos, 1989 Illinois EPA, 1988 Leuser et al., 1989
1988	BROS site	USEPA	Acurex	PCB	<600	99.992-99.9998	test burns	USEPA, 1989a

Table 2.1 Summary of On-site Rotary Kiln Incineration Projects (Cont'd)

Date	Site	Customer	Contractor	Contaminants	Initial Concentra- tion (ppm)	DRE (%)	Initial Quantity Contamina- ted Soil (tonnes)	Reference
1988/Prentiss 89		USEPA	Williams	PAH	1,400 phenanthrene	>99.999	9,200	McGowan & Harman, 1989
1989	Fort A.P. Hill	U.S. Army	Metcalf & Eddy	2,3,7,8 TCDD	<1.03	99.9999	190	Mineo & Edwards, 1989 Chaudhari et al., 1989
1990	Paxton Lagoons	Illinois EPA	Weston	PAH Volatiles semi-volatiles	--	--	16,000	Weston, undated(b)

DRE = destruction removal efficiency (see page 14)

-- = no data available

afterburner retention times and high air enrichment ratios (180%) were required to achieve a DRE of 99.9999%.

Additional applications of mobile rotary kilns to PCB contaminated soil include the Bridgeport Rental and Oil Service (BROS) superfund site at which DRE's ranged from 99.992% to 99.9998% and the Beardstown, Il. site involving the incineration of 8,500 tonnes of soil (>99.99998% DRE).

Test burns were also performed on dioxin contaminated soil (0.5 ppm) at the USAF Tyndall AFB. These burns were conducted using an ENSCO MWP-2000 incinerator and exhibited a DRE of 99.9999%. Dioxin contaminated soil (190 tonnes) was also incinerated at the Fort A.P. Hill site in Bowling Green, Virginia. DRE's of >99.9999% were reported (Chaudhari et al., 1989).

Test burns were conducted at a National Priority List (NPL) site at Aberdeen N.C. on soil contaminated with DDT and α BHC. DRE's of 99.993% and 99.998% were obtained for each of these contaminants.

PAH contaminated soil has been incinerated at a variety of sites including Stuttgart, FRG (99.99% DRE) by Ed. Zublin Inc., John Zinc test site in Edison N.J. (DRE of 99.99%), in Switzerland by Von Roll-Dentag Mischwerke (DRE 99.9%) and the Prentiss Creosote site in Mississippi (DRE>99.999%).

Finally a number of applications have demonstrated the suitability of mobile rotary kiln incineration technology for remediating large quantities of hydrocarbon contaminated soil. One such application is the Lenz Oil site which involved processing 7,000 tonnes of BTX contaminated soil. DRE's at this site were greater than 99.99%. Additional information on the Lenz Oil site is provided in the case study information (Case Study 1, Appendix B). Weston's transportable rotary kiln was used to incinerate 16,000 tonnes of soil, debris and drums contaminated with a variety of volatile (toluene, methyl chloride, PCE, TCE, benzene), semi-volatile (phenol, naphthalene) and PAH's (phenanthrene, fluorene, chrysene). DRE's of 99.9999% were attained for PCE. Another application to hydrocarbon contaminated soil is the Sydney Mines site in Florida involving the treatment of an unspecified volume of material.

Other applications of mobile/transportable rotary kiln technology include the incineration of 22,000 tonnes of explosives contaminated soil at the Cornhusker Army Ammunition Plant (CAAP) and the incineration of naphthylamine contaminated soil (50,000 tonnes) at Oak Creek, Wi.

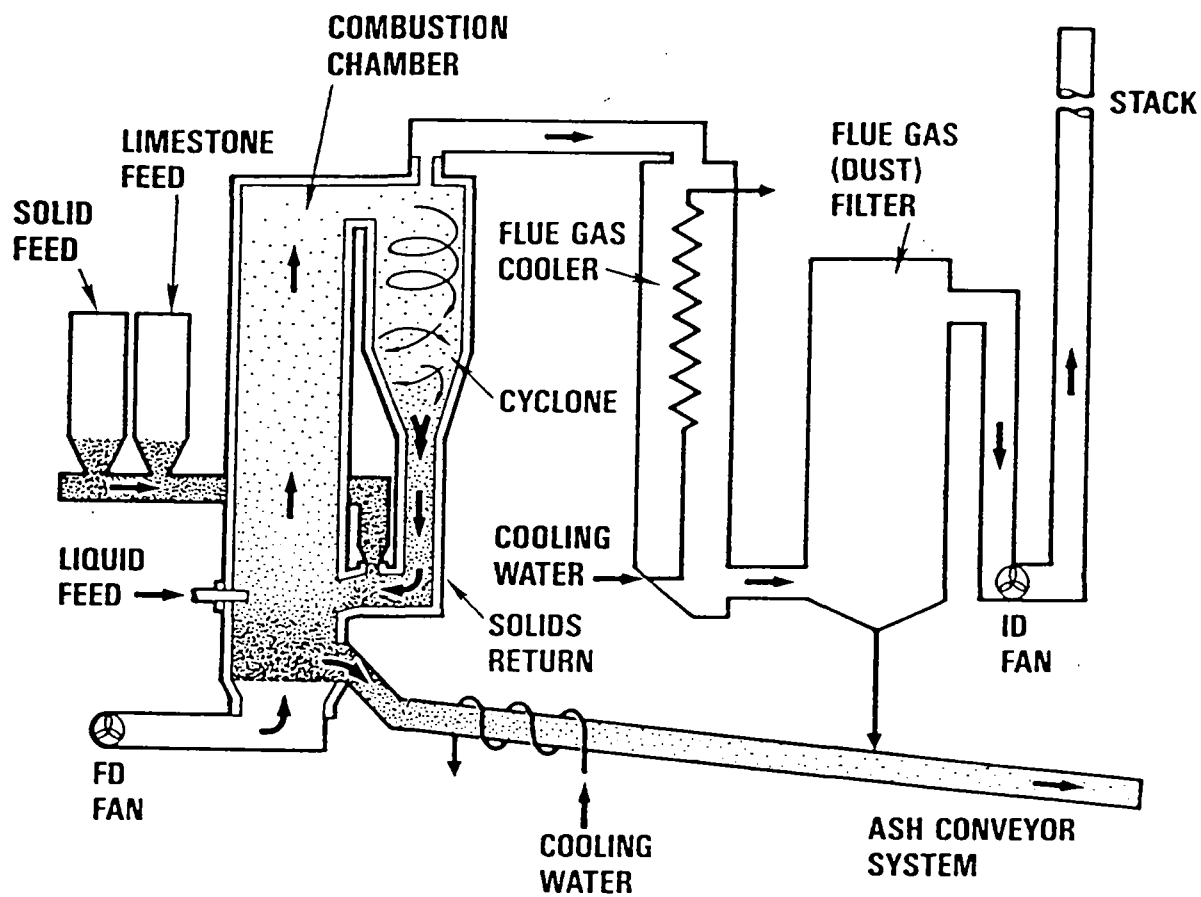
iv) Need for Additional Research

Rotary kiln technology is relatively well developed. Additional research should concentrate on improving throughput rates.

2.1.1.2 Fluidized Beds and Circulating Bed Combustors

i) Process Description

The technology employed in fluidized bed incinerators has long been used by the chemical processing industry for reactor vessels in which intimate contact between gases and particulate solids is required. A typical fluidized bed incinerator consists of a vertical refractory lined vessel containing a bed of granular material laying on a distributor plate. Combustion air is pumped into the bed through the bottom plate at sufficient velocity to cause fluidization (suspension) of the bed material and rapid mixing of the waste material, bed, and air. The bed is maintained at a constant temperature (600° - 900°C; 1110° - 1650°F) through use of supplementary fossil fuel. A variation on the typical fluidized bed configuration is the circulating bed combustor (CBC) which utilizes higher gas velocities (14-20 ft/s) and finer granular bed materials. A typical circulating bed combustor is shown in Figure 2.2. In addition to the primary combustion chamber other key components include a cyclone and return leg for circulation of bed material. Exhaust gases are cooled through a flue gas cooler and subsequently pass through a particulate filter before exiting the exhaust stack.



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Checked by	Date
Revisions	Date

CIRCULATING BED COMBUSTOR (CBC)
(Ogden Environmental Services, undated)

INTERA KENTING

FIGURE 2.2

Conventional fluidized beds are typically fixed systems used for applications other than hazardous waste incineration. CBC technology was developed principally for hazardous waste incineration. In the United States CBC technology was originally developed by G.A. Technologies and is now marketed by Ogden Environmental Services. In Canada an affiliated company, Ogden Allied Canada is marketing this technology. Ogden developed a pilot 16 in. CBC and used test data on this unit to design a 32 in. transportable system. The transportable system can be transported by single drop truck trailers and requires three weeks for assembly.

The CBC incineration units offer some advantages over conventional incinerators due to the highly turbulent nature of the combustion which results in a very efficient incineration process. As a result secondary combustion chambers are not required and the operating temperature is lower than that of conventional incinerators. Acid gases that are formed during the combustion process are captured and neutralized by crushed limestone that is added to the incinerator with the waste feed. In most applications the use of scrubbers is not required (Wilbourn and Anderson, 1989).

The nature of the CBC process also imposes some limitations on the waste stream. For example, waste must typically be less than 1 in (2.54 cm) in diameter to maintain fluid conditions (Shu, 1989). The need for significant quantities of high velocity gas also renders the use of CBC technology difficult for pyrolytic applications.

The treatment rate of contaminated soil varies significantly depending on the feed's moisture content and its caloric value. Wilbourn and Anderson (1989) report a treatment for the 36 in. CBC of 70 tonnes/day and 50 tonnes/day for PCB contaminated soil with moisture contents of 10% and 20%, respectively. Shu (1989) reports typical treatment rates of 78 to 124 tonnes/day and Ogden (undated, a,b) report actual field rates of 100 tonnes/day.

Treatment costs vary as a function of the heat generating capacity of the waste, the volumes treated and the moisture content of the waste. Shu (1989) reports a value of \$118 - \$188/tonne for a medium sized site. Anderson and Wilbourn (1989) suggest typical costs of \$118-\$353/tonne including capital/operating and excavation costs.

ii) Wastes Treated

To date CBC technology has been used to incinerate PCB (having concentrations <801 ppm) and hydrocarbon contaminated soils. Test burns have been performed on spiked (with carbon tetrachloride) soil as well as contaminated sludges. Soils must be less than 1 in. (2.54 cm) in diameter. Liquid wastes can also be incinerated by injecting the fluid directly into the combustor.

Johnson and Cosmos (1989) indicate that wastes containing large amounts of heavy metals, no organic contamination and salts may be unsuitable for these incinerators.

iii) Applications/Demonstrations

Ogden Environmental Services appears to be the only company to have actually applied CBC technology to contaminated soil remediation. Three applications have been documented as summarized in Table 2.2.

The first application consisted of test burns conducted on McColl Superfund Site contaminated soil. These burns were conducted at a fixed facility and involved both mixing waste soil with clean sand and using samples spiked with an unspecified amount of carbon tetrachloride. Destruction and removal efficiencies (DRE) were reported to be 99.9937% for organic contaminants (Anderson and Wilbourn, 1989).

A major application of CBC technology was performed by Ogden Environmental Services at Swanson River, Alaska. At this site over 70,000 tonnes of PCB contaminated soil will eventually be incinerated. At a rate of 100 tonnes/day, Ogden estimates to complete the site remediation within three years.

Table 2.2 Summary of On-site CBC Incineration Projects

Date	Site	Customer	Contractor	Contaminants	Initial Concentra- tion (ppm)	DRE (%)	Initial Quantity Contamina- ted Soil (tonnes)	Reference
1986	McColl	EPA	Ogden Environmental	BTX	<165	99.9937	2 (Test Burns)	Wilbourn & Anderson, 1989 Anderson & Wilbourn, 1989
1988	Swanson River, Al	ARCO	Ogden Environmental	PCB's	<801	99.99993	80,000	Shu, 1989 Wilbourn & Anderson, 1989 Ogden (undated,b) (see Case Study 2)
1988	Stockton, Ca	--	Ogden Environmental	Fuel Oil	--	--	11,000	Shu, 1989 Wilbourn & Anderson, 1989 Anderson & Wilbourn, 1989

DRE = destruction removal efficiency (see page 14)

-- = no data available

To obtain the necessary permit from USEPA, Ogden was required to perform 5 test burns using the contaminated soil. The test burns indicated DRE efficiencies averaging 99.99993% on soil having concentrations ranging from 289 to 801 ppm of PCB (averaging 595 ppm). The soil at this site was described as silt, clay and gravel. The application of this technology during the winter of 1988 has significant positive implications as to its suitability for Canadian conditions. Additional information on this application is presented as Case Study 2 in Appendix B.

CBC technology was also used to remediate approximately 11,000 tonnes of hydrocarbon contaminated soil in Stockton, Ca. Little information is available describing this project. It is known that the soil was clay, and that a DRE of approximately 99.99960% was achieved on naphthalene spiked soil (4383 ppm).

iv) Need for Additional Research

CBC technology is relatively well developed. The only additional research that may be required are better definition of interferences in the waste stream and improved treatment rates.

2.1.1.3 Plasma Arc/Torch

i) Process Description

Plasma torch technologies have been used commercially in metals industries for some time (Staley, 1989) but have only recently been used in incinerators. The process consists of a number of high power electrodes that are used to create an electric arc in the presence of low pressure air. Electrical energy is absorbed by the air molecules raising them to highly excited states. During relaxation these molecules release thermal energy creating a plasma. Process gas (generally air) is passed through the plasma resulting in an extremely hot (10,000 - 20,000°C) gas (Joseph and Barton, 1987).

Initial applications of plasma torch technology in the hazardous waste incineration field were limited to liquid wastes, although more recently a number of companies are examining its suitability to hazardous contaminated soils. Westinghouse is examining two possible plasma torch designs for solid hazardous waste incineration, the Electric Pyrolyser and the EPRI plasma fired cupola (see Figure 2.3), the latter of which is still in the development stage. Retech Inc. has developed a plasma reactor system which is similar to the Westinghouse systems (see Figure 2.4). Basically all of these systems use the heat from a plasma torch to create a molten bath which is used to decontaminate soils. Organic contaminants are destroyed due to the extremely high temperatures and metals are encapsulated into the molten material which turns into a vitrified slag upon cooling. All systems typically have some form of treatment for exhaust gases.

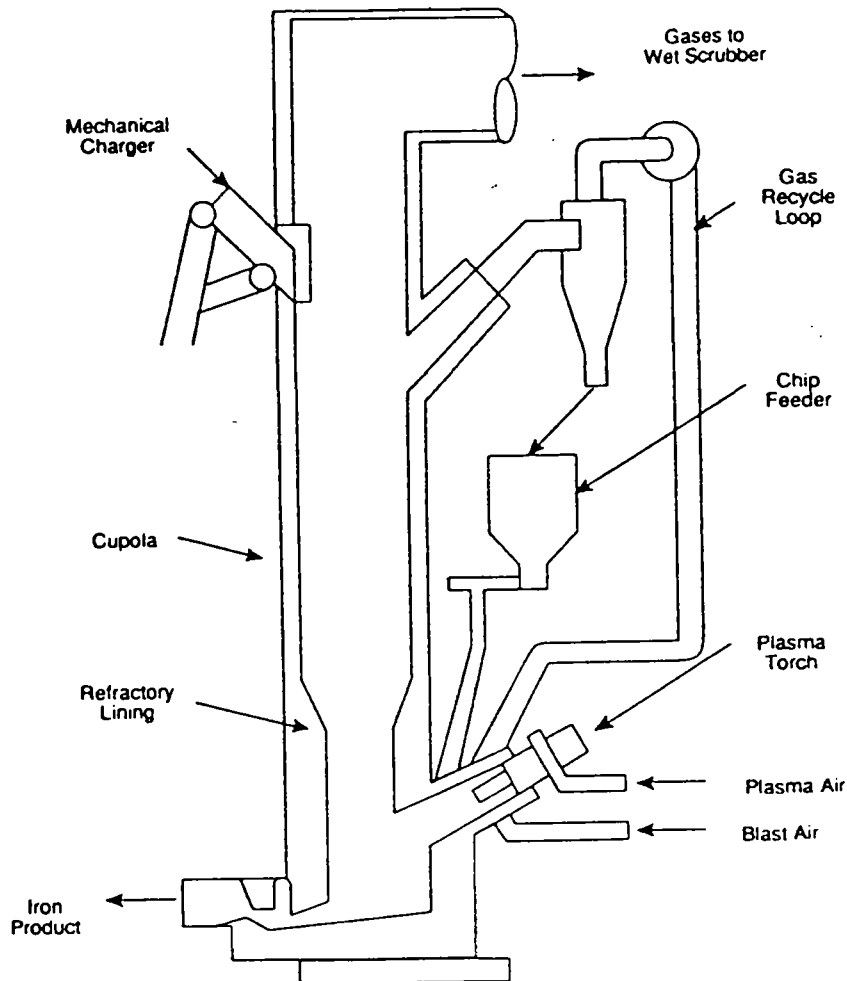
Joseph and Barton (1987) suggest several advantages of plasma incinerators over conventional systems. The high combustion temperatures yield high DRE's. The pyrolytic (or reducing) environment does not require large volumes of excess air, reducing equipment requirements.

Disadvantages associated with these systems include the high electrical power requirements - 1 Mw for the Westinghouse Electric Pyrolyser (Johnson and Cosmos, 1989) and relatively low feed rates. The capacity of the Electric Pyrolyser is less than 1 tonne/hr and although the capacity of the plasma fired cupola could be as high as 50 tonne/hr the size of a cupola for such an operation would make it untransportable. Cupolas with capacities up to 5 tonne/hr were judged to be (conceptually) transportable (Johnson and Cosmos, 1989). Set-up time for the Electric Pyrolyser is approximately one week.

No information describing the cost of running a plasma torch system could be obtained.

ii) Waste Treated

Initial applications of plasma torch incinerators were to organic contaminated liquids. More recent designs have centred on the treatment of contaminated solid materials, including metals, glass, plastics and soils

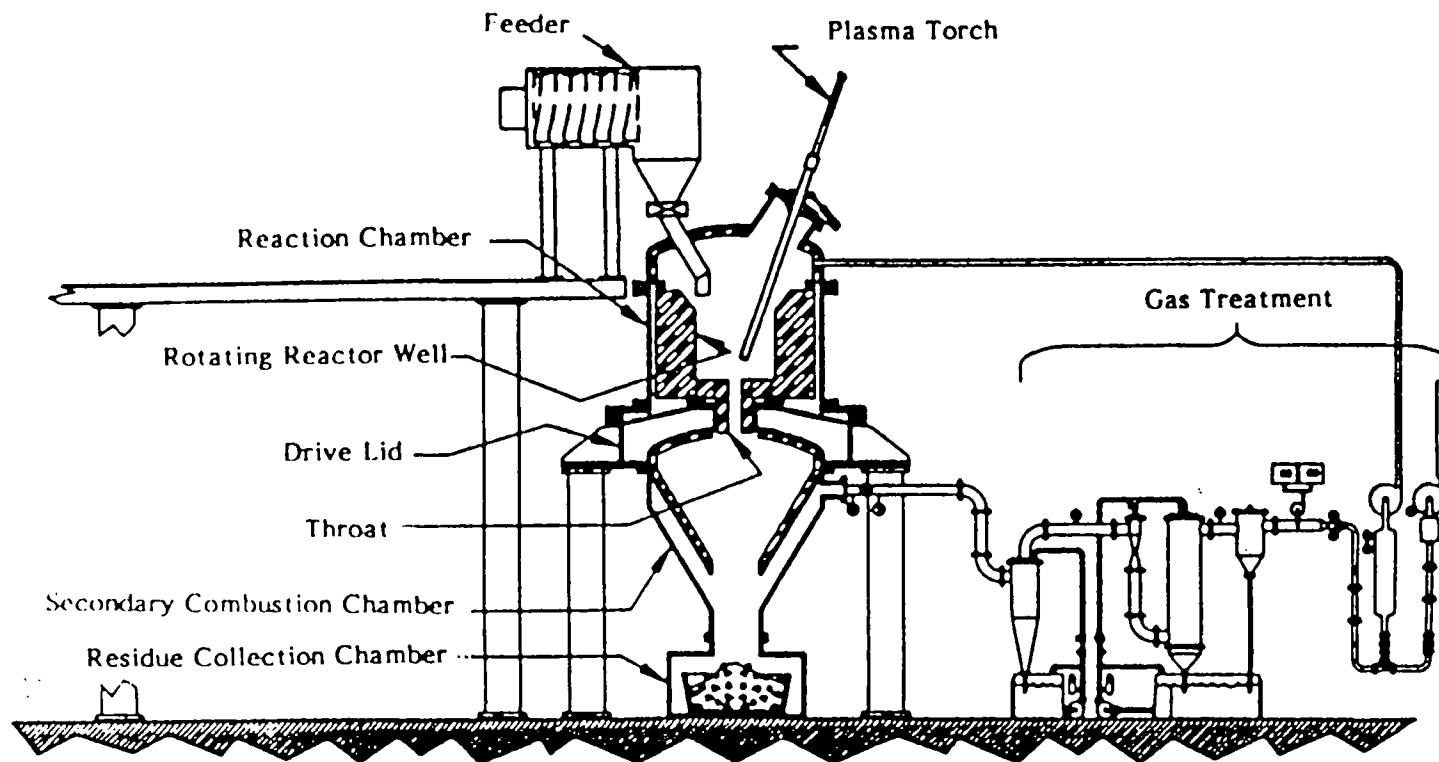


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EPRI PLASMA FIRED CUPOLA (Johnson and Cosmos, 1989)

INTERA KENTING

FIGURE 2.3



INTERA KENTING

RETECH ELECTRIC PYROLYSER (USEPA, 1989)

FIGURE 2.4

(Eschenbach et al., 1987). Test burns have been conducted on a variety of soils including clay, silt, sand, gravel and topsoil. Contaminants that have been treated included tetrachloroethylene (3,277 ppm), anthracene (7,361 ppm), bis(2-ethylhexyl) phthalate (3,702 ppm) as well as zinc (28,306 ppm) and chromium (1,898 ppm).

iii) Applications/Demonstrations

Plasma arc technologies are still very much in the developmental stage and only very limited bench-scale testing has been performed for contaminated soils. The only documented application of this technology to contaminated soils is Eschenbach et al. (1987), who describe bench-scale tests performed on 300 lbs. (136 kg) of synthetic soil. Destruction and removal efficiencies (DRE's) of 99.99% and 99.999% were attributed to a malfunction in the feeder. Additional information on this application is presented as Case Study 3 in Appendix B.

iv) Need for Additional Research

This technology needs additional work to evaluate whether it is economically justifiable, to improve waste treatment rates and evaluate the sensitivity of the output concentrations to process variables.

2.1.1.4 Heat Soaking Furnace

i) Process Description

PPM Canada Inc. is in the process of developing a mobile heat soaking furnace for the destruction of solid material contaminated with PCB's. The unit is primarily designed to treat shredded PCB capacitors although it will be capable of treating small quantities of soil (Crittenden, 1990).

The system will be mounted on five trailers, one each for the primary furnace, secondary combustion chamber, air pollution control system, laboratory and control unit, and miscellaneous support equipment. The primary combustion chamber is designed to operate at 649°C (1200°F) to allow the recovery of metal from transformers or capacitors. The secondary combustion chamber is designed to ensure complete destruction of organics in exhaust gases and operates at a temperature of 1204°C (2200°F). The system utilizes a combination of mineral oil, no. 2 fuel oil and PCB liquids as a fuel source. Figure 2.5 presents a schematic of PPM's proposed mobile heat soaking furnace.

No information on treatment costs or set-up time could be obtained for this unit.

ii) Wastes Treated

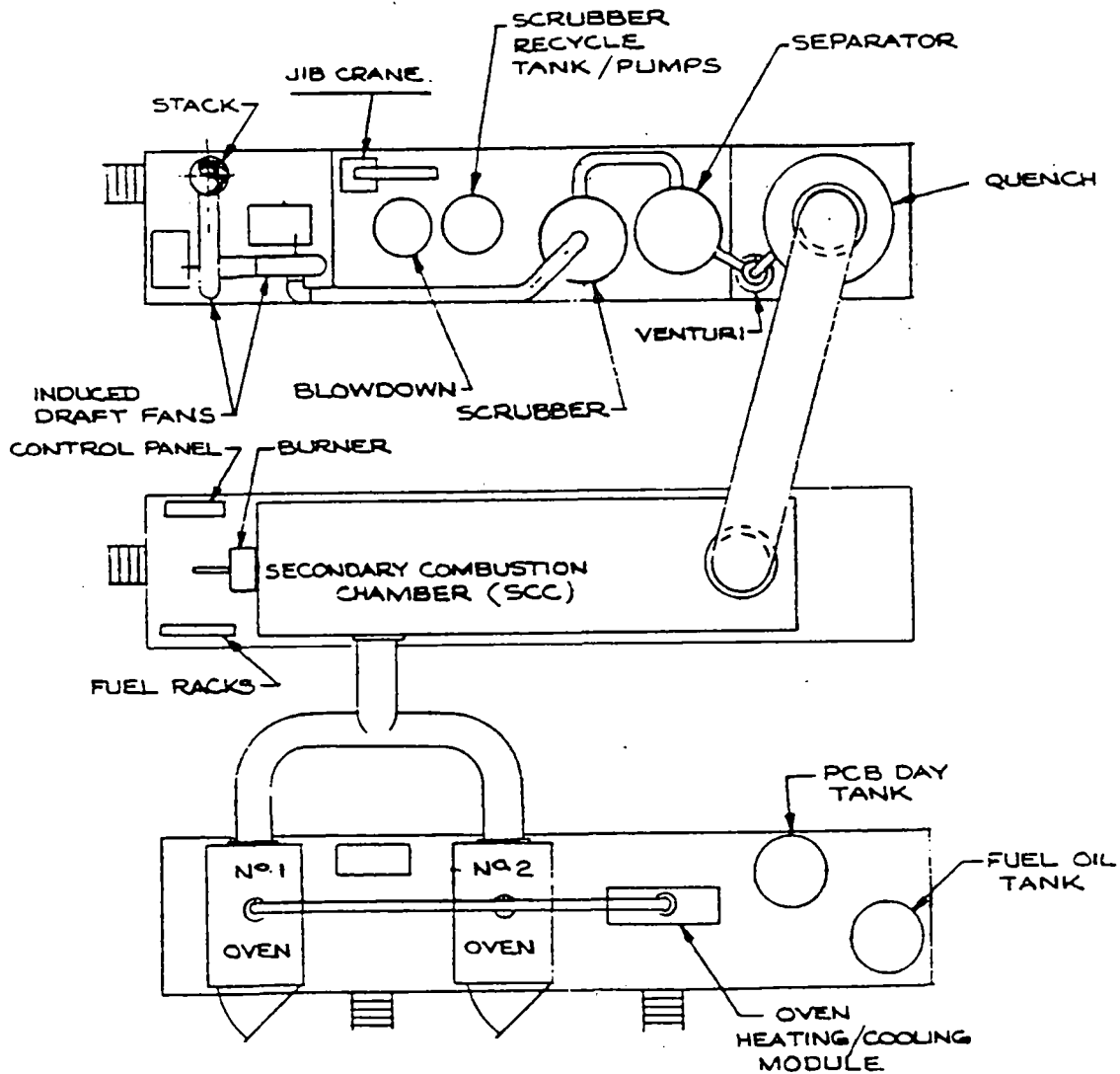
This unit is primarily intended to treat PCB contaminated liquids and metals. Although it may be possible to treat other wastes, such applications are unproven.

iii) Applications/Demonstrations

This technology is still in the developmental stage, consequently no information on applications or demonstrations exist.

iv) Need for Additional Research

Until a pilot-scale unit is constructed and tested, areas requiring additional research cannot be identified.



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PPM CANADA'S HEAT SOAKING FURNACE
(Crittenden, 1990)

INTERA KENTING

FIGURE 2.5

2.1.1.5 Infrared

i) Process Description

Infrared incineration systems were developed primarily by Shirco Infrared Systems Inc. of Dallas, Texas. A number of firms (e.g., OH Materials, Westinghouse/Haztech, ECOVA) have purchased Shirco units for site remediation projects but the units are no longer being commercially manufactured (Johnson and Cosmos, 1989). Shirco manufactured both a mobile and a transportable system, with the primary difference between the two systems consisting of smaller components for the mobile system resulting in faster set-up times but lower processing rates. The mobile system has a treatment rate of 68 kg/hr and the transportable system has a treatment rate of 100 tonnes/day (Johnson and Cosmos, 1989). Set-up time for the mobile system is less than one day (Welsh, 1987) while set-up time for the transportable system (mounted on five trailers) is on the order of a month.

Both systems consist of the following components:

- Waste feed system - consisting of a variable speed woven wire conveyor belt.
- Primary combustion chamber - constructed of carbon steel and lined with ceramic fibre. Infrared energy is supplied by electrically powered silicon carbide heating elements attaining a maximum temperature of 1850°F (1010°C). Residence time of the solid material is variable, typically ranging between 10 and 180 minutes (Welsh, 1987).
- Secondary combustion chamber - also constructed of carbon steel and lined with ceramic fibre. A 375,000 BTU/hr propane burner is typically used as the secondary combustion chamber heat source. The chamber normally operates at temperatures up to 2300°F (1260°C) and

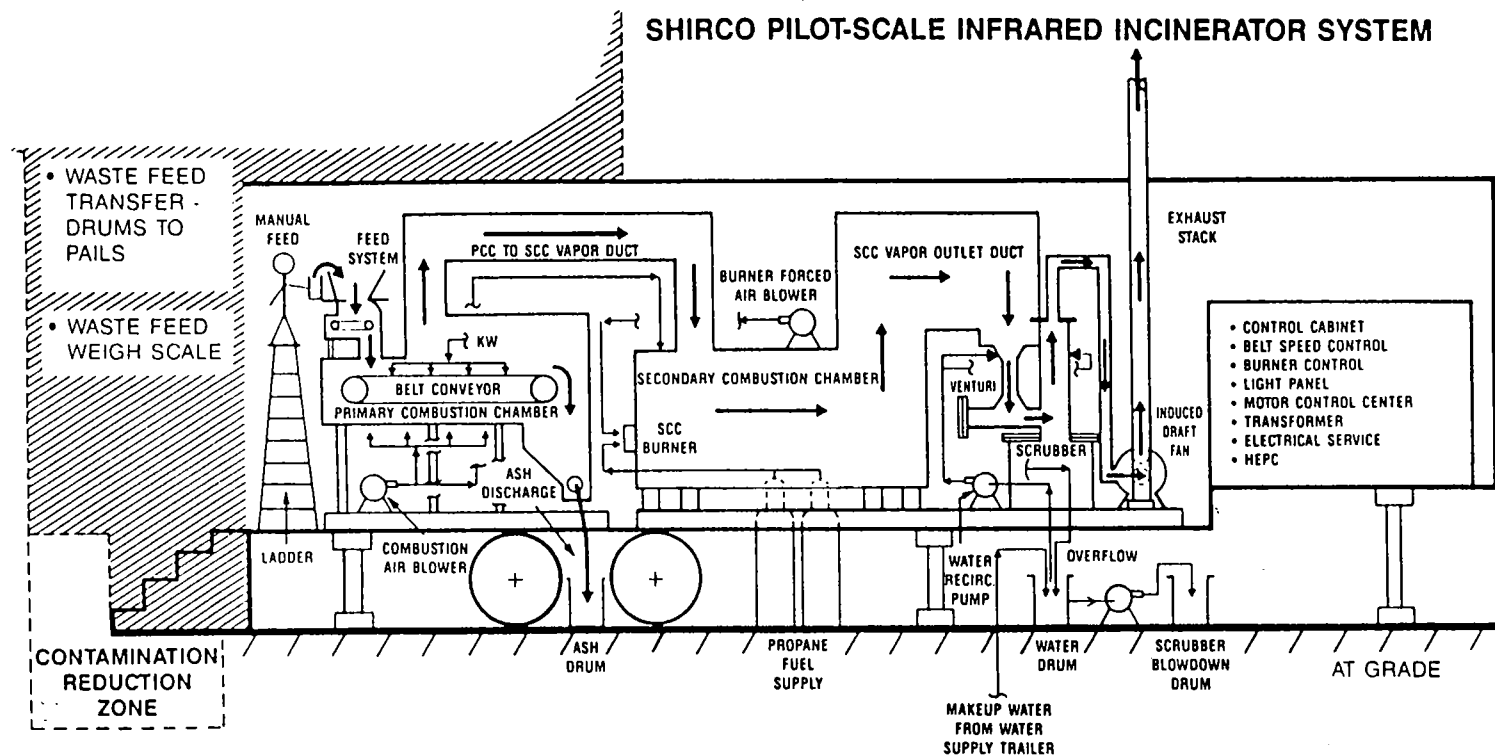
provides a minimum gas residence time of 2 seconds. Excess air within the chamber can also be controlled.

- Emissions control system - typically consists of a venturi, scrubber (water based) and droplet separator tower. The system is designed to remove both acid gases and particulates and to cool exhaust gases to 180°F (82°C).
- Exhaust system - an induced draft fan located downstream of the scrubbing system exhausts gas through the stack.
- Control system - designed to ensure the various process operating conditions provide effective thermal treatment of the waste.

Figure 2.6 presents a schematic of the major components of the Shirco infrared system.

The Shirco infrared system has some advantages over other incineration systems. The electrically powered heating system and conveyer belt system allow for more precise control over the primary combustion temperature and solid residence time. The use of an infrared heating system also reduces particulate emissions compared to conventional fossil fuelled incinerators.

Drawbacks associated with the Shirco system include the need for electric power at the site, 30 kva/480 v service for the mobile unit and 1700 kva/480 v for the transportable unit, and higher maintenance costs associated with the relatively higher proportion of moving parts. It has also been suggested (Shu, 1989) that the lack of solid turbulence within the combustion chamber may result in higher concentrations of organics remaining in the ash.



The Shirco system operates only on small sized solid material (5 um to 5 cm) having a moisture content up to 50% and chlorine and sulfur contents not exceeding 5% (USEPA, 1989d). Material containing significant amounts of free product may require pre-processing (e.g., mixing with soil) to achieve an acceptable waste stream.

Cost estimates for the Shirco System, as with most incineration systems, vary significantly depending on the nature of contaminated soil which dictates the required solids residence time. USEPA (1989d) suggests a cost range of \$180-\$240/tonne US (\$212-282 Can) for a mobile unit. These costs do not include such factors as waste excavation, feed preparation or ash disposal which could raise the disposal cost to \$800/tonne US (\$940 Can).

ii) Waste Treated

Historically infrared systems have been primarily used to incinerate PCB contaminated soil although presumably virtually any organic contaminant could be treated. Treated wastes have included lagoon sludge (Peak Oil Site), sandy silt clay (Demode Road site) and topsoil (LaSalle, Il.). Maximum reported concentrations of the waste feed include 113,000 ppm for PCB (LaSalle, Il.), 7500 ppb dioxin, 5700 ppb furans and 16,600 ppm for chlorobenzenes (Boehringer's Lindane facility). Welsh (1987) also indicates that PAH contaminated soil having concentrations up to 22,000 ppm of phenanthrene) and pentachlorophenol concentrations (11,000 ppm) was incinerated as part of test burns conducted at a wood preserving plant in Joplin, Mo.

iii) Applications/Demonstrations

Shirco Infrared Incineration systems have been used at numerous sites since 1985 as indicated in Table 2.3. Most of these applications have involved test or demonstration burns and only a few have involved actual remediation of a site. Sites that have been remediated include the Peak Oil site (10,000 tonnes of PCB contaminated sludge 5 to 100 ppm), the Indiantown Mill Site (12,000 tonnes of PCB contaminated soil approximately 3,000 ppm) and the LaSalle, Il. site (more than 30,000 tonnes ranging up to 113,000 PCB). In Canada a Shirco incinerator



is currently being used to incinerate PCB oils (by mixing with soil) and solids at Goose Bay. OH Materials is the Dept. of National Defence contractor for this site.

Reported destruction and removal efficiencies (DRE) vary as a function of the waste feed and operating conditions although in all cases reviewed RCRA requirements of 99.99% DRE were met. For the Demode Road site, USEPA (1989d) reported DRE's varying from greater than 99.9922% to greater than 99.9976% for PCB contaminated soil, although it was acknowledged the low concentration of feed necessitated using the sum of the analytical detection limits. Consequently, these numbers can only be viewed as lower limits. Additional information on this case is presented as Case Study 4 in Appendix B. DRE's at the Brio Refinery site exceeded 99.9997% (USEPA, 1989b) for carbon tetrachloride spiked soil and Wall and Rosenthal (1988) reported an average DRE (five test burns) of 99.99931% for PCB contaminated soil.

iv) Need for Additional Research

Shirco infrared systems are relatively well developed. Additional research should concentrate on performance characteristics as a function of waste feed properties.

Table 2.3 Summary of On-site Infrared Incineration Projects

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	DRE (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1985	Times Beach, Mo	EPA Region VII	Shirco	TCDD	<0.156	>99.99	Test Burn <1	USEPA, 1989 Welsh, 1987
1985	Joplin, Mo	International Paper Co.	Shirco	Dioxins PAH PCP	-- <22,000 <11,000	-- >99.99 >99.99	Test Burns (unknown)	Welsh, 1987
1986	Peak Oil, Fl	EPA Region IV	Haztech	PCB's Some VOC	<100 <1	>99.99 --	10,000	Wall & Rosenthal, 1988 James, 1988 USEPA, 1989 NATO/CCMS, 1988
1986	Boehringers Lindane Facility, FRG	Dekonta	ECOVA	Hal Aromatics Dioxins Furans	<16,600 <7.5 <5.7	>99.99 >99.99 >99.99	Test Burn <2	USEPA, 1989
1987	Indiantown Mill Site, Fl	Florida Steel	OH Materials	PCB's	<3,000	>99.99	12,000	Frank et al., 1989 Shu, 1989
1987 on-going	La Salle, Ill.	Ill.EPA	Westinghouse/Haztech	PCB's	<113,000	>99.99	>30,000	Welsh, 1987 USEPA, 1989 Shu, 1989

Table 2.3 Summary of On-site Infrared Incineration Projects (Cont'd)

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	DRE (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1987	Brio Site, Tx	EPA Region I	Shirco	Various VOC	N.S.	>99.9997 99.99931	Test Burn <1	USEPA, 1989
1987	Rose Township Demode Rd. Site	EPA Region V Michigan DNR	ECOVA	PCB's lead	<669	>99.9922 >99.9976	Test Burn <2	USEPA, 1989 (see Case Study 4)
1989	Goose Bay, Nfld.	DND Env. Canada	OH Materials	PCB's	--		Test Burns (unknown)	Petipas, 1989

DRE = destruction removal efficiency (see page 14)

-- = no data available

2.1.1.6 Oxygen Enriched

i) Process Description

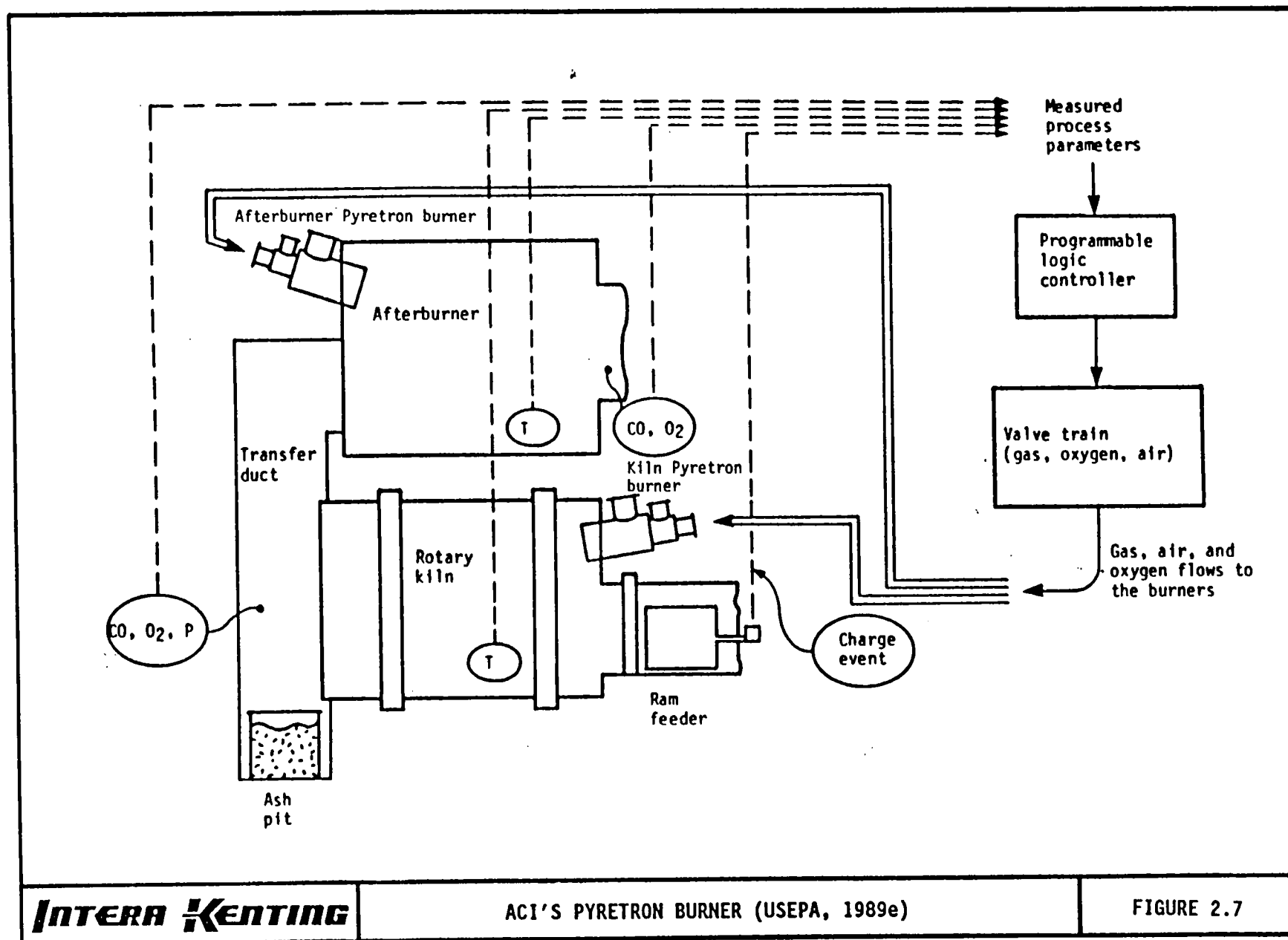
A number of firms have recently developed enrichment technologies that can be incorporated into existing incinerators. The Pyretron burner by American Combustion Inc. (see Figure 2.7) and the Oxygen Combustion System developed by the Linde Division of Union Carbide are two examples. The Pyretron system typically consists of two special burners (one installed in each the primary and secondary combustion chambers), valve trains for supplying the burners with auxiliary fuel, oxygen and air, an oxygen supply system, a computerized control system and a water based cooling system. The Linde Combustion System consists primarily of an Aspirator Burner in which furnace gases are aspirated into the oxidant jets prior to mixing with the fuel. By proper positioning of the oxygen jets and the fuel flow the flame temperature can be reduced to a value equivalent to an air flame temperature.

These units are not designed as standalone units but are meant to be retrofit to existing incinerators (either transportable or fixed systems). The enrichment of oxygen causes higher reaction rates which in turn affects the following combustion characteristics (Ho and Ding, 1988):

- Higher flame speed
- Lower ignition temperature;
- Wider flammability range;
- Higher flame temperature.

Proponents of oxygen enrichment have made several claims regarding their system's advantages:

- Lower fuel consumption;
- Higher throughput rates;
- Improved DRE;
- Reduced pollution control costs.



EPA has evaluated the American Combustion Inc. Pyretron System and concluded that most of the claims had some validity (USEPA, 1989e). The exception was the claim of reduced pollution control costs which EPA was unable to substantiate due to data limitations.

There also exist several disadvantages with oxygen enrichment technologies, most of which are associated with the higher combustion temperatures that exist. These higher temperatures can cause localized refractory damage, slag formation and the generation of NO_x .

The increase in throughput rates is a function of many factors (e.g., heat content of waste, enrichment percentage, etc.). Ho and Ding (1988) report increases of 10-20% in throughput for a few per cent change in oxygen concentration. Waterland and Lee (1989) indicate that the throughput of contaminated soil for USEPA's Mobile Incineration System (MIS) was doubled and auxiliary fuel consumption was reduced by 63%. Johnson and Cosmos (1989) report that the Linde system achieved a fourfold increase in capacity and a 50% reduction in auxiliary fuel consumption for sludges containing approximately 40% water.

The cost savings associated with oxygen enriched incineration versus conventional incineration may be substantial. Ho and Ding (1989) report that for a doubling of the throughput rate the cost of incineration can be reduced by \$118-\$588/tonne, while the cost of the oxygen required (for the Linde burner) is less than \$18/tonne of waste. This analysis also ignores the additional savings that would arise from reduced supplemental fuel usage. USEPA (1989e) indicated cost savings of \$34/tonne for ACI's Pyretron burner based on the incineration of 4,930 tonnes of waste.

ii) Wastes Treated

The oxygen enrichment technologies can be applied to any existing incinerator, consequently, it is difficult to make definitive statements regarding the waste feed characteristics since these will be largely dictated by

the incinerator. However, when this system has been fit to a rotary kiln incinerator it has been shown to be beneficial in the incineration of a variety of organically contaminated soils and sludges. USEPA (1989e) concluded that ACI's Pyretron burner was best suited to organically contaminated waste with low heating value and low nitrogen contents. High heating value wastes required water cooling to avoid refractory damage and excessive slag formation.

iii) Applications/Demonstrations

A number of organizations and companies throughout the world have been exploring the merits of oxygen enriched incineration. Many of these applications have been performed on fixed systems for incineration of materials other than hazardous waste. The best documented tests of oxygen enriched incineration of contaminated soils are those conducted by USEPA.

In late 1987, USEPA conducted tests on ACI's Pyretron burner by installing it in a fixed rotary kiln incinerator at USEPA's Combustion Research Facility. The waste incinerated during the demonstration was a mixture of 60% coal tar sludge and 40% contaminated soil from the Stringfellow Superfund site. The resulting waste stream had high levels of PAH's (naphthalene 62,000 ppm, acenaphthalene 15,000 ppm, fluorene 7.6 ppm, phenanthrene 28,000 ppm, anthracene 8.3 ppm, fluoranthene 14,000 ppm, pyrene 13.8 ppm). In addition to six test burns using the blended waste stream two burns were conducted on Stringfellow Superfund soil each spiked with 4,500 ppm of hexachloroethane and 1,3,5 trichlorobenzene. The actual quantities of waste incinerated during these tests were relatively small, between 4.1 and 7.9 kg (9 and 17 lb.) for each test. Destruction and removal efficiencies (DRE) for all principal organic hazardous constituents exceeded 99.99% although in some cases analytical precision did not permit a more accurate determination of these efficiencies. It should be noted that elevated phthalate levels were detected in exhaust stack gas, an observation which USEPA attributed to scrubber components.

In June, 1987 USEPA performed test burns using the Linde A burner installed on USEPA's Mobile Incineration System (MIS). The test burns were performed at the Denney Farm site in McDowell, Mo., on clay soil contaminated

with PCB, carbon tetrachloride, hexachloroethane and trichlorobenzene. DRE's for PCB averaged 99.999997% for three test burns using an unspecified waste concentration (Gupta et al., 1988). DRE's for the remaining contaminants were less than those for PCB's but were always greater than 99.99%.

As a result of these tests USEPA installed the Linde "A" Burner on their MIS. Ho and Ding (1988) report that the modified MIS was subsequently used to decontaminate more than 5 million pounds of dioxin contaminated soil from several sites in southwest Missouri.

iv) Need for Additional Research

Both the Linde and ACI systems themselves appear to require little additional research. However, the operating characteristics of these burners once installed into conventional systems need to be better understood.

2.1.1.7 Advanced Electric Reactor

i) Process Description

Advanced electric reactor (AER) technology was developed by J.M. Huber Co. (Dallas, Tx) specifically for the treatment of contaminated soils. The system is composed of a reactor vessel, two post-reactor zones and off-gas treatment works. The reactor vessel consists of a porous carbon core surrounded by carbon electrodes which are used to heat the core. A "fluid wall", created by injecting inert gas through the core, is used to protect the core from chemical attack. Solid waste is fed into the top of the reactor through a screw feeder. The wastes pass through the core by gravity where destruction occurs in a pyrolytic environment at a temperature of 4000°F (2204°C). The waste then moves into the post-reactor zones to ensure complete destruction. The off-gas treatment system removes acid gases and particulate matter from the exhaust stream.

J.M. Huber's AER is transportable, with a pilot-scale unit capable of being contained on a truck trailer. The AER does suffer from waste feed restrictions (smaller than 0.5 mm) which necessitate preprocessing of waste feed material. Proctor and Redfern et al. (1985) report that J.M. Huber is in the process of building two transportable units with capacities of 55 to 135 tonne/day. However Dibbs (1989) reports that J.M. Huber is no longer intending to pursue hazardous waste applications.

ii) Wastes Treated

The AER was designed to treat liquid and solid waste contaminated by various hydrocarbon and chlorinated hydrocarbon compounds, including dioxins, PCB's and nerve gas. It was intended to process both high and low heat content wastes.

iii) Applications/Demonstrations

No field scale applications of this technology could be found. Proctor and Redfern et al. (1985) report that a pilot-scale unit was used to incinerate dioxin contaminated soil from the Times Beach Site in Missouri. Contaminant levels in the stack gas and ash were below detection limits. No further information describing this test was available.

iv) Need for Additional Research

If this technology is to be applied to large quantities of contaminated soil, it will be necessary to improve the feed restriction of 0.5 mm.

2.1.1.8 High Temperature Slagging Incinerators

i) Process Description

The generation of slag occurs in all incineration processes where there is sufficient fusible material in the waste feed and the primary combustion

temperature exceeds 1200°C. In Belgium the Nuclear Research Centre (SCK/CEN) has developed a system which uses this slag to encapsulate hazardous waste (USEPA, 1988).

The Belgium high temperature slagging incinerator (HTSI) was originally developed for incineration of radioactive contaminated solids. The system consists of a bell shaped refractory, slag quench apparatus and off-gas treatment. Waste is shredded to less than 5 cm and placed into the refractory. The upper surface of the waste is converted to a molten slag through the use of an enriched oxygen and fuel burner. The slag droplets flow off the end of the refractory where they are quenched. The system operates at a temperature of 1400°C (Vanbrabant and Van de Voorde, 1987).

Throughputs for this system are relatively low, about 0.06 tonnes/hr and costs are relatively high at \$4,000/tonne. The unit is not transportable.

ii) Wastes Treated

The developer of this technology indicates that it is suitable for all chlorinated organics, however due to its high cost, it is best suited to high hazard wastes such as PCB's and dioxins.

iii) Applications/Demonstrations

The Belgian HTSI is located at Mol, Belgium and to date has only undergone limited testing. Test burns have been conducted for liquid PCB's but no results for solid hazardous tests could be found.

iv) Need for Additional Research

The high cost and low treatment rates are prohibitive to the use of this technology. Unless these factors can be significantly improved this technology will not be able to compete with other incineration processes.

2.1.1.9 Molten Salt

Molten salt incineration is a relatively new technology that is being examined by Rockwell International. The process is still in the developmental stage but involves the simultaneous combustion and sorption of hazardous organics by mixing the waste and air in a pool of molten sodium carbonate. The pool is maintained at a temperature of 1500°F - 2000°F (815°C - 1093°C) using auxiliary fuel. The molten pool is contained in a refractory lined vessel and supporting equipment includes air pollution control devices for particulate removal. Acid gases are eliminated through the formation of salts within the molten bed.

In addition to exhaust gases, the process will generate quantities of waste salt that cannot be recycled and will require disposal (Hitchcock, 1980).

No information regarding cost or transportability was available for this technology.

ii) Wastes Treated

This technology should be applicable to virtually any type of organic waste (liquid or solid), provided it is relatively low in ash content. CH2M Hill (1989) report that the technology has been demonstrated to be highly effective for PCB's, chlorinated solvents and malathion, although no references to the demonstration were provided.

iii) Applications/Demonstrations

No documentation on applications or demonstrations of this technology could be obtained.

iv) Need for Additional Research

This technology is still very much in a developmental stage. Before areas requiring additional research can be identified organized testing of pilot-scale units must be conducted.

2.1.1.10 Industrial Processes

There have been many instances where an industrial process has been used or proposed for incineration of hazardous solid wastes. These processes generally involve the use of fixed facilities, and consequently are generally not well suited to site clean-up. For the sake of completeness however we have presented brief descriptions of these technologies in the following sections.

i) Multiple and Fixed Hearth

Fixed hearth incinerators typically consist of a refractory lined chamber, a secondary combustion chamber and air pollution control equipment. Fixed hearths typically operate in a batch mode with waste being introduced through a side port. The waste accumulates on the floor where it is combusted through the use of supplementary fuel. Air flow is controlled by side ports.

Multiple hearth incinerators are similar (in principle) to fixed hearths. Multiple hearths generally consist of a vertical cylindrical refractory containing multiple horizontal hearths. Waste is fed onto the uppermost level which is plowed by a rabble arm or rake. The rabble arm moves the waste over the hearth to a drophole through which the waste falls onto the next lower hearth. This process is repeated until ash is discharged at the bottom of the refractory. Air and combustion products typically flow counter current to the waste flow. Auxiliary fuel is added (if required) through side ports.

Fixed and multiple hearths are widely used to incinerate sewage sludges, municipal solid waste and manufacturing waste. Multiple hearths cannot easily handle variations in waste feed properties resulting in variations in processing temperatures. USEPA (1986) does not recommend this technology for hazardous waste applications.

ii) Molten Glass

Molten glass incineration is a technology that is based on existing glass making technology. The process uses a pool of molten glass to destroy and capture organics. The technology is being evaluated by several companies for hazardous waste applications but to date no applications have been demonstrated (USEPA, 1987).

iii) Cement Kilns

Industrial cement kilns generally consist of high temperature (3000°F; 1649°C) rotary kilns constructed of steel casings and lined with refractory brick. The high temperature and long residence time (7-10 sec, Zeller, 1990) provide for thorough combustion of hazardous materials. Cement kilns are most useful for the incineration of high heat content waste which can be used as a fuel source. This technology has been used to incinerate tires in Germany since 1978 and USEPA (1987) reports that 15 cement kilns are now using hazardous waste (liquid) to supplement fuel requirements. The suitability of this technology to low heat content soils is unproven and unlikely to prove economically justifiable.

2.1.2 Non-Destructive Thermal Processes

2.1.2.1 Taciuk

i) Process Description

The Taciuk process was developed in 1975 by the Alberta Oil Sands Technology (AOSTRA) and Research Authority and the Industrial Processes Division of UMA Engineering Ltd (UMATAC). Originally the process was designed to extract and upgrade oil product from oil sand and oil shale material. It was used for this purpose for approximately nine years before demonstrating its treatment capability for hazardous waste.

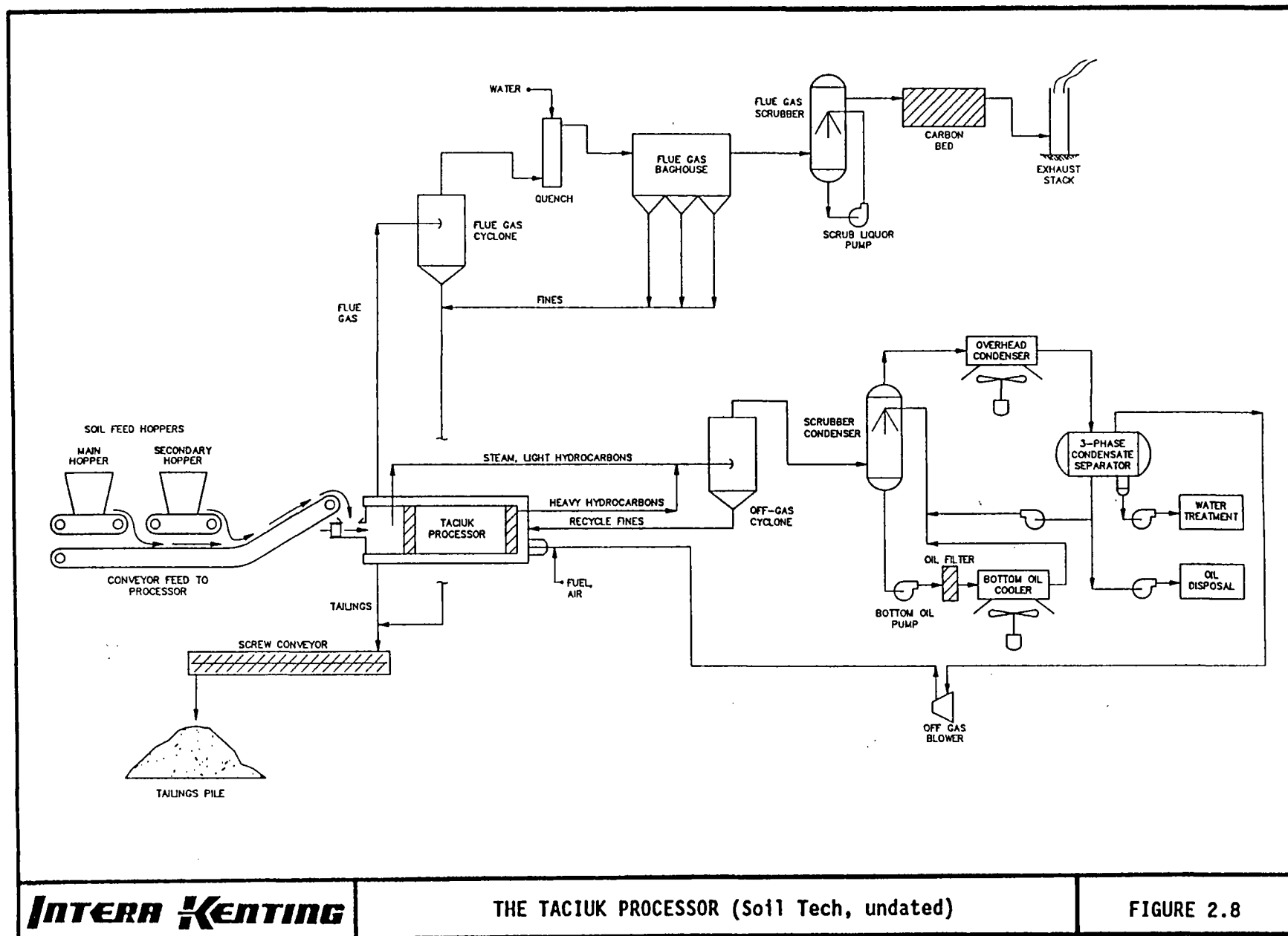


The major component of the Taciuk System is the Taciuk Processor, a single horizontal rotating chamber. The unit consists of four zones: preheat, reaction, combustion and cooling. Low temperature volatiles and water are removed in the pre-heat zone by heating the soil up to temperatures of 500°F (260°C). Oils and other heavy volatiles are distilled in the reaction zone at temperatures between 700°F to 1150°F (371° - 621 °C) in a pyrolytic (oxygen depleted) environment. A coke by-product is formed in the reaction zone as a deposit on the solid material. This material is subsequently burned off (at 1100° - 1500°F) in the combustion zone, where combustion air is added. Waste heat from the combustion zone is used to fuel both the pre-heat and reaction zones and also results in cooling of the decontaminated soil. Figure 2.8 presents a schematic of the Taciuk processor.

The Taciuk processor does not eliminate hazardous waste contamination but serves to remove it from the solid material and concentrate it in either (or both) the water and oil phases. When treating hydrocarbon contaminated solids, a salable oil product is generated which can be used to offset the cost of remediation. When treating solids contaminated with hazardous waste, the waste concentrated oil must be further treated by on or off site treatment processes. In virtually all cases the water generated by the process also requires some form of treatment. The cleaned solids can generally be backfilled on site.

Soiltech Inc. is the commercial vendor of the Taciuk process and currently has a variety of transportable and permanent plants with feed rates ranging from 3 to 25 tonnes/hour (Soiltech, undated). The time and equipment required for set-up were not specified.

Turner (1989) suggested a unit cost ranging from \$125-\$140/tonne for treatment rates of 5 tonnes/hour to \$60-\$70/tonne for treatment rates of 20 tonnes/hr. This analysis incorporated several assumptions including a waste composition having 8% oil and a market value of \$12/bbl. In addition these estimates ignore feed preparation costs and waste disposal/treatment costs. The costs estimated by Turner (1989) were based on a nine month operating period due to the difficulty of handling frozen material in the winter months in Alberta.



INTERA KENTING

THE TACIU PROCESSOR (Soil Tech, undated)

FIGURE 2.8

ii) Wastes Treated

The Taciuk process is well suited to hydrocarbon contaminated soils, where recovery of petroleum product will off-set remediation costs. It is also applicable, from a technical standpoint, to chlorinated hydrocarbon wastes, but such applications may be less justifiable economically due to the additional ultimate disposal costs required for the contaminated oil. The vendor of this technology is also advocating its use for incineration of shredded tires and municipal solid waste.

iii) Applications/Demonstrations

AOSTRA and UMATAC in conjunction with Environment Canada and Energy Mines and Resources conducted a two phase program in 1987/88 to test the capability of the Taciuk Processor for treating various heavy oil production wastes. The Phase I program consisted of batch tests conducted on 17 different feed wastes (primarily oil refinery sludges). The Phase II program consisted of continuous feed tests performed on four different feed wastes (Turner, 1989). Little information is available describing the results of these tests or the nature of contaminants in the waste materials. General conclusions based on the results of these tests included the combusted solids are free of oil and grease, PAH concentrations in exhaust gases from the combustion chamber were below detection limits while BOD and COD concentrations of the pyrolysis water were sufficiently high to warrant treatment.

Another series of tests were conducted by the American Petroleum Institute in 1987 (Bowman, 1988). These tests were conducted on a blend of three oily refinery wastes (separator sludge, dissolved air flotation float, emulsion solids). The waste feed contained BTX (180, 1800 and 1890 ppm), naphthalene (360 ppm), phenols (26 ppm) and lower concentrations of other assorted PAH's. The concentration of most of the organic contaminants within the ash was reduced to below detection limits.

Full scale tests examining the applicability of the Taciuk process to PCB contaminated soils were performed by UMATAC (Soiltech, undated). These tests



were performed in a 5 tonne/hr. demonstration unit on oil sands spiked with PCB's. Two tests were conducted, one over a two hour period with a feed rate of 4.2 tonnes/hr and the other over a four hour period with a feed rate of 3.7 tonnes/hr. The shorter duration test had input feed concentrations of 7,000 ppm and the longer test had input feed concentrations of 14,950 ppm. PCB recoveries were 94.5 % in the first test and 93.17% in the second test. No dioxin levels were detected in any of the waste process streams. Low levels of furans detected in the flue gas were attributed to furans in the waste feed. Additional information on this application has been provided as Case Study 5 in Appendix B.

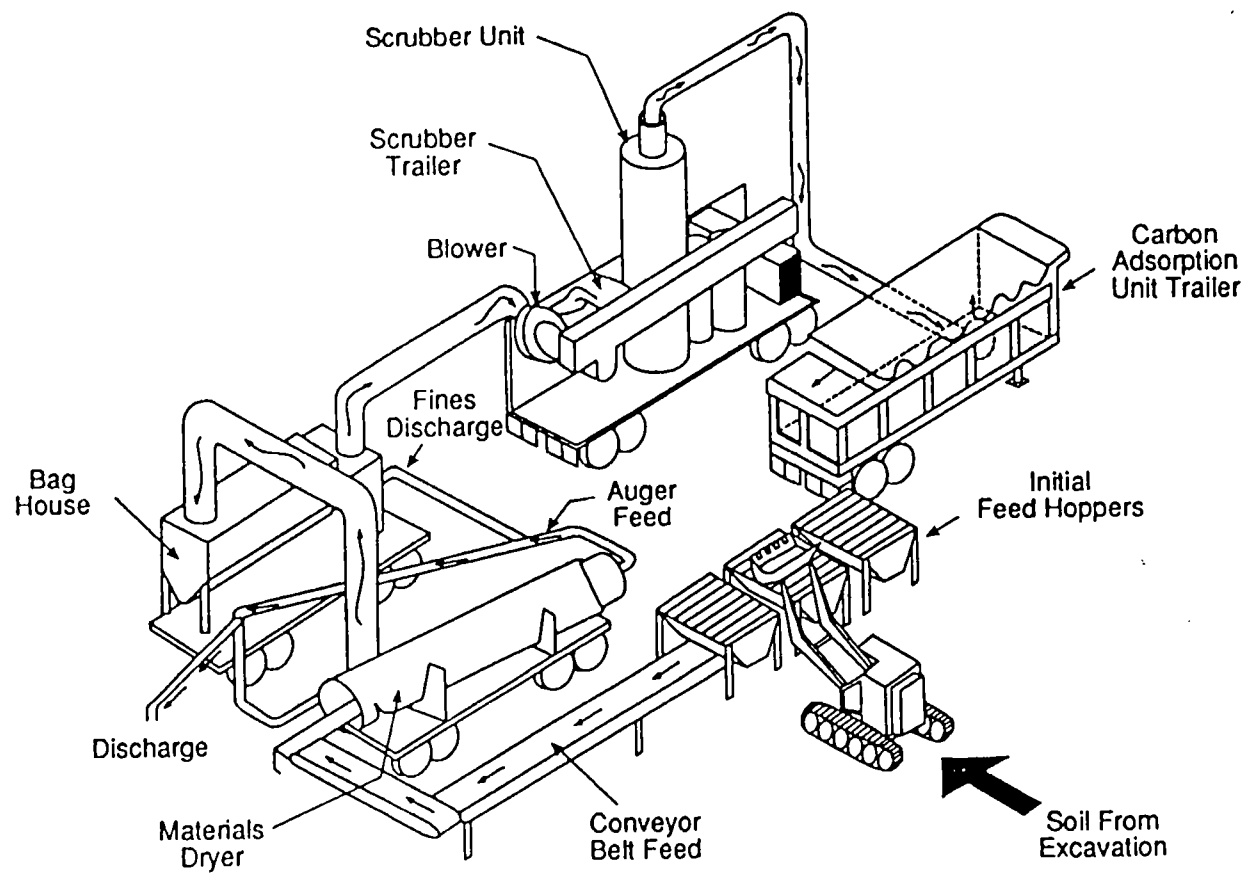
This system is also being demonstrated at a Superfund Site in northeastern Illinois to remediate PCB contaminated soils (Soiltech, undated).

iv) Need for Additional Research

The Taciuk process must be used in a field situation so that its mobility/transportability can be evaluated.

2.1.2.2 Low Temperature Thermal Process

A number of companies are currently marketing low temperature thermal processes for the treatment of soil contaminated with organics. For example, Weston Services Inc. is marketing their Low Temperature Thermal Treatment (LT³) system, Canonie Environmental Services Inc. is marketing their Low Temperature Thermal Aeration (LTTA) system (see Figure 2.9), American Toxic Disposal Inc. has a Vapour Extraction System (VES) and O.H. Materials has a Mobile Thermal Volatilization System (MTVS). It is also known that Camp Dresser McKee is proposing to utilize similar technology at a superfund site in Duval County, Florida and Chemical Waste Management is in the process of developing a system called XTRAX. In Canada, the Soil Recycling Company of Gormely, Ontario is using a low temperature thermal desorber (LTTD) manufactured by Ariel Industries, Inc. of Tennessee to treat hydrocarbon contaminated soil.



Most of these systems operate on the same principles and are similar in configuration. The main component is generally a thermal dryer (operating at temperatures of 300°F to 400°F (150°C to 205°C) that serves to aerate and mix the soil thereby vaporising VOC's. The contaminated air is treated (using filters) to remove particulates, and subsequently (using scrubbers, a combination of either carbon adsorption or a condenser) the organic contaminants. O.H. Materials and Ariel Industries, Inc. use an afterburner to treat the off-gases in their MTVS and LTTD respectively.

The major advantage of these low temperature thermal desorption systems is their ability to treat large quantities of contaminated soil at relatively low cost. Canopies's LTDA system is capable of treating between 30 and 50 tonnes/hr at a cost of \$94/tonne to \$176/tonne (Johnson and Cosmos, 1989) and Weston's LT³ system can treat up to 10 tonnes/hr at unit costs of \$118/tonne to \$176/tonne. Other advantages of these units include:

- mobility - systems can generally be contained on two or three truck trailers;
- product recovery - the system can be used to recover a salable oil product;
- low temperature minimizes heavy metal emissions.

A disadvantage of these processes may be the inadvertent generation of additional hazardous contaminants. Borkent-Verhage et al. (1986) have found that for clay-peat soil, lindane decomposes into various chlorobenzene and chlorinated phenol compounds. In addition they found that when humic material was heated to temperatures above 300°C in a pyrolytic environment production of alkenes, styrenes, alkylbenzenes and phenols occurred.

ii) Wastes Treated

Low temperature thermal treatment systems are well suited to the treatment of large quantities of hydrocarbon, VOC and semi-volatile contaminated soil. O.H. Materials and Ariel Industries, Inc. indicate that their systems are



intended for the decontamination of hydrocarbon contaminated soil only. Other systems have been used to treat a variety of compounds including TCE, PCE and BTX and PAH's at concentrations up to thousands of ppm (Table 2.4).

These systems have been used to treat virtually any kind of soil (clay, silt, sand and gravel) but large diameter material (greater than 5-7.5 cm) must be screened or crushed. Generally performance is optimum for low moisture contents and low levels of volatile contaminants. Chemical Waste Management suggest that their system be used only on soil containing less than 10% organics.

iii) Applications/Demonstrations

Soil cleaning by low temperature volatilization appears to have been most widely used in North America. Weston Services Inc. first used their LT³ process to decontaminate approximately 7 tonnes of soil contaminated with VOC's (total concentration 3503 ppm) including TCE (up to 2,678 ppm), PCE (up to 1,422 ppm) and xylene (27,197 ppm) at the Letterkenny Army Depot in Chambersburg, Pa. A removal efficiency of greater than 99.99% was demonstrated in the soil and concentrations of VOC in the exhaust gases was below detection limits. Other applications of Weston's LT³ system include Tinker AFB where 6,500 tonnes of TCE contaminated soil (up to 6,100 ppm) were treated, and a number of demonstration runs for the City of St. Petersburg and a number of confidential clients (Weston, undated b,c). The trial runs were typically conducted on small quantities of contaminated soils containing low levels of PAH's (100 ppm BAP, BAA), dichlorobenzene (less than 525 ppm) or methylene chloride.

Canonie Environmental Systems Inc. first used their LTTA system at the McKin Superfund Site in Gray, Maine. At this site over 16,500 tonnes of soil contaminated with TCE (up to 7.3 ppm), toluene (up to 35 ppm) and xylene (up to 84 ppm) were treated. As part of the remediation at this site extensive testing was performed to identify optimum operating conditions for their system in order to meet a USEPA performance standard of 0.1 ppm of TCE. It was found that an operating temperature of 300°F (149°C) and a blower speed of 15,000 cfm provided

Table 2.4 Summary of On-site Low Temperature Thermal Treatment Projects

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Final Concentration (ppm)	Initial Quantity Contaminated Soil (tonnes)	Reference
1986	Letterkenny Army Depot	U.S. Army		Weston	VOC	3503 (total)	<0.357	USEPA, 1989a Kostecki & Calabrese, 1988
1986	Mckin Superfund Site	USEPA	Canonie	TCE Toluene Xylene	<7.3 <35 <84	<0.02-0.04 <0.02 <0.02	16,500	USEPA, 1989a Johnson & Cosmos, 1989 Gerkin & Bell, 1986 (see Case Study 6)
1987	Ottati & Gross Superfund Sites	--	Canonie	TCE PCE Toluene Xylene	<460 <1,200 <3,000 <2,600	<0.025 <0.025 <0.025 <0.03	--	Canonie, undated Johnson & Cosmos, 1989
1988	Lab Test	City of St. Petersburg		Weston Naphthalene Pyrene	BAP BAA <1,200 <275	<82 <100 1.2 3.1	1.6 test run 2.1	Weston, undated
1986	Colorado Spy, Co.	--	Weston	1,4 Dichlorobenzene	<525	0.006	test run	Weston, undated
1988	Lionville, PA	--	Weston	Methylene Chloride Methanol	<120 <30	0.022 <6	test run	Weston, undated
1988	Tinker, AFB	USAF	Weston	TCE	<6,100	--	6,500	Weston, undated
1988	Cocoa, FL	--	OH Materials	gasoline	<200,000	<50	1,200	McCartney & Hay, 1989

optimum operating conditions, although this necessitated using at least two cycles (averaging 2.5 - 3 minutes) in the thermal dryer. Additional information on this application is provided as Case Study 6 in Appendix B. Canonie has since applied a similar system to 24,500 tonnes of solvent and petroleum contaminated soil at the Ottati and Gross Superfund site in New Jersey. This site had contamination levels of 1,200 ppm PCE, 460 ppm TCE, 3,000 ppm toluene and 2,000 ppm xylene.

O.H. Materials used their MTVS system to remediate approximately 1,200 tonnes of gasoline contaminated (up to 2%) soil at a service station in Cocoa, Florida. Based on the operational experience gathered on this application, a larger capacity unit capable of treating up to 10 tonnes/hr was developed.

iv) Need for Additional Research

This technology appears to be readily applicable to volatile hydrocarbon compounds. Its suitability to all chlorinated hydrocarbon compounds and the possible generation of hazardous by-products needs to be evaluated more fully.

2.2 PHYSICAL TREATMENT

Physical treatment technologies for contaminated soils are processes that affect the physical characteristics of the soils and the contaminants. These processes separate the contaminants from the soils or immobilize the contaminants within the soil matrix. Most physical treatment technologies do not destroy contaminants but rather transform the state of the toxic materials into an end-product that is less hazardous to the environment and easier to handle and store. Three main physical treatment technologies have been identified for contaminated soils:

- solidification/stabilization
- soil washing
- flotation

Solidification/stabilization technologies, sometimes called fixation technologies, involve the immobilization of the contaminants by transforming the soil/contaminant mixture into a block of solid material. The solidified material reduces the ability of contaminants to react with or leach into the environment. The purpose of the solidification/ stabilization technologies is to change the contaminated soil into a stable matrix that will be resistant to freezing/thawing and wetting/drying, will have a low permeability, will be mechanically competent (resistant to mechanical stress), will be resistant to biodegradation and will minimize the emission of volatile compounds and dust to the atmosphere.

Soil washing technologies involve the separation of the soils and contaminants by using pressurized water or steam. Additives such as acids or bases, surfactants or chelating agents may be added to the water to help mechanically remove and/or dissolve the contaminants from the soil. The end-product should be decontaminated soil and residue (fluid and sludge) containing the hazardous compounds. The residue may require further treatment to avoid the reintroduction of the contaminants into the environment.

Flotation technologies involve the separation of contaminants from the solid particles of soil by means of adsorption onto air bubbles that rise through a slurried mixture. The technology has been used extensively in the mining industry and is now being used in the treatment of contaminated soil.

2.2.1 Solidification/Stabilization

Solidification/stabilization technologies involve processes of solidification and stabilization. During stabilization, reagents are mixed with waste soil to enhance adsorption or chemical binding so that the mobility of the waste is significantly reduced.

During the solidification process, reagents react with the stabilized waste to form a solid mass which is resistant to infiltration and leaching. It is not clear to what extent stabilization of organic compounds occurs. Soils contaminated by creosotes and PCP are not effectively stabilized and are only solidified by these technologies resulting in the possible leaching of

contaminants in the event of structural failure of the solidified mass (Hoffman and Hrudehy, 1990).

Several solidification/stabilization technologies have been developed in the last 20 years, some of which can be applied to treat contaminated soils. The general process scheme of these technologies is shown in Figure 2.10 and can be described as follows:

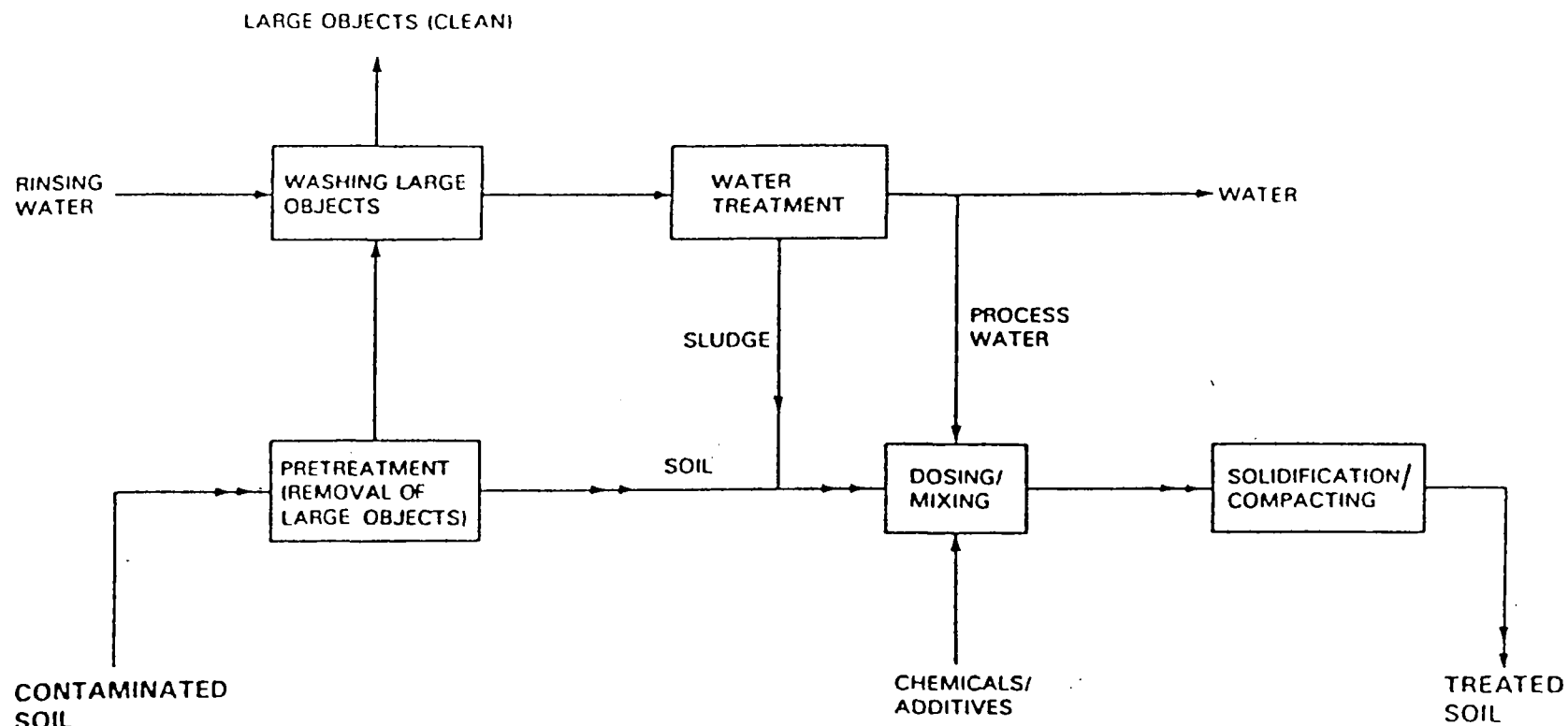
1. Pretreatment of contaminated soil to remove large objects;
2. Washing and removal of large objects or crushing. If washing is used, an option for water treatment may be required;
3. Mixing of contaminated soil with chemicals, cementitious, pozzolanic (fine grained siliceous material) or other additives and water;
4. Pouring of mixture into molds and allowing to cure into volumes of solid material;
5. The volumes of treated material are landfilled on-site or transported for off-site disposal.

The solidification/stabilization technologies described in the following sections utilize Portland cement, lime, thermoplastics, organic polymers, silicates and clays or involve processes like glassification and encapsulation.

2.2.1.1 Portland Cement

i) Process Description

Solidification/stabilization using Portland cement is a modification of technology which has been used in the construction industry for centuries. The process consists of a blending unit that mixes contaminated soils with Portland cement, water and additives. The mixture is then poured into molds and allowed to cure. During curing, hydration products from silicate compounds and water are generated, resulting in the generation of a calcium-silicate-hydrate-gel (Kyles et al., 1989). The gel swells and forms interlocking silicate fibres.



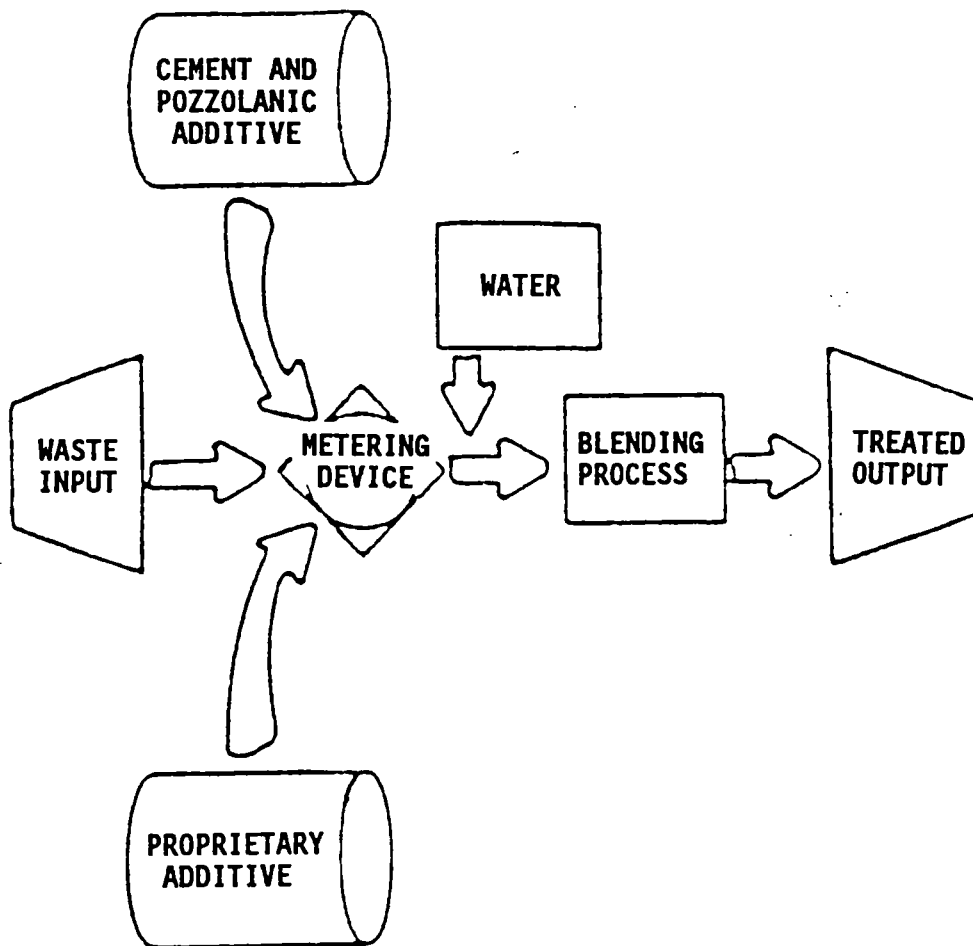
As the gel cures, the soil becomes incorporated into a hardened concrete material. The cured materials are then landfilled. Several additives can be used to increase the compressive strength or to reduce the curing time. These include pozzolanic materials (such as fly ash and volcanic ash), clays and some silicates (e.g., sodium silicate). The exact ratio of soil/chemicals/water is usually proprietary. In general, the amount of cement and other additives significantly increases the volume of treated waste soil compared to the pre-treated waste soil by up to 50%. A typical process diagram is shown on Figure 2.11.

There are several advantages of using cement-based solidification to treat contaminated soils:

- the chemicals used are generally inexpensive, but special wastes may require expensive additives;
- cement mixing is a standard and well known procedure;
- dewatering is not necessary;
- method is tolerant to some chemical variability of the contaminated soil;
- strength and permeability are partly controlled by the amount of cement.

Common disadvantages of the method are that:

- it requires large quantities of cement resulting in significant volume increase;
- the final strength and leachability are influenced by several contaminants (see below);
- ammonia gas is released due to the presence of NH_4^+ ;
- the method may be costly if specialized additives or cement types are required, for example, the use of corrosion-resistant cements for aggressive wastes;
- the method is unsuitable for organics if cement alone is used.



Drawn by	Date
Checked by	Date
Revisions	Date

PROCESS SCHEME FOR PORTLAND CEMENT
SOLIDIFICATION/STABILIZATION (After USEPA, 1989b)

INTERA KENTING

FIGURE 2.11

A number of compounds can interfere with the solidification process and limit the applicability of the technology. Some soluble salts of manganese, lead, copper, zinc and tin can increase the curing time and reduce the compressive strength (Levin et al., 1985). Fine grain materials under 0.075 mm (No. 200 mesh sieve) such as silt and clays can coat larger particles and weaken the soil/cement bond. Large amounts (1-5%) of organic compounds, like peat or organic contaminants in the soil, can slow or prevent the curing of the cement (Rulkens et al., 1985). As a result, cement based technologies are usually not suitable for soils highly contaminated with organic compounds.

The treatment rate varies with the complexity of the mixture (number of additives) and is a function of the hazardous nature of the contaminants to be treated. In general, the treatment rate varies with site-specific conditions. However, De Percin (1988, 1989) reports treatment rates using cement based solidification of 8 tonnes/hour during a pilot-scale test and 65 tonnes/hour for a similar commercial scale unit.

Treatment costs are also a function of the volume treated, organic content of the contaminated soils and other site conditions. De Percin et al. (1988) report costs in the range of \$125 - \$275 per tonne of contaminated soil. For a commercial unit, costs closer to the lower value would be anticipated.

The available information is encouraging for the applicability of the cement-based solidification/stabilization technology to Canadian climatic conditions. Wet/dry and freeze/thaw weathering tests are reported by de Percin et al. (1988) for contaminated soils solidified by a cement-based technology. Results show that after 12 cycles, the weight losses for the test specimens were quite small at about 1% and only slightly greater for the controls.

ii) Wastes Treated

Cement-based solidification/stabilization technologies have been very successfully used on contaminated soils containing different inorganic contaminants such as heavy metals. However, it has only been recently applied to the solidification of soils containing a significant amount of organic

compounds. Applications can now be found for soils containing various concentrations of volatile organics, PCB's, oil and grease, BNA's (base/neutral and acid extractables) and sludges containing PAH's and volatile organics. However, for soils having a high concentration of organic contaminants, the method has not been proven totally effective. Fine grained materials such as silt and clay can reduce the strength of the solid. Sand is the ideal material for application of this technology.

iii) Applications/Demonstrations

Several companies have started to apply the Portland cement solidification/stabilization process to treat soils contaminated by hydrocarbons. Three companies that offer on-site treatment on a commercial basis include Hazcon Inc., Canadian Waste Management Corporation, and Soliditech Inc., as shown in Table 2.5. Another company, Acurex Corp., has reported on the performance of the Portland cement solidification process to treat Synthetic Analytical Reference Mixtures (SARM) containing various concentrations of organic compounds.

Two major applications have been evaluated by the Superfund Innovative Technology Evaluation Program (SITE) of the USEPA. The first was the Hazcon Inc. Demonstration Test at the Douglasville, Pennsylvania Superfund site in 1987 (USEPA, 1989b). The site, a former oil reprocessing plant, showed a wide range of organic contaminants in the soils including the general indicator for organics, oil and grease, VOC's, base, neutral and acid extractables (BNA's such as PAH's, phenols, and phthalates), PCB's. Lead contamination was also present. The Demonstration Test results reported by Sawyer (1989) showed that the organic contaminant concentrations were reduced in the treated soil by a factor that is consistent with the increase in volume and density of the soil due to the addition of Portland cement and other additives. However, a Toxicity Characteristic Leachate Procedure (TCLP) leaching test showed that the oil and grease and some VOC's and BNA's were not effectively immobilized in the solidified matrix. Details of the Hazcon demonstration test can be found as Case Study 7 included in Appendix B.

Table 2.5 Summary of On-Site Cement Solidification/Stabilization Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Process Efficiency (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1987	Douglasville Superfund Site, Pennsylvania	USEPA	Hazcon Inc.	VOC's PCB's Oil & Grease BNA's	0-150 1.2-54 10,000-253,000 12.2-534	-93-+183 0 0-+100 0-+630	--	DePercin (1988, 1989) DePercin et al. (1988) Sawyer (1989) (see Case Study 7)
1987	Mountain View, California	USEPA	Acurex Corp.	VOC's PAH's Halogenated & Non-halogenated Hydrocarbons	2000-20,000 total organics	--	--	USEPA (1989a)
---	Bridgport, New Jersey	--	Canadian Waste Management Corp.	PAH's VOC's Phthalates	2.3-4.7 1.5-9.2 3.5-330	-- -- --	--	Canadian Waste Management Corp. (undated,a)
1988	Imperial Oil/Champion Chemicals, Superfund Site, Morganville, New Jersey	USEPA	Soliditech Inc.	VOC's Semi-VOC's Oil & Grease PCB's	ND-50 ND-79 25,000-170,000 28-43	-100 +155-+166 +50-+530 0	--	Grube et al., (1989) (see Case Study 8)
--	--	--	Wastech Inc.	Lubricating Oil Aromatic Solvents	ppm to 40%	--	--	USEPA (1989b)
1990	To be determined	USEPA	Wastech Inc.	--	--	--	--	USEPA (1989b)

ND = not detected

* process efficiency calculated as % difference in toxicity contaminant leachate procedure (TCLP) before and after treatment

The second evaluation of a solidification/stabilization process under the USEPA Site Program was the Soliditech Demonstration Test at the Imperial Oil/Champion Chemicals Superfund Site in Morganville, New Jersey in 1988. Contaminated soils and other solid wastes containing PCB's, VOC's, semi-VOC's, oil and grease and lead were treated at the site. Results reported by Grube(1989) indicate that, although lead leaching concentration was effectively reduced after the treatment, the TCLP leaching concentration of oil and grease and semi-volatiles stayed the same or increased after the treatment. Details of the Soliditech Demonstration test can be found as Case Study 8 in Appendix B.

Another company that provides commercial on-site solidification/stabilization of contaminated soils is the Canadian Waste Management Corporation that uses a Portland cement process containing different additives (lignin sulphonic acid, soda, stearic acid, tripolyphosphate soda and others). The Portland cement and additives are processed to a size of less than 2 um prior to blending with the contaminated material and water. Their process, called Fujibeton, has been used extensively in Japan in the last 15 years where it solidified more than 580,000 m³ of contaminated sludges and around 20 million m³ of contaminated sediments from lakes and rivers. It was also used in Bridgeport, New Jersey to treat a sludge contaminated with VOC's, PAH's and phthalates. Canadian Waste Management Corp. (undated, a), based on TCLP leaching tests, claims to have immobilized contaminants like benzene, toluene, TCA, PCA, PAH's, and some phthalates in addition to a dozen metals. This process has the potential to treat soils contaminated by hydrocarbons, however, little information is available on the case mentioned.

iv) Need for Additional Research

The Portland cement solidification/stabilization process is well developed and commercially has been demonstrated to immobilize inorganic contaminants like heavy metals. However, research is needed to identify those conditions and additives under which it can be applied to treat soils containing organic contaminants. Unfortunately, most commercial vendors of this technology keep their process confidential.

2.2.1.2 Lime

Lime based solidification/stabilization methods rely on the reaction of fine-grained siliceous (pozzolanic) material and water with lime products (such as calcium hydroxide, calcium oxide and calcium carbonate) to produce a solidified/stabilized material (Kyles et al., 1987). When the natural soils contain enough siliceous material, the addition of lime generates calcium silicate and alluminate gels that bring about fixation of water and reduce the leachability of contaminants.

Lime can also be used without siliceous pozzolanic material (Rulkens et al., 1985). In such a case, lime in the form of quicklime (CaO), reacts with water and generates significant heat. This heat is responsible for enlarging the surface area of the lime in such a way that wastes, like oil are adsorbed on and micro-encapsulated into solid calcium hydroxide. This process causes densification of the soil resulting in an end-product that is compact and stabilized but not solidified. As a variation, pozzolanic materials such as fly ash, kiln dust and Portland cement may be incorporated with lime and water to produce a solidified material known as pozzolanic concrete (Kyles et al., 1987).

A typical process configuration is composed of a conveyor belt and crusher if the contaminated soil is mixed with rocks. The conveyor feeds the soil into the mixer where the lime and other additives are added to the soil. Because of the exothermic nature of the process, gas-purifying components may be added to the configuration to treat the exhaust air. The mixture is poured into molds and allowed to cure. In some cases, it may be necessary to apply a confining pressure during the curing of the material.

The advantages of the solidification/stabilization process using lime are:

- the chemicals are very inexpensive and easily available;
- the equipment is easy to operate and the procedures are standardized;
- the chemical reactions are well known;
- dewatering is not necessary.

Disadvantages of the method include:

- the addition of lime increases the volume and density of the contaminated soil;
- significant leachability in the case of acids;
- curing time is slower than for cement;
- the final product may require compaction;
- handling of lime can be difficult.

Typical treatment rates are in the order of 10-20 m³ (12-30 tonnes) of contaminated soil although rates vary depending on-site specific conditions (Canadian Waste Management Corporation, undated,b). Costs are on the order of \$150-200/tonne depending on the amount of stabilizing material that is required.

This process could be applied under Canadian conditions as long as the processed material is allowed to cure before freezing. However, no information has been found in the literature on the resistance of lime stabilized material to freeze/thaw cycles.

ii) Wastes Treated

Lime based solidification/stabilization can be applied to any type of granular soil containing certain levels of organic contaminants. Canadian Waste Management Corporation (personal communication, 1990) claims to have treated soils that had up to 50% oil and grease in Europe using a lime based technology. From the information currently available, this technology seems to be promising for soils contaminated with high levels (percent rather than ppm) of oil and grease. Because of the heat generated during the process, this method may not be applicable to the treatment of volatile organic compounds (VOC's) since they would be removed mainly by volatilization during the mixing process and the curing period. Special exhaust air treatment components may be required in the case of soils containing VOC's. The end-product of this process is a cured molded material that may be compacted to reduce the permeability to the order of 10^{-5} - 10^{-9} cm/s. The cured material can be buried on-site, disposed of at a

landfill, and in some instances, used as construction material for roads and runways.

iii) Applications/Demonstrations

The lime based solidification/stabilization method has been used since 1975 in Europe by the company of Voest-Alpine Montage which developed the VAM process. They have treated oil contaminated soils, sludges and tars at more than 50 sites as shown in Table 2.6. Their technology is now commercially available in Canada by Canadian Waste Management Corporation. However, no performance data are available from Canadian site cleanup projects.

The USEPA also had tests done in 1987 on four different types of Synthetic Analytical Reference Mixtures (SARM) containing concentrations of between 2000 and 20000 ppm of organics including VOC's, PAH's and halogenated and non-halogenated hydrocarbons. The SARMS were treated with lime/kiln dust and with lime/fly ash mixtures (50/50 by weight). Available information (USEPA, 1989a) is limited and indicates only that the lime/fly ash samples took two weeks to set-up and that volatile emissions occurred during the mixing process and the curing period.

A laboratory experiment reported by Evans (1988) has tested the solidification of a sludge containing organic contaminants (see Table 2.6) using lime/fly ash solidification. The results show that in general the solidified material showed high total organic carbon (TOC), phenol and relative hydrocarbon concentrations in the leaching tests.

The USEPA is in the process of sponsoring the demonstration of a lime based treatment technology developed by Separation and Recovery Systems Inc. (USEPA, 1989b). The technology is potentially applicable to wastes containing at least 5% hydrocarbons and up to 80% organics. The process uses lime and other minor chemicals that are mixed with the waste in a blending pit. After treatment, the waste is returned to the excavation site and compacted to a very low permeability. The USEPA is in the process of locating a demonstration site for the technology.

Table 2.6 Summary of On-site Lime Based Solidification/Stabilization Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Process Efficiency (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1975-87	in Europe	51 sites Companies	Several Montage (VAM Process)	Voest-Alpine soils & sludges	Mainly oil in	--	--	--Canadian Waste Management Corp. (undated,b)
1980	Montreal, Quebec	Tricil	Voest-Alpine Montage (VAM Process)	Oil in sludge	--	--	--	Canadian Waste Management Corp. (undated,b)
1986-87	Vienna, Austria	Austrian Federal Railways (OBB)	Voest-Alpine Montage (VAM Process)	Oil	--	--	9000 m ³	Canadian Waste Management Corp. (undated,b)
1987	Mountain View, California	USEPA	Acurex Corp.	VOC's PAH's Halogenated & Non-halogenated Hydrocarbons	2000-20000 total organic	--	--	USEPA (1989a)
1988	--	Sun Refining & Marketing Co.	Bucknell University	Aliphatics Aromatics Alcohols Ketones PAH's Phthalates	up to several hundreds	--	Laboratory Experiment	Evans et al., (1988)
1990	To be determined	USEPA	Separation & Recovery Systems Inc.	Organics	--	--	--	USEPA (1989b) Hill (1988)

* process efficiency calculated as % difference in toxicity contaminant leachate procedure (TCLP) before and after treatment

iv) Needs for Additional Research

The lime based solidification/stabilization technology has been extensively used in Europe to treat oil contaminated soils. However, documented case histories proving the effectiveness of the method are unavailable. Research may be required to demonstrate which organic compounds may be stabilized using this technology and the extent to which these compounds remain immobilized over time.

2.2.1.3 Thermoplastics

i) Process Description

Thermoplastic technologies utilize bitumen (asphalt), polyethylene or paraffin to stabilize contaminated soils. In this type of treatment, the contaminants are physically incorporated into thermoplastic materials but not chemically bonded (Environment Canada, 1989). The contaminated material is dried before it is mixed with the thermoplastic. After cooling and solidification, the final product is plastic and can be disposed of safely. Specialized equipment such as a kiln and an asphalt mixer are needed to dry the soil and to mix it with the thermoplastic (Rulkens et al., 1985). Apparatus for asphalt production offers large capacities but may require modification before being used to treat hazardous wastes. The temperature required to stabilize soils with thermoplastic depends on the type of thermoplastic, contaminants, and equipment but generally varies between 100°C and 230°C. Because of the temperature, it is advisable to limit the concentration of flammable compounds to avoid potential risks of explosion. Measures should also be taken to reduce the emission of volatile compounds in the exhaust gases.

The use of paraffin and polyethylene is only in the development stage and will not be further discussed.

The process of thermoplastic solidification of contaminated soil by asphalt batching as reported by Morin et al. (1989) is shown in Figure 2.12. The soil is excavated and transported to the asphalt batching plant. Large debris is removed or reduced from the soil using screens and crushers. The soil is then heated in a primary chamber (kiln) to vaporise water. After the soil is dried, it is mixed with an asphalt emulsion and aggregate if desired. The entire process takes place in a closed system to minimize dust emissions.

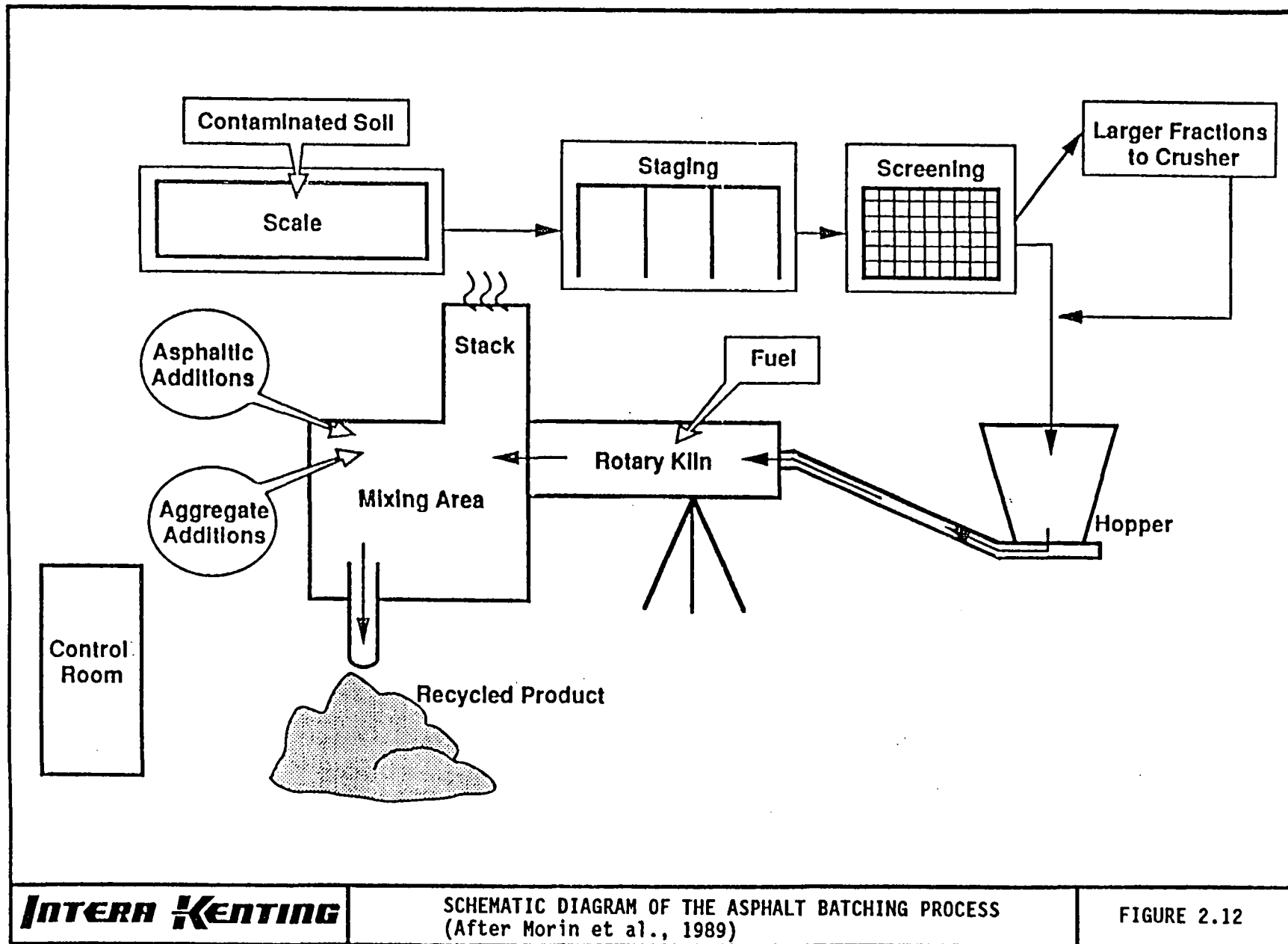
The end-product may have to be placed in a secondary container before it is transported and disposed of. A variation of this process is to add 5% - 7% moisture to the dried soil exiting the primary chamber and to store this mixture until it can be incorporated into the asphalt mix (Morin et al., 1989).

Advantages of the thermoplastic solidification process are:

- the removal of water may reduce end-product volume;
- the leachability of contaminant is lower than for most other techniques (e.g., cement based methods);
- the end-product is fairly resistant to aqueous solutions;
- the thermoplastic material adheres well to the soil material;
- it is resistant to biodegradation;
- in some cases, the end-product may be used as construction material.

Disadvantages and limitations of the method include:

- the soil has to be transported and dried;
- the method requires specialized equipment and well-trained personnel;
- a danger of explosion or fire exists;
- more hazardous compounds could be generated during the process;
- it requires that air emissions be controlled;
- rehydration of salts may cause fracturing of the solidified material;
- the end-product may require the use of a secondary container because of its plastic nature.



Treatment rates are on the order of 35 tonnes/hour and may be limited by the rate at which the contaminated soils are transported to the plant.

The costs of asphalt batching are in the order of \$100 - \$130 per tonne of contaminated soil depending on the excavation, loading and transportation costs. In addition, the capital costs of the asphalt plant fully equipped to receive contaminated soils may be fairly high but were not included in the literature reviewed.

The applicability to Canadian conditions should not be a problem since asphalt plants are widespread throughout the country. Although no information was available on the resistance of the final material to wetting/drying and freezing/thawing, the treated end-product should behave similarly to road asphalt.

ii) Wastes Treated

The ideal soil type to be treated by thermoplastic technologies and especially by asphalt batching is sand. Wet heavy clays are unsuitable for almost any plant (Morin et al., 1989). Some plants can accept a higher silt and clay content than others.

Acceptable contaminants include gasoline, fuel oil, tar, lubricating oil and grease. Specific regulations in United States may apply for the maximum allowable levels of contaminants. For example, in Pennsylvania, PCB's have to be lower than 1 ppm in the contaminated soils (Morin et al., 1989) because the method is not suitable to treat PCB's. The flash point of the soil may have to be high enough to prevent potential explosion or fire. Usually, this results in a maximum allowable concentration for petroleum hydrocarbons. VOC's should not be present in the soil to be treated unless the plant is equipped with gas-purifying equipment. Lead contamination should also be limited.

There are numerous waste types that are incompatible or may adversely affect the process and the properties of the end-product. For that reason,

bitumen solvents (like xylene and toluene) and strong oxidizing salts should not be present in the waste material (Wagner et al., 1986).

iii) Applications/Demonstrations

Thermoplastic treatment technologies have not been widely used for treating contaminated soils. One documented case of asphalt batching from the state of New Jersey has been identified during our literature review. The firm Environment Resources Management Inc. has been undertaking the cleanup of a former steel bracket manufacturer site in east central New Jersey (Morin et al., 1989).

The soils contained primarily petroleum hydrocarbons in excess of 3%. More than 3000 tonnes of soils were excavated, transported and treated at an asphalt batching plant. The contaminated soils were treated during 12 days at a rate of 275 tonnes/day. The contaminated soils were incorporated into asphalt mixes. Morin et al. (1989) do not report further on the performance of the treated material nor on its leachability characteristics.

iv) Need for Additional Research

There is a need to verify the leaching characteristics of the thermoplastified material. Gas emissions should be investigated to prevent the emission of even more hazardous compounds to the atmosphere. Maximum input concentrations should be regulated if this technology is permitted in Canada. Finally, volatile emissions should be measured in the event that the end-product will be used as a road pavement.

2.2.1.4 Organic Polymers

i) Process Description

In the organic polymer solidification/stabilization technology, a monomer is added and mixed to the contaminated soils (Pojasek, 1979). A catalyst is then added to enhance the reaction that forms the polymer. The resulting solid entraps particles in a spongy mass (Environment Canada, 1989) but the

polymer does not chemically react with the contaminated material (Kyles et al., 1987). The water and liquids associated with the contaminated soils will remain in the polymer after the process. As a result, the end-product has to be dried or containerized prior to final disposal.

Urea formaldehyde (UF) is the most common polymer technology and was developed for nuclear waste handling. It is used with catalysts that are strongly acidic. Other organic polymers, such as polyesters and polyvinyl resins have been developed for use in waste solidification.

The advantages of the organic polymer technology include:

- small reagent quantities are generally needed for the polymerization of wastes;
- the density of the polymer is lower than that of cement;
- high temperatures are not necessary and the solidified material is non-flammable.

Some disadvantages have also been identified:

- the end-product has to be dried or contained;
- contaminants are not chemically bound to the polymer and may be leachable if the structure of the polymer changes;
- in the case of the urea formaldehyde technique, the strongly acidic catalysts may solubilize several contaminants and require the use of corrosion-resistant equipment;
- water contained in the soil may be strongly acidic and have elevated contaminant levels;
- hazardous or noxious gases may be released during the process and gas-purifying equipment may have to be included in the configuration;
- some urea-formaldehyde polymers are biodegradable.

No information regarding treatment rates and operating costs could be found for this technology.

ii) Waste Treated

The organic polymer process has been applied to solidify/stabilize wastes containing inorganics and radionuclides. However, no specific information was available on the use of this technology for the treatment of soils contaminated with organic compounds.

iii) Applications/Demonstrations

Although the process has been applied for several years for the treatment of inorganic contaminated wastes, no application was found in the literature for soils containing organic contaminants.

iv) Need for Additional Research

Before considering this technology, a well documented pilot-scale demonstration on organic contaminated soil would have to be implemented.

2.2.1.5 Silicates

i) Process Description

Silicate based solidification/stabilization processes involve the use of siliceous materials together with lime, cement, gypsum or other suitable setting agents (Wagner, et al., 1986). The siliceous material added to the waste may be fly-ash, furnace slag, kiln dust or other pozzolanic materials. Soluble silicates like sodium silicate or potassium silicate may also be used. Extensive research and development is underway on the use of silicates to solidify contaminated soils.

The process involves a reaction that takes place between the silicate and polyvalent metal ions which act as initiators of silicate precipitation and/or gelation. The metal ions can come from the treated soil and/or from added setting agents. The most common added agents are cement and lime although gypsum, calcium carbonate and other compounds containing metals such as aluminum,

iron, and magnesium can also be used. The stabilized end-product varies from a damp clay-like solid to a hard and dry concrete-like material. It provides entrapment of water, oils and other organics as well as inorganics (Kyles et al., 1987).

Additives used in the silicate solidification technology include selected clays, emulsifiers or surfactants (to incorporate immiscible organic liquids) and proprietary adsorbents such as carbon, zeolite and cellulosic sorbents (Wagner et al., 1986).

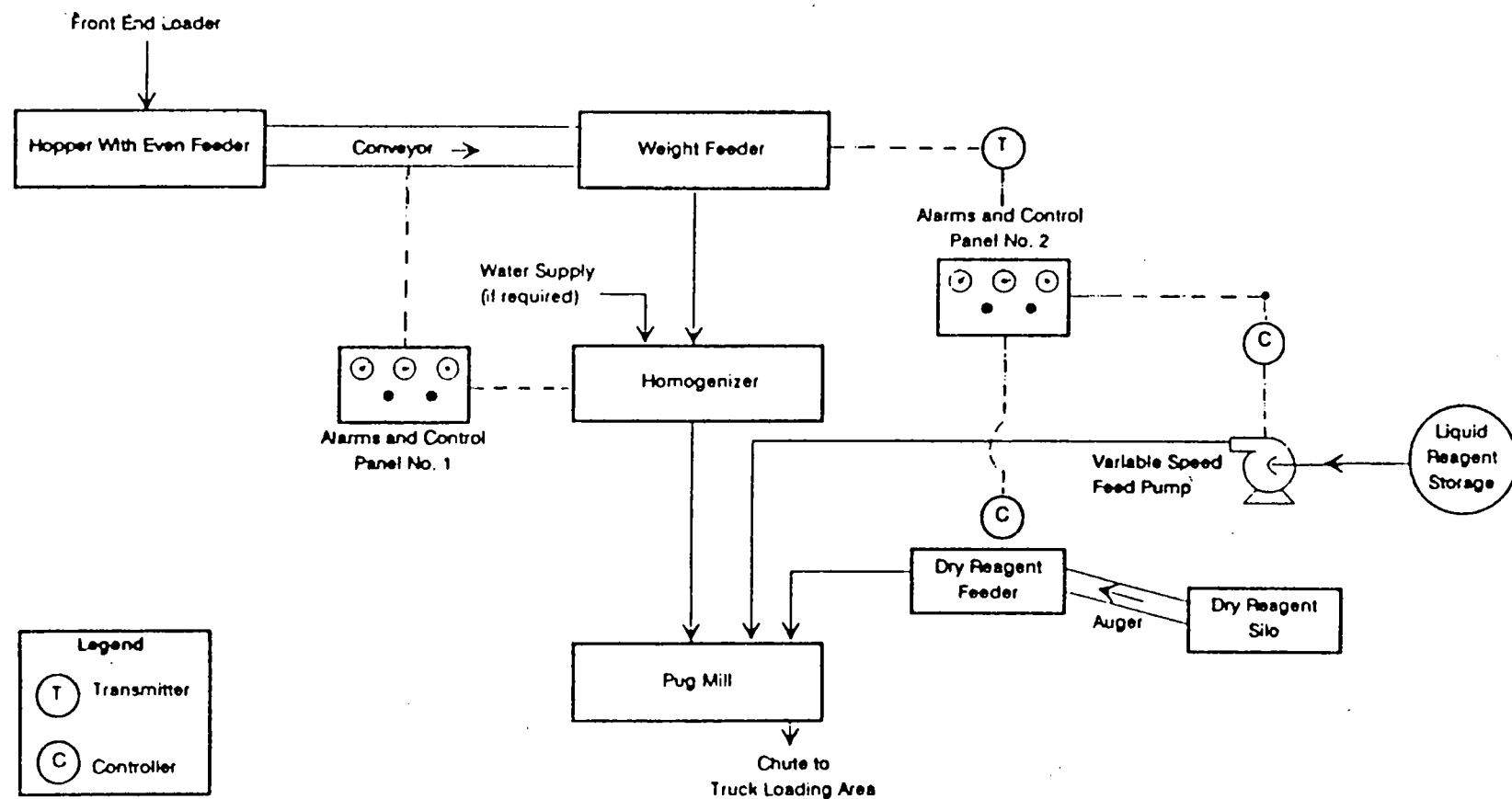
Commercial cement mixing and handling equipment can be used in the train-configuration of the silicate solidification process. The equipment needed includes hoppers, conveyers, weight feeder, water supply, chemical storage, mixing apparatus and end-product handling equipment as shown in Figure 2.13. The equipment can be trailer mounted and mobilized on-site.

Advantages of the silicate solidification technology are:

- additives are available and the majority have a reasonable cost;
- the water content of the soil may vary without affecting the process;
- commercial mixing and handling equipment can normally be used;
- the permeability of the soil is reduced after the treatment.

Disadvantages of this method include:

- slow to very slow solidification rate;
- common problem with fly-ash lime and fly-ash cement material relates to interference preventing bonding of the treated soils;
- large amount of water not chemically bound remains in the treated soil after solidification and may result in possible leaching of contaminants;
- to prevent water losses, a secondary containment may be required.



Treatment rates can be in the order of 400 tonnes/day of contaminated soils. Treatment costs will vary depending on site specific conditions but are estimated at a minimum of \$80 per tonne for unpumpable wastes (Wagner et al., 1986).

This technology may be applicable to Canadian conditions if the processed material is allowed to cure before freezing.

ii) Wastes Treated

Commercial vendors contend they are able to treat a variety of contaminated soils containing organic compounds. High molecular weight organics and base/neutral or acid extractable organics included in refinery wastes, creosote and wood-treating wastes are potentially fixed by a silicate based technology developed by Chemfix Technologies Inc. (USEPA, 1989b). Silicate Technology Corporation claims to be able to stabilize soil wastes with high molecular weight organics including halogenated, aliphatic and aromatic compounds (USEPA, 1989b). However, the process is not recommended for low molecular weight organic contaminants such as alcohols, ketones, glycols and volatile organics.

Siallon Technologies Incorporated claims to be able to treat soils contaminated with fuels, crude oil, coal tars, and creosote (Siallon Technologies Inc. undated).

iii) Applications/Demonstrations

Two demonstrations were sponsored by the USEPA and were carried out in 1988 and 1989 as shown in Table 2.7. A third demonstration sponsored by the USEPA will be carried out in 1990.

The first demonstration was performed using soils from the Tacoma Tar Pits Superfund site in Tacoma, Washington. Approximately 4000 m³ of coal tar contaminated soil is present at the site (Rupp et al., 1989). A bench-scale treatability study was conducted using roughly 200 kg of soil, tar and foam fluff

materials from the site. The contaminated soil and foam fluff contained phenol, PAH's, PCB's and lead at concentrations shown in Table 2.7. The tar contained phenols, BTX and PAH's. Soils, soil-fluff mixes (1:1 and 3:1), soil-tar mixes (1:1) and tars were solidified using silicates and additives provided by Silicate Technology Corporation. Treatment rates were not reported due to the small volume. More information on this application is available as Case Study 9 in Appendix B.

The results (Rupp et al., 1989; Rupp, 1989) show that because this is a fixation technology, the treated soils could not be considered as being decontaminated. However, the permeability of the fixed materials was reduced to 10^{-7} to 10^{-9} cm/s. The leaching characteristics were also influenced by the treatment. The process reduced the leaching concentration of PCB's from 0.06 ug/l to below detection for the treated soil. However, the data presented do not allow an evaluation of whether the process can effectively immobilize the phenols and PAH's present in the soil. More details on this demonstration can be found in Case Study 9 in Appendix B.

The second demonstration was carried out by Chemfix Technologies Inc. at the Portable Equipment Salvage Co. site in Clackamas, Oregon. Preliminary results (USEPA, 1989b) show that the treatment increased the volume of the waste by 20% to 50%. The permeability of the solidified material was one order of magnitude lower than the permeability of the untreated waste. The raw waste contained up to 14% of lead initially but no data on the organic contamination of the waste were reported. The solidified wastes showed little or no weight loss after 12 cycles of wetting/drying or freezing/thawing. The unconfined compressive strength was 27-307 psi after 28 days. The available information indicates that there was no significant volatilization of PCB's during the treatment process.

Table 2.7 Summary of Silicate Solidification/Stabilization Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Process Efficiency (%)	Initial Quantity Contaminated Soil (tonnes)	Reference
1988	Tacoma Tar Pits, Wa.	USEPA	Silicate Technology Corporation	Phenols PAH's PCB's Lead	377 13.5 6.2 2490	0 0 0 -99.96	Roughly 200 kg	Rupp et al., (1989) Rupp (1989) (see Case Study 9)
1989	Clackamas, Oregon	USEPA	Chemfix Technologies Inc.	--	--	--	--	USEPA (1989b)
1990	Kaiser Steel, Fontana, CA	USEPA	Silicate Technology Corporation	--	--	--	--	USEPA (1989b)
1987	--	--	International Waste Technologies	PCB's PCP	1140-6000 290-11000	--	--	Newton (1987)
1987	--	--	International Waste Technologies	Oil & Grease Ethyl benzene Xylenes PAH's	249000 10 83 341-817	--	--	Newton (1987)

* process efficiency calculated as % difference in toxicity contaminant leachate procedure (TCLP) before and after treatment

Two applications by International Waste Technologies are also mentioned in Newton (1987). Their technology uses sophisticated silicate-based chemicals that can fix mixtures of organic and inorganic wastes to prevent leaching of the toxic contaminants. Treated soils had PCB leaching concentrations of 0.08 - 6 ppb in the first application. The leaching concentration in the second application was below the detection limit for ethylbenzene, xylenes and PAH's after solidification.

iv) Need for Additional Research

Although this technology seems very successful to reduce the leachability of lead and other metals, its ability to reduce the leachability of organic contaminants is not well documented. This aspect should be investigated in greater detail.

2.2.1.6 Clays

i) Process Description

Organophilic clays may be used to enhance the stabilization of organic hazardous wastes. When mixed with additional solidification agents such as cement, kiln dust or fly ash, the waste can be solidified into a stable mass with low leaching potential (Alther et al., 1988).

The types of clay that can be used in solidification/stabilization processes are mainly montmorillonite (in the form of bentonite) and attapulgite. To increase their capacity for adsorbing organic compounds, these clays are organically modified by organic ion exchange where a cationic organic surfactant is exchanged with sodium, calcium or magnesium ions on the surface of the clays. After this treatment, the clays become organophilic and can swell and disperse in a variety of organic solvents.

This process seems relatively new and no further information on the process description treatment rates and costs was available.

ii) Wastes Treated

In a laboratory experiment reported by Alther et al., (1988), organically modified clays could swell in a variety of organic compounds including acetone, carbon tetrachloride, hexane, kerosene and xylene. The process seems to be potentially applicable to soils in combination with solidification/stabilization agents such as cement, kiln dust or fly ash. These agents can form a solid matrix around the clay particles that adsorb organic contaminants. Another laboratory experiment was reported by Evans et al., (1988) in which clays with different agents were used to stabilize petroleum clayey sludges. Compounds detected in the sludges included phenols, PAH's, alkanes and phthalates.

iii) Applications/Demonstrations

The laboratory experiment reported by Evans (1988) was the only documented application of the use of clays to stabilize wastes containing geologic material and organic contaminants in the form of an acidic oil sludge. Different types of clays were tested to solidify the sludge: two unmodified clays (bentonite and attapulgite) and six organically modified clays provided by Southern Clay Products and by NL Baroid. The sludge included a variety of organic contaminants as shown in Table 2.8 having concentrations up to several hundreds of ppm.

The results showed that the organically modified clays generally improved the containment of the organic constituents of the sludge. One of these clays, the Claytone APA of Southern Clay Products, had favourable total organic carbon concentrations in the leaching tests. The leaching TOC concentrations were still in the tens of ppm levels but were as high as 200 ppm for the material stabilized with unmodified clays. Evans et al., (1988) concluded that the stabilization mixes using organically modified clays hold the organic contaminants more effectively than the unmodified clays. They also concluded, based on comparison with other solidification/stabilization agents, that processes using organically modified clays show more promise in effectively stabilizing organic contaminants than those using cement and fly ash.

Table 2.8 Summary of Clay Solidification/Stabilization Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentra- tion (ppm)	Process Efficiency (%)	Initial Quantity Contamina- ted Soil (tonnes)	Reference
1988 --		Sun Refinery & Marketing Co.	Bucknell University	Aliphatics Aromatics Alcohols Ketones PAH's Phthalates	<500	--	--	Evans et al., (1988)

* process efficiency calculated as % difference in toxicity contaminant leachate procedure (TCLP) before and after treatment

The organic clays, used in conjunction with some type of binder material, may provide the method that would adequately stabilize and solidify organic-bearing wastes.

iv) Need for Additional Research

The process using organically modified clays should be further investigated to identify both the types of soils and contaminants that could be treated using this technology and potential problems.

2.2.1.7 Glassification

Glassification, sometimes called vitrification, involves fusing the wastes with silica at a temperature of 1350°C or higher (Wagner et al., 1986). This process has been restricted to extremely toxic wastes (Env. Canada, 1989) such as radioactive wastes. To be considered for glassification, a waste should be stable or totally destroyed at the process temperature. No information regarding process description, treatment rate or capacity was available from the literature reviewed. Costs are believed to be extremely high because of the energy consumed by the process.

The advantages of the process include:

- it offers the highest degree of containment;
- resultant solids have an extremely low leach rate;
- additives are relatively inexpensive.

Disadvantages of the glassification technology are:

- high energy demand;
- necessitate specialized equipment and trained personnel;
- some volatile compounds may be lost during the process.

ii) Wastes Treated

The process has been applied to highly toxic wastes such as radioactive wastes. It has also been applied to heavily contaminated soil containing several thousand ppb of total PAH's. The soil treated was sandy with 47% silt/clay (Barich et al., 1987).

iii) Application/Demonstration

The only available demonstration of glassification was completed during a USEPA treatability study reported by Barich et al., (1987) as shown in Table 2.9. This study was conducted at the Western Processing Superfund Site in Kent, Washington.

The toxicity of the untreated soil on aquatic species was moderate to extremely high depending on the species used in the bioassays. The contaminated soils showed no toxicity on three terrestrial species and did not leach any priority organic pollutants. The contaminated soils were vitrified with clean matrix soil into a 275 kg monolith. The vitrified soils were also subjected to aquatic and remedial bioassessment tests and to leaching tests (EP Toxicity and TCLP) for seven metals and in some cases for priority organic pollutants. No leaching of priority organic pollutants was detected, however, leaching of metals was high for the vitrified soils. Vitrification improved the conditions of the soils since no toxicity was measured for the aquatic species and for two of the three terrestrial species.

No costs were mentioned for the treatment performed. Geosafe Corporation is also in the process of testing an in-situ vitrification technology within the USEPA SITE Program (USEPA, 1989b). This technology could be potentially applied to excavated soils. The method uses electrodes to melt the soil between 1600°C and 2000°C destroying organic pollutants by pyrolysis and immobilizing inorganic pollutants within the vitrified mass. Air emissions are collected into a hood for treatment that removes particles and other pollutants. The in-situ process melts soil at a rate of 4-6 tonnes/hour. The vitrified material shows a volume reduction because the void volume of the soil is removed

Table 2.9 Summary of Glassification Applications

Date	Site	Customer	Contractor	Contaminants	Concentration (ppm)	Quantity (kg)	Reference
1987	Western Processing Superfund Site Kent, WA	USEPA Region 10	Battelle Pacific Northwest Laboratories	Polycyclic Aromatic Hydrocarbons (PAH)	8-740	22	Barich et al., (1987)



during processing. The system is transportable, being mounted on three trailers and requires electric power of 12500 volts. Pilot-scale tests have been performed on PCB and dioxin wastes and other solid and liquid chemicals. USEPA is now in the process of choosing a site for the demonstration of the technology.

iv) Need for Additional Research

Additional research is needed to prove that the glassification technology can effectively immobilize organic contaminants that are leachable in the untreated soils. Verification of the volatile emissions during and after the treatment should also be investigated.

2.2.1.8 Encapsulation

i) Process Description

The encapsulation technology, also referred to as jacketing technology, is a method for enclosing wastes by completely surrounding them with an impermeable coating (Levin et al., 1985). The method involves sealing the contaminated material in polyethylene or polyethylene-lined drums which can have a welded cover. This method is commercialized by Environmental Protection Polymers.

Another encapsulation method from the same company involves mixing the contaminated material with 1,2-polybutadiene which coats the particulates with a dry resin (Wagner et al., 1986). The mixture is compressed into a block which is then surrounded by powdered polyethylene and heated under pressure. The final product is an encapsulated waste block with a high density polyethylene jacket fused on it. Various proportions of the two polymers can provide a matrix which has good mechanical properties and is resistant to permeation by water. As a final step, a 6 mm thick high-density polyethylene jacket is fused to the micro-encapsulated wastes.

A third encapsulation technique uses an organic binder to seal a cement-stabilized mass (Wagner et al., 1986). United States Gypsum Company produces a binder called Envirostone Cement which is a blend of polymer modified-gypsum cement. A proprietary binder is used to seal the solidified material.

The main advantages of the encapsulation are:

- very soluble pollutants are totally isolated from the environment;
- the end-products do not require a secondary container and the hazard of accidental leak is eliminated;
- the encapsulation materials are commercially available, chemically stable, mechanically resistant and nonbiodegradable;
- the end-product can support the mechanical and chemical stresses of landfilling.

The disadvantages include:

- the inert materials used in the process (polybutadiene, polyethylene) are expensive;
- the process is energy intensive and requires skilled technicians to operate the equipment;
- polyethylene is combustible, creating a fire hazard;
- volatile organics in the coating may provide a pathway for leaching soluble organics from the waste.

No description of the treatment rate was available in the literature reviewed. Updated costs for the polybutadiene/polyethylene technique are on the order of \$165 per tonne (Wagner et al., 1986). Encapsulation in drums with welded tops costs approximately \$90-125 per 0.5 m³ drum. The process should be applicable to Canadian climatic conditions, however no information on the resistance of the treated material to wetting/drying and freezing/thawing was available.

ii) Wastes Treated

The encapsulation technology may be employed to contain very soluble toxic wastes (Levin et al., 1985) because it can completely isolate the wastes from the environment. The method can be used for organic and inorganic wastes (Wagner et al., 1986) including contaminated soils. However, each of the available encapsulation techniques is unique, so the feasibility of stabilizing a waste material should be evaluated on a case by case basis.

iii) Applications/Demonstrations

The encapsulation technique to seal cement-stabilized wastes has been used for both inorganic and organic wastes (Wagner et al., 1986). It has effectively immobilized an oily waste having an oil concentration of 36% per volume. No further information on the application of encapsulation was available.

iv) Need for Additional Research

The encapsulation method potentially stabilizes waste material such as contaminated soils. However, the type of soils and contaminants it can effectively treat and the long term behaviour of the treated material should be further investigated.

2.2.2 Soil Washing

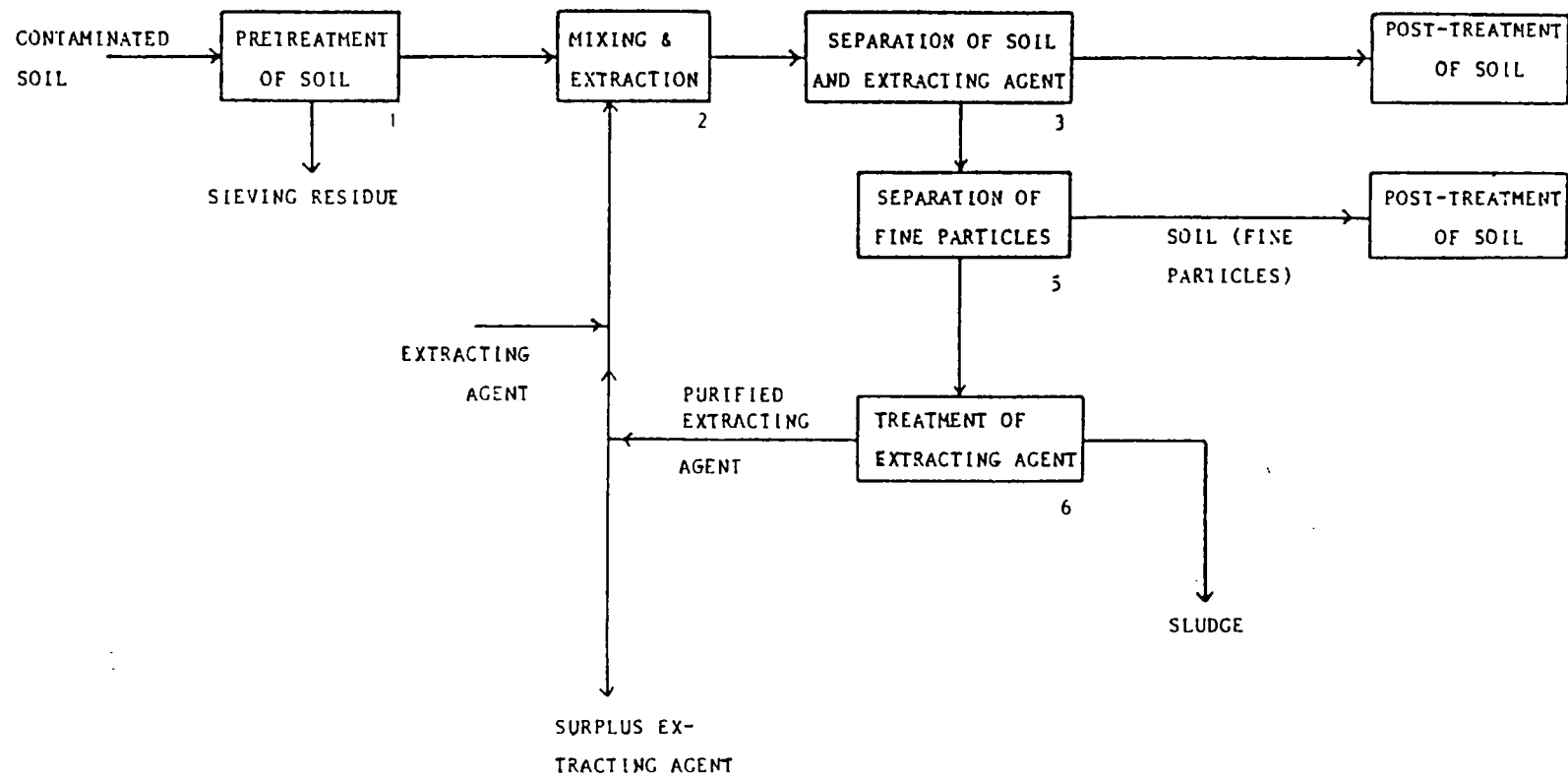
Soil washing technology has undergone significant development in the last decade for the cleanup of contaminated soils. It has been used extensively in Europe and is now emerging in the United States and Canada. Soil washing is a physical transfer process in which contaminants are removed from the soil and become dissolved or dispersed in a fluid such as water with or without chemical additives such as detergents and surfactants (Offcut et al., 1988).

The basic process of soil washing involves breaking the bond between the contaminant and the soil particle. Two distinct removal mechanisms may occur during soil washing (Assink, 1986, 1987):

- the contaminants are dissolved in a (chemical enhanced) washing solution;
- the contaminants are dispersed in the washing solution in the form of particles. In this case, subsequent separation of the contaminated particles and the clean soil particles is based on particle size, settling velocity, surface properties or a combination of these characteristics.

The general process scheme of soil washing is shown in Figure 2.14 and is described in the following points (Assink, 1986) where numbers correspond to those of the figure:

- 1) The contaminated soil is pretreated to remove large objects and hardened soil is crushed. The sieved residue may be cleaned separately.
- 2) The pretreated soil is mixed thoroughly with the washing (extracting) fluid. This process transfers the contaminants from the soil to the fluid as solute or to suspended particles as sorbed material.
- 3) The soil and the washing fluid are separated: contaminants, fine soil particles (silt and clay) and the soluble components of the soil stay in the washing fluid.
- 4) The soil may be submitted to a post-treatment which consists of another washing with clean fluid and/or water only.
- 5) Fine soil particles suspended in the washing fluid are separated and may be submitted to a subsequent washing with clean fluid (post-treatment).
- 6) The contaminated extracting fluid is cleaned and partially recycled to the system after replenishment of chemicals. The residue of the fluid cleaning is a contaminated sludge.



The soil washing (extraction) can be accomplished by three different methods (Assink, 1986, 1988):

- Classification which refers to grain size separation where the contaminants and the soil particles are dispersed with water and separated by gravity or settling velocity.
- Aqueous Extraction where different chemical additives are used to remove contaminants from soil. These additives include:
 - acids/bases
 - surfactants
 - complexing or chelating agents.
- Organic Extraction where organic solvents are used to extract the contaminants from the soils. This method is called Solvent Extraction and is discussed in Section 2.2.3.

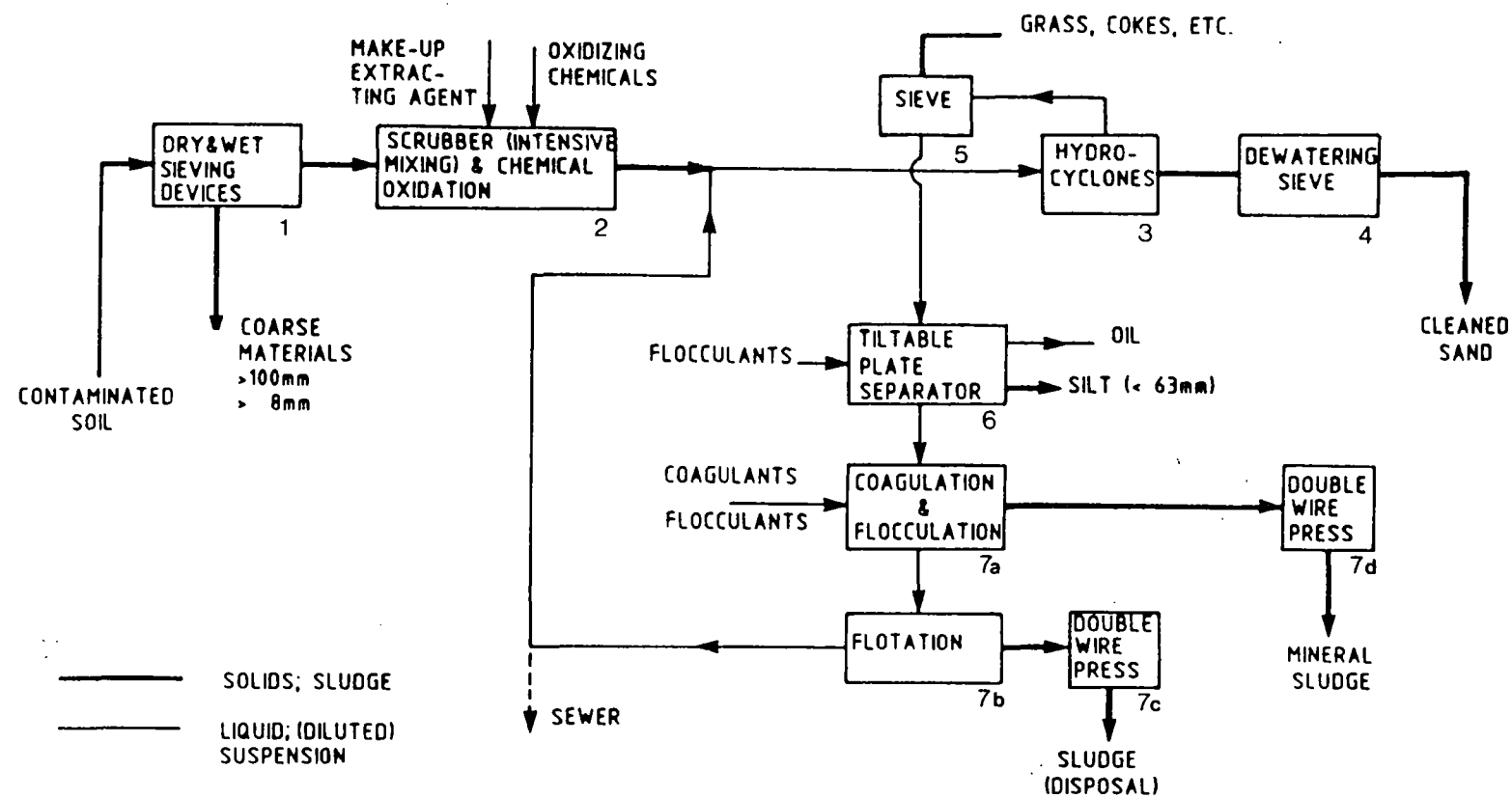
Classification and Aqueous Extraction with chemical additives may be used separately or combined for soil washing. The different soil washing techniques are discussed in the following subsections.

2.2.2.1 Classification and Washing with Water

i) Process Description

Soil classification and washing using water with or without chemical additives rely on the assumption that a significant fraction of the contaminants in the soil are attached to the smaller sized soil particles such as silt, clay and organic matter (Esposito et al., 1989). A typical soil classification and washing scheme using water is shown in Figure 2.15 (based on Assink, 1986) and is summarized below (numbers correspond to numbers on the figure).

- 1) Separation of coarse fraction (>10 mm)
- 2) Mixing of soil and water to disperse all particles and to physically remove contaminants
- 3) Separation of sand (>60 μ m) using hydrocyclones
- 4) Dewatering of the cleaned sand



- 5) Separation of glass and other coarse low-density materials
- 6) Separation of silt (<63 μm) using a tiltable plate separator and removal (skimming) of floating oil
- 7) Coagulation and flocculation of the contaminated water followed by flotation of flocs and recycling or disposal of the water. Other treatment of the water may include detoxification and biological treatment.

One variation to the soil washing process is the use of high pressure water applied to the contaminated soils with water jets. This technique has been used in the Netherlands by Bodemsanering Nederland BV (Assink, 1986). A second variation is the use of heated water in the mixing process as demonstrated by Ecotechniek BV in the Netherlands. A third variation developed by Harbauer in Germany (Raghavan et al., 1989; Sonnen et al., 1989) consists of submitting the soil/water mixture to intense vibrations or oscillations to separate the contaminants from the soil particles. A last variation is to add an oxidizer such as hydrogen peroxide or ozone during the mixing process (Assink, 1986).

Some of the advantages of water classification are:

- The process does not use complex or expensive chemicals;
- Dewatering is not necessary;
- Mostly applicable to soluble contaminants;
- Safe for users and the environment.

The process limitations include:

- Difficulty in separating clay particles from the water solution;
- Generation of large amounts of sludge when the soil fine fraction is significant;
- Water can only partly remove the less soluble compounds such as oils, PAH's and non-volatile organic compounds.

The treatment rate is on the order of 10-20 tonnes/hour to 45-55 tonnes/hour for large plants for soils with small amounts of fines and around 5 tonnes/hour for soils containing a larger amount of fine particles. Costs are

a function of the treatment rate but are estimated at \$95-132 per tonne for soil washing by Heijmans Milientechniek (Nunno et al., 1988). These costs exclude sludge disposal costs. Capital costs for such washing plants are between \$3.5 and \$6 million (Biotrol, undated).

The treatment facilities can be transportable or fixed. Most of the European facilities are or will be fixed. The USEPA has a mobile system. Both types of facilities are applicable to Canadian climatic conditions with some restrictions for cold weather.

ii) Wastes Treated

The soils that can be treated using this technology should preferably be sandy and contain less than 20-30% fine solids (<63 μ m or under # 200 sieve). Potential contaminants treated include volatile organics, semi-volatile organics (to a lesser extent) and water immiscible low-density hydrocarbons like oil.

iii) Applications/Demonstrations

Several applications of soil classification and washing using water are described in the literature. The method is also widely commercialized in European countries such as the Netherlands and Germany. It is also developing rapidly in the United States. GKN Keller was the only Canadian vendor identified. They combine jet drilling with soil washing and stabilization. Identified applications of this technology are presented in Table 2.10.

One of the first companies that applied soil classification and washing with water is called Bodemsanering Nederland (BSN). Since 1983, they have operated a transportable installation capable of treating 20 tonnes of contaminated soil per hour (Assink, 1986). Their process uses water under high pressure to wash the soil, separates the fine soil fraction using sieves and hydrocyclones and uses an optional biological post-processing unit. BSN claims to treat all types of soil with a maximum amount of 20% of fines (<63 μ m) and

Table 2.10 Summary of Soil Classification and Washing with Water Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Final Concentration (ppm)	Initial Quantity Contaminated Soil (kg)	Reference
1983	Several Sites in the Netherlands	--	Bodemsanering, Netherland (high pressure washing)	Aromatics PAH's Crude Oil	240 295 79000	46 15 2370	--	Assink (1986)
>1985	Gasworks, Netherlands	--	Heijmans Milieu-techniek (water washing)	PAH's	250-400	--	--	Nunno et al., (1988)
>1985	Diesel Fuel, Netherlands	--	Heijmans Milieu-techniek (water washing)	Mineral Oil	3000-8000	90-120	--	Assiuk (1986)
--	Several Sites in Germany	--	Harbauer (washing with vibration)	Total Organics Total Phenol PAH's Chlorinated Organics PCB's	4400-5400 115 728 90 3.2	176-216 7 95 0 0.5	10,000	Nunno (1986) (see Case Study 10)
--	Beach in the Netherlands	--	Ecotechniek (hot water washing)	Crude Oil	200,000	20,000	5,000	Assink (1986)
--	Several Sites in Germany	--	Klockner (high pressure washing)	PAH's Chlorinated Hydrocarbons Phenols PCB's Aromatics	333-1550 0.04-0.20 0.26-20.1 ND-250 1.9-9400	-- -- -- -- --	7,000	Heimhard (1988)

Table 2.10 Summary of Soil Classification and Washing with Water Applications (Cont'd)

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Final Concentration (ppm)	Initial Quantity Contaminated Soil (tonnes)	Reference
1989	MRW Site, Germany	--	Klockner	Mineral Oil PAH's BTX Chlorinated Hydrocarbons	1230-9040 6.8-56.3 2.8 85-130	-- -- -- --	19	Klockner (undated)
1987	Synthetic Soils	USEPA	PEI Associates	Volatile Organics Semi-Volatile Organics Metals	770-18666 325-7573 1047-60879	7.7-6350 23-7573* --	Bench-Scale Study	Esposito et al., (1989)
1989	MacGillis & Gibbs Superfund Site New Brighton, Minnesota	USEPA	Biotrol Inc.	PCP	300-1000	--	25	USEPA (1989b)

* final concentration dependant upon soil grain size fraction

-- = no data available

containing all low-density (lighter than water) aliphatic and aromatic compounds, volatile contaminants and some water soluble and biodegradable hydrocarbons. Practical experience has shown removal efficiencies of 81% for aromatics, 95% for PAH's and 97% for crude oil.

A second company from the Netherlands called Heijmans Milieutechniek (Assink, 1986) has applied water classification and washing to contaminated soils since 1985. Their process treats 10 tonnes/hour of soil using only water and operates on the principle that most contaminants are adsorbed to the fine (<63 μm) particles (Nunno et al., 1988). The company applies its process to soil containing less than 30% fines and humic substances, and light immiscible hydrocarbon liquids. Results from test runs with silt containing mineral oil showed a removal efficiency of approximately 98% from 3000-8000 ppm to 90-120 ppm (Assink, 1986). Results for coarse sand containing PAH's showed a decline in concentration from 250-400 ppm to 0.5-10 ppm.

Harbauer has developed a soil washing system considered to be one of the best in Germany (Nunno et al., 1986). The system has treated more than 10,000 tonnes of soil contaminated by organics. The process combines low frequency mechanical vibration with water washing to separate particles as small as 15 μm . The system is fixed and has a treatment rate of 20-40 tonnes/hour. This process has been applied to various types of soil containing phenol, PAH's, extractable chlorinated organics, PCB's and other aliphatic and aromatic compounds (Nunno et al., 1988; Sonnen et al., 1989). Performance of the system to treat sandy soils shows removal efficiencies of 96% for total organics, 94% for total phenols, 87% for PAH's, 84% for PCB's and 100% for extractable chlorinated organics (Nunno et al., 1988). Similar results were obtained for clayey soils, however, a higher residual volume was generated. A case study for the Harbauer soil washing system is included as Case Study 10 in Appendix B.

The company of Ecotechniek in the Netherlands has applied hot water washing to contaminated soils for several years (Assink, 1986). The installation is best suited for sandy soil heavily contaminated with oil and crude oil and treats approximately 20 tonnes of soil per hour. The process heats the slurried sand to a maximum of 90°C and separates the oil by skimming. Removal efficiency reached 90% for 5000 tonnes of beach sand heavily contaminated by an oil spill

(oil concentration up to 200,000 ppm). The sand was subsequently treated by asphalt batching.

The German company Klockner also runs a soil washing system with a capacity of 35-55 tonnes/hour (Klockner, undated). Two applications of this treatment technology are shown in Table 2.10.

The last two applications of Table 2.10 were sponsored by the USEPA. PEI Associates performed a bench-scale treatability study using the EPA Mobile Soils Washing System to treat a Synthetic Analytical Reference Matrix (SARM). The system uses a rotary drum to separate the coarse fraction (>2 mm) from the fine fraction (<2 mm) of the soil (Esposito et al., 1989). A high pressure water knife breaks up soil lumps and strips the contaminants from the soil particles. The system was used to treat the SARM (3% gravel, 56% sand, 28% silt and 12% clay) that had been spiked with low and high concentrations of the contaminants shown in Table 2.10. The water wash removed more than 99% of the volatiles from the fraction of soil greater than 250 um and 66-87% of the volatiles from the fraction finer than 250 um. Semi-volatile removal was higher than 93% for the coarse fraction (>2 mm) of the soil but was limited to 0-56% in the medium (250 um - 2 mm) and to 0-60% in the fine (<250 um) fraction.

The Biotrol Inc. application was a demonstration under the USEPA Site Program that took place at the MacGillis & Gibbs Superfund Site in New Brighton, Minnesota (USEPA, 1989b). A pilot-scale soil washing unit with a treatment rate of 0.2-0.5 tonne/hour was used in the demonstration. Soils with low levels of PCP (300 ppm) were treated for two days and soils having high levels of PCP (1000 ppm) were treated for seven days. The process water was treated using a bioreactor and recycled to the system. No further information on the performance of this application was available.

iv) Need for Additional Research

Soil classification and washing technologies using water are extremely well developed in Europe. However, there is a need to adapt or transfer that technology to Canada and the United States. Research efforts should be directed

towards the reduction of the amount of residual sludge produced by the process. The use of chemicals in the water will be addressed in the following subsection.

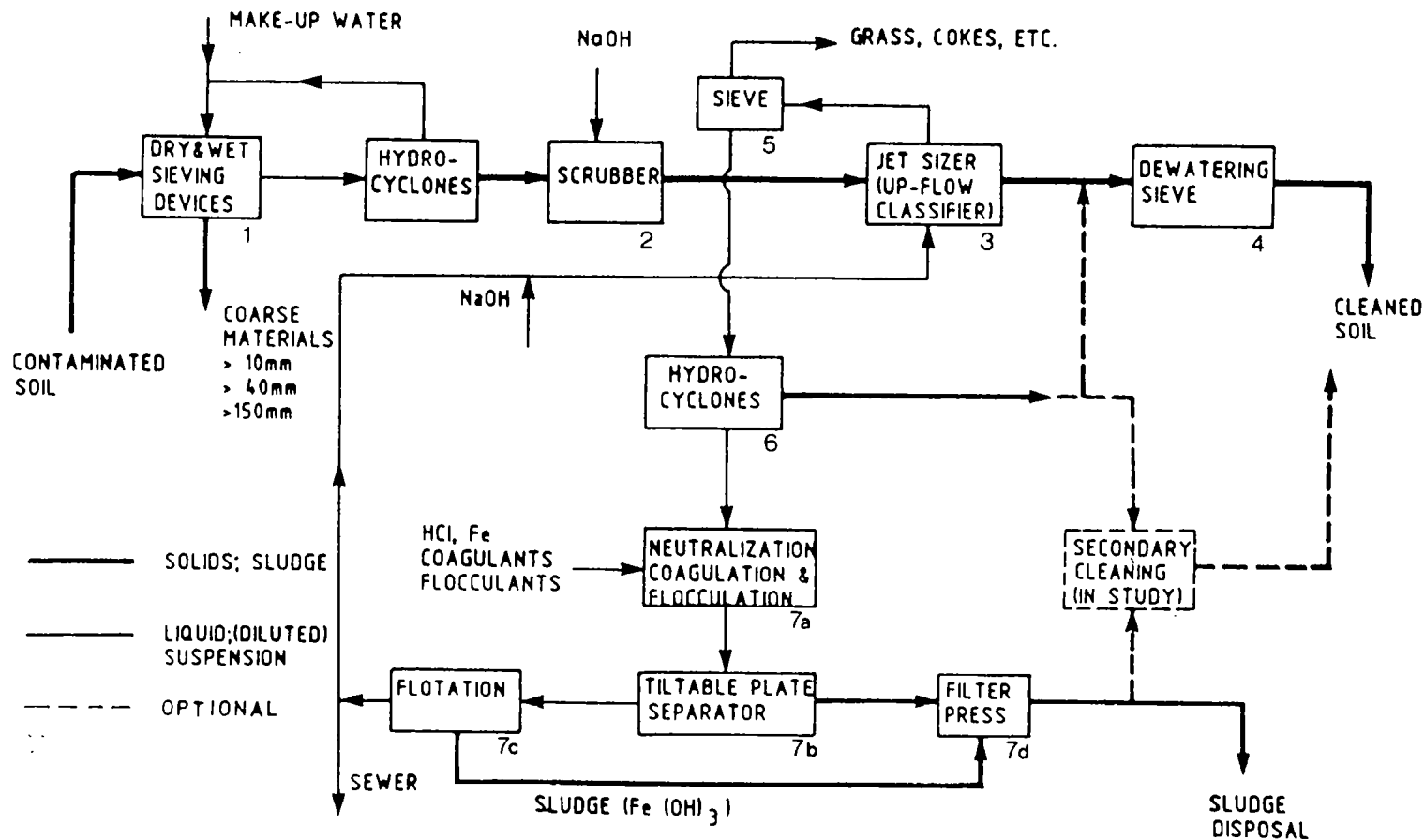
2.2.2.2 Soil Washing with Acids/Bases

i) Process Description

Soil washing with water is most effective for soluble compounds (volatile organics) and for easily dispersed compounds such as oil. However, chemicals added to the wash water may improve the efficiency of the process (Assink, 1986). Acids such as HCl, H₂SO₄ and HNO₃ are added to water to dissolve inorganic contaminants, especially heavy metals. Since this report deals with organic contaminants, this process will not be discussed in greater detail. Bases such as NaOH and Na₂CO₃ are used to dissolve or disperse contaminants in the washing fluid and more specifically to disperse clay and humus (organic matter) which contain a large quantity of organic contaminants.

A typical scheme of a soil washing process using water and bases is that of the company HWZ from the Netherlands as shown in Figure 2.16 and described by Assink (1986) as follows (numbers refer to the figure):

- 1) The coarse materials (>10 mm) are separated.
- 2) Water, NaOH and soil are mixed intensively to disperse all soil particles and to physically remove contaminants.
- 3) The soil is washed with the water-based fluid in a jet-sizer which rejects the sand particles larger than 100 μ m.
- 4) The clean soil is dewatered.
- 5) The low-density (grass, coke) materials are removed by sieving.
- 6) The silts (40-100 μ m) are separated by hydrocyclones.
- 7) The remaining water is cleaned by pH adjustment, coagulation, flocculation, sludge separation, iron removal and final pH adjustment. The water is recirculated.



Advantages of soil washing using bases include:

- the process can potentially improve organic recovery
- the demand for chemicals is moderate.

Disadvantages of this process include:

- the amount of residual sludge may be significant because of the removal of the fine particles and humus from the soil.
- the method has some difficulty treating soils contaminated with PAH's and oily material.

The treatment rate is on the order of 20 tonnes/hour (Nunno et al., 1988). Treatment costs are in the range of \$70-\$105 per tonne but are a function of the quantity of fine particles, chemicals necessary and nature of the contaminated soil. Capital costs are between \$2.5 and \$4 million.

The system may be fixed or mobile. The HWZ system was built to be mobile but it has become a fixed plant located in Amsterdam. The process would have to be isolated from cold temperatures to be applicable to Canadian conditions.

ii) Wastes Treated

The HWZ facility was developed to treat soil contaminated with cyanides but it may be applied to the treatment of volatile compounds, chlorinated hydrocarbons, aromatics, mineral oil and PAH's (Assink, 1986). The maximum amount of fine particles in the soil should not exceed 20% for the process to be economical.

iii) Demonstration/Applications

HWZ has applied its process commercially to treat contaminated soils since 1984. Results reported by Assink (1986) and by Nunno et al., (1988) show

that PAH's could be removed by 80-98% and chlorinated hydrocarbons could be decreased by more than 98%.

iv) Need for Additional Research

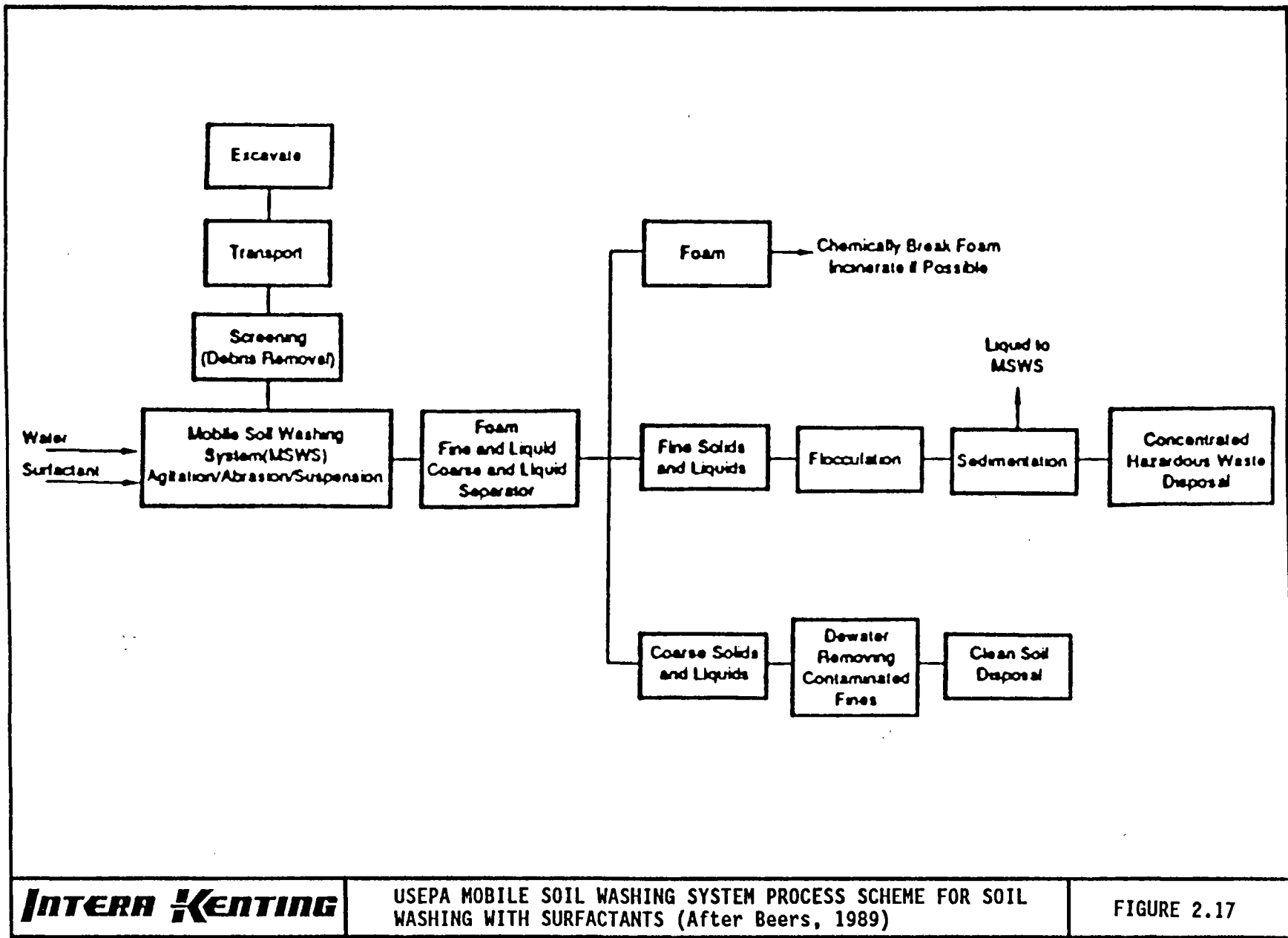
This process has been used commercially in the Netherlands to treat cyanides, chlorinated hydrocarbons and PAH's. Research effort should be directed to ways of improving the recovery of oil and other organics by the use of other chemical additives.

2.2.2.3 Aqueous Surfactants

Surfactants (or surface active agents) may enhance the recovery of some organic contaminants by facilitating the dispersion of oil (Assink, 1986) and other immiscible liquids. A typical process for a soil washing system using water with surfactants is shown in Figure 2.17. The process is the USEPA Mobile Soil Washing System (Beers, 1987) and includes:

- 1) Screening of the excavated soil;
- 2) Mixing and agitation of soil with water and surfactants;
- 3) Separation of foam, fine solids and liquid, and coarse solids and liquid;
- 4) Subsequent treatment (detoxification or incineration) of the foam;
- 5) Flocculation and sedimentation is applied to separate the fine solids from the water; the residual sludge is a hazardous waste and the water is recycled in the system;
- 6) Dewatering of the coarse solids is followed by disposal of the treated soil.

A variation to the process is the use of ultrasonic extraction which removes organic contaminants from a sand/silt slurry via high shear fluid action (Coles et al., 1989).



Advantages of using surfactants are:

- the contaminants are detached from the solid particles;
- the removal performance can be increased for organic contaminants from the fine particles;
- decontamination of the soil can be optimized with the proper choice and dosage of the surfactants.

Disadvantages of the treatment are:

- it may be more difficult to treat the process water because of the presence of the surfactant;
- the amount of surfactant required for sufficient cleaning may be prohibitive for the process to be economical.

The treatment rate of the EPA Mobile unit ranges between 2.3 and 3.8 m³/hour (Beers, 1987) or approximately 4-8 tonnes/hour. Treatment costs were not available for this pilot-scale study. The system is mobile and would have some restrictions for its use during Canadian winters.

ii) Wastes Treated

Surfactants have been used for a number of years by the petroleum industry to recover oil from the subsurface (Vigon et al., 1989). Surfactants have been investigated for the treatment of contaminated soil and aquifers by Ellis et al. (1985). They reported that aqueous surfactants are potentially useful for cleanup of hydrophobic and slightly hydrophilic organic contaminants in soil. They have used a mixture of nonionic surfactants to treat a crude oil distillate, PCB's and chlorophenol. The treated soil was a sand-sized material without clay and with a low organic content. Esposito et al. (1989) have also used aqueous surfactant washing to clean soils composed of 59% sand/gravel, 28% silt, 12% clay, and 3.2% organic carbon, contaminated with volatile and semi-volatile organics.

iii) Applications/Demonstrations

No full scale applications of aqueous surfactant soil washing have been found in the literature. However, several laboratory, bench-scale and pilot-scale studies are reported. The earliest identified demonstration of soil washing using surfactants to clean contaminated soil is a 1985 USEPA study as shown in Table 2.11. In this study (Ellis et al., 1985), a low clay and organic carbon content sand contaminated with an oil distillate, PCB's and chlorophenols was cleaned during bench-scale shaker tests and larger scale column tests with an aqueous solution containing two nonionic surfactants. Mass recoveries were 93% for the oil distillate hydrocarbons, 92% for the PCB's but incapable of being determined for the chlorophenols because of their high solubility.

A laboratory study was conducted in 1986 by the University of Cincinnati and was designed to look at the effectiveness of fourteen surfactants (4 anionic, 8 nonionic, 1 blend and 1 cationic) for cleaning soils contaminated with chlorinated hydrocarbons and pesticides (Table 2.11). This study revealed that 27-33% of the total organic halogens (TOX) were removed with a 0.5% solution of any aqueous surfactant and 86-100% of the TOX were removed using a 2% solution. Further details are given in Case Study 11 in Appendix B.

Another demonstration is the bench-scale study performed by PEI Associates using a synthetic soil (SARM) spiked with contaminants as shown in Table 2.11. This study showed that 0.5% surfactant (TIDE) solution could remove 93-99.9% of volatile organics from all the size fractions of the soil. It also removed more than 90% of the semi-volatile organics in the coarse fraction (>2 mm) of the soil. However, the surfactant solution had less success in removing semi-volatile organics from the finer soil fractions (<2 mm). More details are available in Case Study 12 included in Appendix B.

Table 2.11 Summary of Aqueous Surfactant Soil Washing Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Final Concentration (ppm)	Initial Quantity Contaminated Soil (tonnes)	Reference
1985	---	USEPA	---	Oil Distillate PCB's Di-, Tri-, Penta-chlorophenols	1000 100 30	70 8 --	Laboratory Study	Ellis et al., (1985)
1986	Chem-dyne, Hamilton, Ohio	USEPA	University of Cincinnati	Chlorinated Hydrocarbons	216-266	0-30	Laboratory Study	Clement et al., (1986) (see Case Study 11)
1987	---	USEPA	PEI Associates	Volatile Organics Semi-volatile Organics Metals	770-18666 325-7573 1047-60879	<1-1306 33-760 --	Bench-scale Study	Esposito et al. (1989) (see Case Study 12)
1988	Lakehurst, New Jersey	USEPA	Roy F. Weston	Oil & Grease	35500-42000	350-400	Pilot-scale Study	Nash (1989)
--	---	---	MTARRI & Heidemij	Oil, Benzene & Toluene PAH's Mineral Oils Chlorinated Hydrocarbons	3000-18000 19 >1000 5.3-276	3-360 0.2 -- --	Laboratory & Pilot-scale Studies	Trost (1987) Nunno et al., (1989)
1989	---	USEPA	Foster Wheeler Enviresponse Inc.	Anthracene PCP Dioctyl-Phthalate	4520 & 1329 38 & 625 320 & 3264	1582 & 465 <.38 & <6.25 <3.2 & <32.6	Laboratory Study	Coles et al., (1989)
---	---	USEPA	---	Anthracene Biphenyl	---	---	---	Vigon & Rubin (1989)

A pilot-scale study was carried out by Roy F. Weston for the USEPA in 1988. This study involved the cleaning of oil and grease contaminated soil using the Pilot Drum Screen Washer capable of treating 50 kg/hr of material. Soils from a military site in Lakehurst, New Jersey were treated using a surfactant/solvent mixture called Citrikleen. Oil and grease concentrations in the soil decreased from 35,500 - 42,000 ppm to 350 - 400 ppm after the treatment.

Commercial firms are also involved in laboratory and pilot-scale studies of soil washing with surfactants. Heidemij from Holland and MTARRI from the United States have developed a process combining froth flotation and aqueous surfactant soil washing. Heidemij has treated soils containing contaminants shown in Table 2.11 with variable success (Nunno et al., 1988a). MTARRI literature gives a removal of 99.9% for volatiles, 98% for semi-volatiles and 99% for creosote (Trost, 1987).

A study of the cleaning of soil with surfactants and ultrasonic extraction was also undertaken by Foster Wheeler in 1989. A de-clayed soil (>74 um) and its clay fraction (<74 um) containing anthracene, PCP and phthalate at levels shown in Table 2.11 were treated in a laboratory. The results reported by Coles et al. (1989) show that more than 98.7% of the three contaminants were removed from the de-clayed soil and >99% of the phthalate and PCP and 65% of the anthracene was removed from the clayey fraction by the process. Finally, Vigon and Rubin (1989) have tested a series of nonionic surfactants on synthetic soils containing two contaminants (anthracene and biphenyl). At dosages of 1% by weight, up to 90% of contaminant removal was achieved by washing and the soil partitioning coefficients of biphenyl and anthracene were reduced by 1 to 3 orders of magnitude.

A bench-scale demonstration was carried out by EEC Inc. of Philadelphia using various solutions of surfactants, acids and chelating agents to remove PCB's, volatile organics, PAH's and metals from silty fill material containing peat. Details are provided in Case Study 13 in Appendix B.

iv) Need for Additional Research

Many laboratory and pilot-scale studies have been performed using aqueous surfactant technology. Additional research may be directed to identify what contaminants and surfactants are compatible for soil washing and to realize large scale demonstrations of the process.

2.2.2.4 Chelating Agents

Chelating agents (also called complexing agents) such as EDTA, citric acid or ammonium acetate can be used in water solutions to wash contaminated soils. The process is similar to the water soil washing process shown in Figure 2.14 and described in Section 2.2.2. The main purpose of a chelating agent is to remove the available fraction of inorganic (metal) contaminants (Assink, 1986) from soil. Consequently this process will not be described in more detail.

2.2.2.5 Steam Stripping

i) Process Description

Steam stripping is a process that is similar to low temperature thermal volatilization except that steam is used in place of air in the process. The loaded steam can be condensed leading to separation and removal of the organic contaminants (Assink, 1988).

ii) Wastes Treated

The process can be applied to cleanup soil that is contaminated with compounds that are volatile at temperatures up to 100°C (Assink, 1986). The contaminants may be water soluble or insoluble. The volatility of the contaminant must be sufficiently high and there must be sufficient contact time between the contaminated soil and the steam.

Types of contaminants that can be treated include immiscible volatile aromatics such as BTEX, immiscible chlorinated hydrocarbons such as trichloroethylene, perchloroethylene and chlorobenzenes and water immiscible hydrocarbons. Soils amenable to treatment should contain a large amount of sand.

iii) Applications/Demonstrations

No application or demonstration of steam stripping to excavated contaminated soil has been found in the literature, but the technique is being used as an in-situ technique.

iv) Additional Research

Steam stripping as applied to soil clean-up is still in the developmental stage. The feasibility of steam stripping should be evaluated compared to techniques such as low temperature air stripping (Low Temperature Thermal Volatilization - see Section 2.1.2.2) which is commercially available and treats similar contaminants.

2.2.3 Flotation

Froth flotation has been utilized by the mining industry for over 75 years and is the major process for the separation of base metals from gangue materials. The technique has recently been used in the clean up of soils contaminated with metals and organic compounds.

The principles of froth flotation are well known and are based on particle surface chemistry phenomena and electric double layer theory. Contaminated material is screened and slurried and separation is obtained by the adhesion of contaminated particles onto air bubbles rising through the slurry. The process is further enhanced by the addition of surface active agents called frothers which are heteropolar in nature and react at the air/water interface to facilitate contaminant particle adsorption onto the air bubbles. In the case of the AgloflotationTM process, coal fines are used as carriers which adsorb

contaminant particles and are themselves adsorbed onto the air bubbles. The air bubbles with adsorbed contaminants are removed as a foam. Froth flotation has advantages of low energy requirements and large treatment capacity. It is capable of treating oils, halogenated organics, cyanide and heavy metals.

2.2.3.1 AgloflotationTM Process

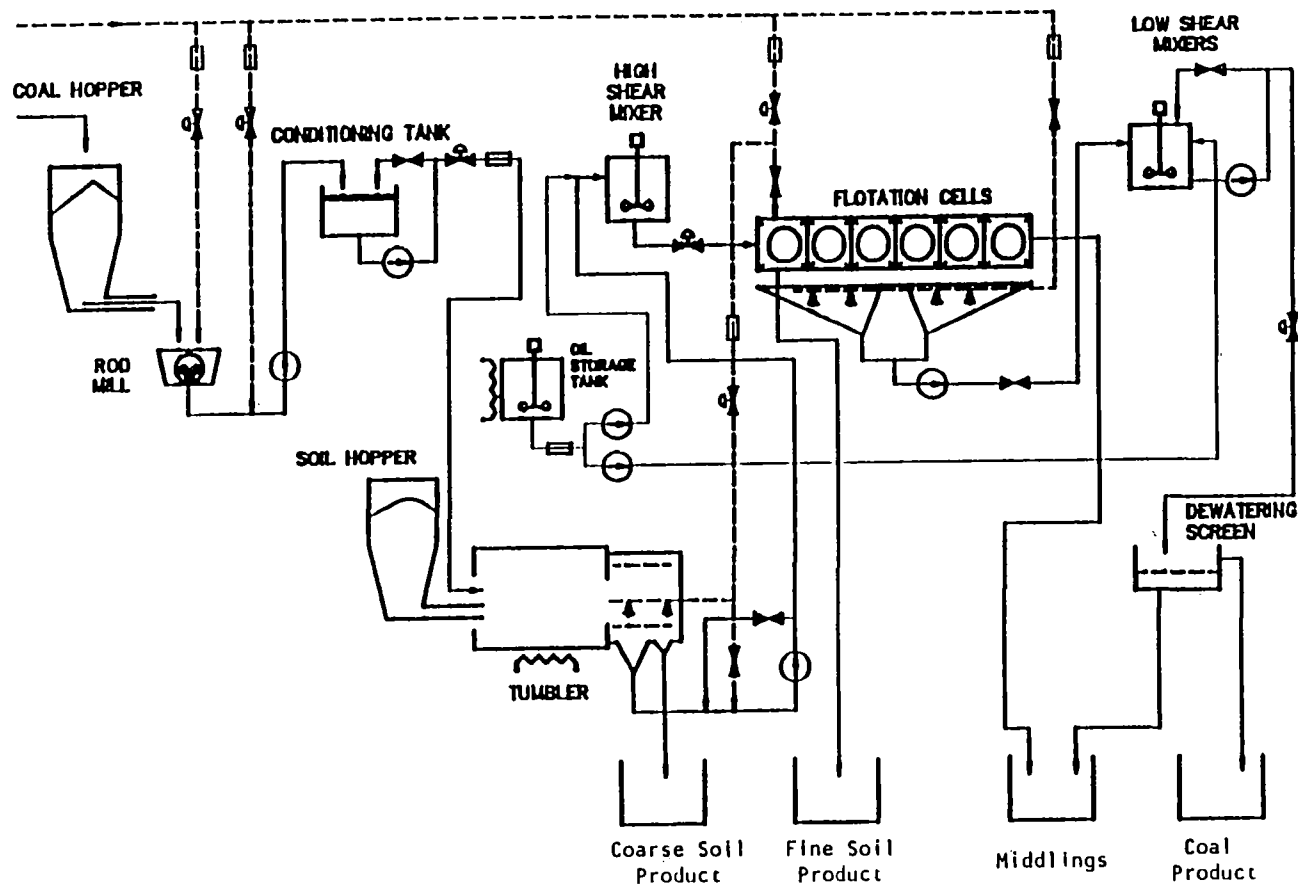
i) Process Description

The AgloflotationTM process can be described in terms of the four main process subsystems which include:

- coal particle and waste material preparation and contact
- waste stream separation into cleaned soil, water and coal/contaminant components
- coal/contaminant agglomeration and dewatering
- dewatering of cleaned solids

Coal is fed to a milling unit where it is milled to a fine particle size and mixed with water. The coal slurry is fed into a tumbler unit and mixed with contaminated soil feed for a period of up to 20 minutes at temperatures ranging from 20-85°C. The ratio of coal mass to the mass of organic contaminants is kept at between 3 and 5. The material is then screened. The greater than 1mm fraction is directed to a grinder and the less than 1mm fraction is sent to a first stage froth flotation unit where the coal/contaminant fraction is separated from the heavier tailings.

The coarse material which is sent to the grinder is separated into coarse clean reject and the less than 1mm material, which is combined with the tailings from the first stage froth flotation unit, undergoes reprocessing and separation in a second stage froth flotation unit. Tailings from the second stage separator are removed as clean soil. The coal/contaminant agglomerates produced during froth flotation are combined as a final combustible product. A flowsheet of the simplified process is provided in Figure 2.18.



INTERA KENTING

AGLOFLOTATION™.M. CONTINUOUS PROCESS FLOW DIAGRAM
(Alberta Research Council 1990)

Figure 2.18

A material mass balance for bench-scale testing of the Agloflotation™ process is given in Alberta Research Council (1990) and verified for the 250 kg/h continuous pilot plant. Total feed recovery was 98.45% of total feed input.

The process has the advantage that it can treat large quantities of contaminated material. Design for a 90 tonne/day unit is planned. The process also produces a combustible product that can offset energy requirements on site. Disadvantages of the process are the requirement for coal, and long distance hauling may be necessary if a local coal source is not available. The process is also less effective for coarse soils with a particle size of >1.2mm (Ignasiak et al., 1989).

Treatment costs for a six tonne/hour mobile unit are estimated at \$15 - 49/tonne depending on availability of coal sources and utilization of the agglomerates (Ignasiak et al., 1989). Alberta Research Council (1990) estimates unit processing costs for a 100 tonne per day demonstration plant at \$45/tonne. The process unit requires two process operators, a loader operator and a foreman. Mobilization and set-up times were not given.

ii) Waste Treated

The process was developed to clean up soil contaminated with coal tar wastes and heavy oils from the petroleum industry. The process would appear to work best in soil free of coke, chars and slags which tend to reduce the extraction efficiency of the process.

iii) Applications/Demonstrations

A pilot-scale six tonne/day continuous feed facility is operating at the Devon Coal Research Centre in Devon, Alberta. Recent testing on a tank bottom sludge contaminated with Cold Lake heavy oil showed that the content of dichloromethane extractable material, following treatment, was reduced to below 0.3 wt% (Ignasiak et al., 1989).

Treatment of contaminated soils from manufactured gas plants where coal tar content varied from 1-66 wt% indicated coal tar removal efficiencies of 94.5% to 100% for three samples (Ignasiak et al., 1989).

iv) Need for Additional Research

Certain soil mineral materials, though not identified, were reported to cause problems with the coal/contaminant separation and recovery process (Pawlak et al., undated). Further investigation of waste feed types that can be handled by the process should be conducted. Construction and testing of a full-scale mobile commercial unit is proposed.

2.2.3.2 Mosmans MethodTM Process

i) Process Description

The Mosmans MethodTM process was developed by Mosmans Mineraltechniek BV of Oss in The Netherlands and has been used for the treatment of contaminated soil since 1983. While the process is based on well known principles of froth flotation considerable bench and pilot-scale testing are required for each site to ensure appropriate plant design including:

- characterization of the contaminants
- froth flotation testing
- design of separation process
- impact of contaminants on water chemistry
- selection of appropriate reactants

The process produces three waste streams:

- a concentrated contaminant
- cleaned soil
- wastewater which is treated and recycled or discharged

Mosmans Mineraltechniek operates a fixed pilot plant for undertaking treatability tests which has a capacity of 13.5 tonnes/hour and a mobile plant which has a capacity of 0.5 tonne/hour. A disadvantage of the method is the generation of large quantities of contaminated sludge (Levin et al., 1985).

ii) Waste Treated

The vendor reports field scale treatment of soils contaminated with oil, monocyclic aromatic hydrocarbons (MAH's), organochlorine compounds, wax, paint residues, pesticides, cyanides, heavy metals, and gas work contaminants including PAH's, but no information regarding initial concentrations or cleanup efficiency are provided.

iii) Applications/Demonstrations

The vendor cites the following field-scale applications:

- 7200 tonnes of soil contaminated with oil and wax from an automobile foundry
- 27,000 tonnes/year of paint residues
- 1800 tonnes of soil contaminated with PAH's and complex cyanides at gas-works in Roosendaal
- contaminated soil from a gas-works in the Hague
- soil contaminated with pesticides and mercury from an industrial plant in Basel, Switzerland

No specific case study information was provided.

iv) Need for Additional Research

Pilot-scale and field scale data must be evaluated before research needs can be identified. Research is being conducted into the use of this process on PCB-contaminated soils.

2.3 CHEMICAL TREATMENT

Chemical treatment technologies include both non-destructive and destructive processes, and for the purposes of this report are divided into two main categories:

- solvent extraction
- substitution and reduction-oxidation

Solvent extraction using either non-critical fluid solvents or critical fluid solvents are non-destructive technologies which serve to reduce waste volumes by solubilizing the waste in a solvent. Solvent extraction is the most widely applied chemical treatment technology and is commercially available through a number of proprietary processes.

Substitution and reduction-oxidation technologies involve the reaction of reagents with the waste or reduction/oxidation reactions to cause a change in the chemical structure of the waste leading to the production of a less toxic or non-toxic transformation product. Substitution and reduction-oxidation technologies are destructive because they lead to a change in the chemical structure of the waste material.

2.3.1 Solvent Extraction Using Non-Critical Solvents

Solvent extraction is not a destructive technology, but like soil washing, is a technique which separates the waste feed and reduces the overall volume of waste requiring treatment. Treatment produces three process streams; a cleaned solids stream which may or may not contain adsorbed heavy metals; a waste water stream, and a contaminated residue stream from which contaminants may be recovered for reuse or disposed of by some destructive or immobilization technology.

Solvent extraction in this report is differentiated from soil washing because it utilizes organic solvents or critical fluids to remove hydrophobic organic compounds from soil, whereas soil washing uses water with or without

water soluble additives. Recent reviews of solvent extraction techniques in the Netherlands and the United States include Assink (1986, 1987), Raghavan et al., (1989) and Hall et al., (1989) (unpublished). As well, the U.S. EPA is preparing a draft Treatment Technology Bulletin for solvent extraction, as yet unpublished, which will provide an overview of the technology and case studies.

To optimize extraction of organic contaminants from soil, the solvent should be selected on the basis of the chemical structure of the contaminant, the degree of contamination, and the physical and chemical characteristics of the soil. The solvent should be stable and should have the appropriate density, viscosity and interfacial tension characteristics. The solvent should have a very high solubility for the contaminant and there should be sufficient difference between the boiling points of the solvent and contaminant to promote post-treatment separation (Raghavan et al., 1989). The efficacy of the solvent extraction technique is dependent on a number of factors including:

- matrix type and grain size
- matrix water content
- contaminant characteristics and concentration
- ratio of solvent to matrix
- number of contact cycles

Sanexan International (1989)

Solvent extraction techniques have been utilized as part of industrial process streams in the food, tobacco, pharmaceutical, metallurgical and resource recovery industries for years, but their application as a fixed or mobile technology for the treatment of contaminated soils is still being developed, although commercial units are available.

Evaluation of solvent extraction systems is based on several performance criteria including:

- separation efficiency
- extraction efficiency (Sudell 1988)
- material mass balance

Separation efficiency is a measure of how well the process separates the feedstock into its component process streams and is calculated as:

$$\left[\begin{array}{c} \text{fraction of desired} \\ \text{product (i.e. 1.0)} \end{array} \right] - \left[\begin{array}{c} \text{fraction of undesired} \\ \text{product} \end{array} \right] \times 100\%$$

Extraction efficiency measures, as a percent, how well the contaminants are partitioned to the various process streams (eg. organic contaminants to the organic stream, heavy metals to the solid stream) and is calculated as:

$$\frac{\text{amount of contaminant in process stream}}{\text{amount of contaminant in feed}} \times 100\%$$

A material mass balance of the feed stream and individual contaminants is required to properly assess the system efficiencies.

Specific treatment processes which have been applied to the treatment of contaminated soil, and which are discussed more fully in this report include the following:

- (i) Basic Extractive Sludge Treatment (B.E.S.T.TM) Process
- (ii) ExtraksoTM Extraction Process
- (iii) Low Energy Extraction Process (LEEP)
- (iv) BP Oil Solvent Extraction Process
- (v) Accurex Solvent Extraction Process
- (vi) Soilex Extraction Process
- (vii) Environment Canada's EETD Solvent Extraction Project

2.3.1.1 Basic Extractive Sludge Treatment (B.E.S.T.^R) Process

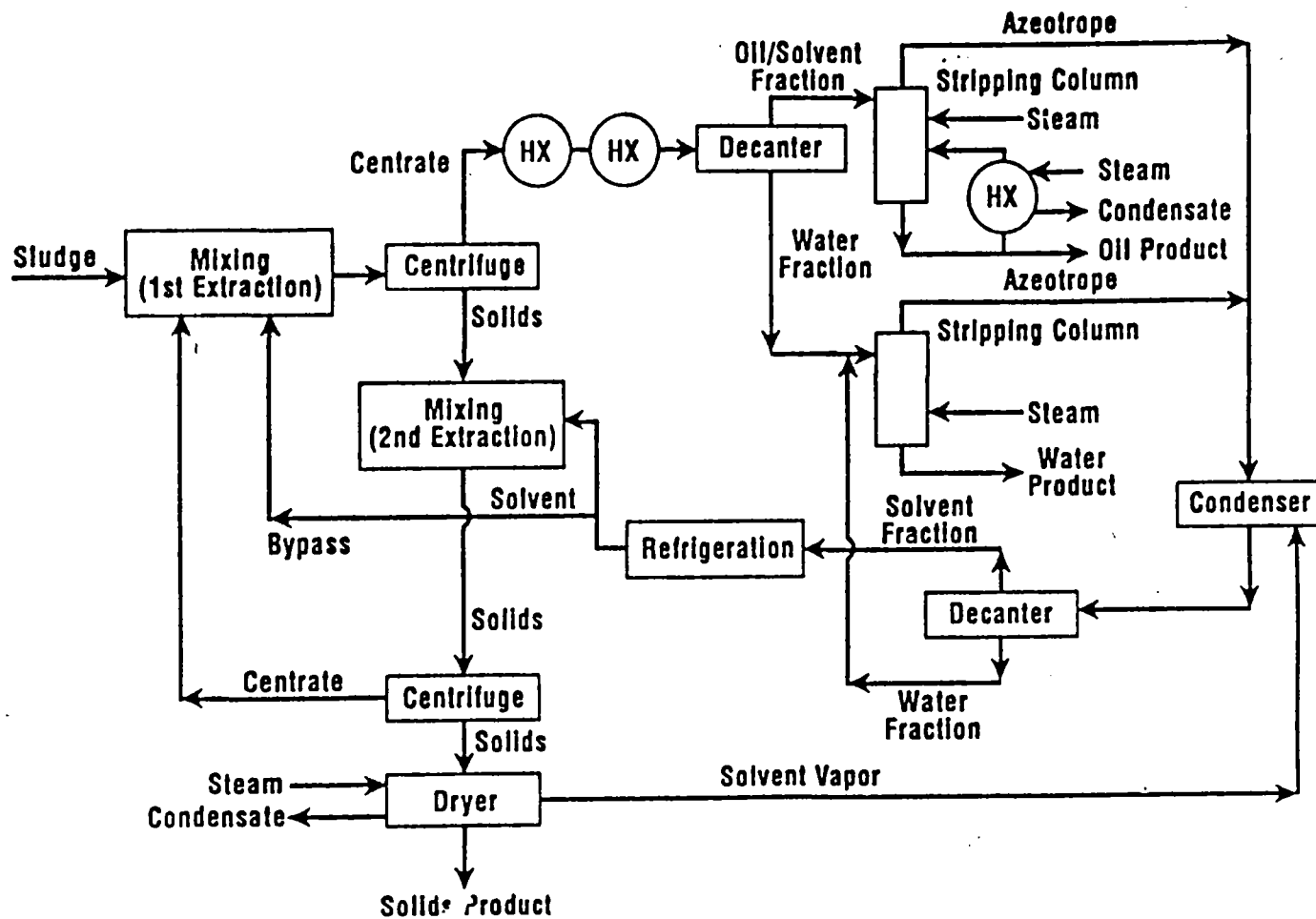
i) Process Description

The B.E.S.T.^R process technology was invented by Boeing Company and has been further developed under patent by Resources Conservation Company (RCC) of Bellevue, Washington (Hall et al., 1989).

The B.E.S.T.^R process utilizes the inverse immiscibility properties of aliphatic amine solvents, particularly triethylamine (TEA), a flammable solvent which is soluble in water at temperatures below 18°C but becomes insoluble at temperatures exceeding 18°C (Raghavan et al., 1989). The solvent functions to break oil/water emulsions and release bonded water. The process is particularly well suited to treat fine grained feed including sludges and produces three product streams; an oily waste stream, a water stream and a solids stream. The process operates at ambient temperatures and pressures, and under closed system conditions thereby preventing emissions of volatiles to the atmosphere. The treatment configuration is shown in Figure 2.19.

Waste feed is initially screened for size through a 6.4 mm hammermill, and treated to ensure an alkaline pH. The waste feed containing organic and water phases is fed to a reactor and mixed with refrigerated TEA to form a homogeneous single-phase slurry. Solids are readily removed by filtration or centrifugation as they are no longer bound by the emulsion. The liquid phase is then heated to above the solubility point (greater than 18°C), causing the water fraction to separate from the organic phase containing TEA. The water fraction may increase in volume due to steam condensation in the system (Sudell 1988). The lighter solvent/organic phase is decanted and TEA is recovered by flash evaporation and steam stripping (Hall et al., 1989). The water phase is redirected to a steam stripper to remove residual TEA before final discharge.

Residence time within the system for oil and water fractions is approximately 2 hours and approximately 30 minutes for solids. TEA recovered from the water phase and the organic phase is recycled back into the process stream. Organic phase material may be recovered as a by-product and reused elsewhere, or destroyed. The residual fine grained solids may be returned to the process stream for additional treatment and finally separated for on site disposal as cleaned material or destroyed if contaminated. Heavy metals in the contaminated feed will precipitate as hydrated oxides onto the solid fraction.



Contaminant feed constraints include particle size and composition. Large particle sizes must be crushed to appropriate processing size. Detergents and emulsifiers in the contaminant feed can reduce separation efficiency, and low-pH feed must be neutralized to prevent loss of TEA (Sudell 1988). Post treatment of product streams may be required prior to final discharge or disposal.

ii) Waste Treated

B.E.S.T.^R technology is capable of treating wastes with variable compositions of oil, water and solids, and has been used to treat municipal wastewater sludge, petroleum refinery waste, PCB contaminated soils and sediments and oily hazardous wastes. Removal efficiencies of up to 98% for organic compounds are reported (Hall et al., 1989).

iii) Applications/Demonstrations

RCC has undertaken several bench-scale tests on hazardous sludges from oil refineries and PCB contaminated sediments.

RCC has a trailer-mounted mobile unit with a processing capacity of 0.78 m³/hour. A 90 tonne unit was used to demonstrate the technology at the General Refining Superfund site near Savannah, Georgia. At this site, the full scale treatment process performed better than laboratory bench-scale testing had predicted (Sudell 1988). Additional information is provided in Case Study 14 in Appendix B.

At the Arrowhead Refinery Superfund site in Hermantown Minnesota, soil consisting of gravelly sands, silt and fill, sludges and peat wastes contaminated with lead, PAH's, volatile organics, and low levels of PCB's was bench tested and mass balance of the various process streams was carried out. While no evaluation of organic extraction efficiency was reported, there was a significant loss from the water process stream (Sandrin and Fleissner, 1990). CH₂M Hill (1989) reports treatment costs of \$65-132/tonne.

iv) Need for Additional Research

Further evaluation of waste feed compositions that affect system performance is required.

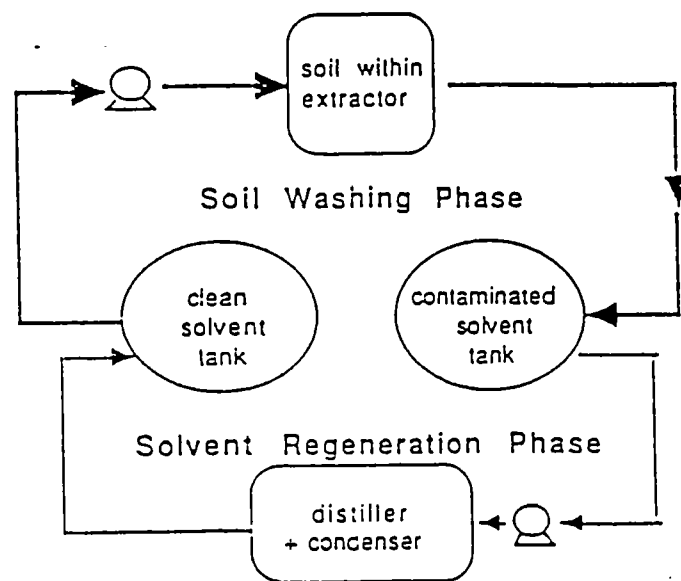
2.3.1.2 ExtraksoTM Extraction Process

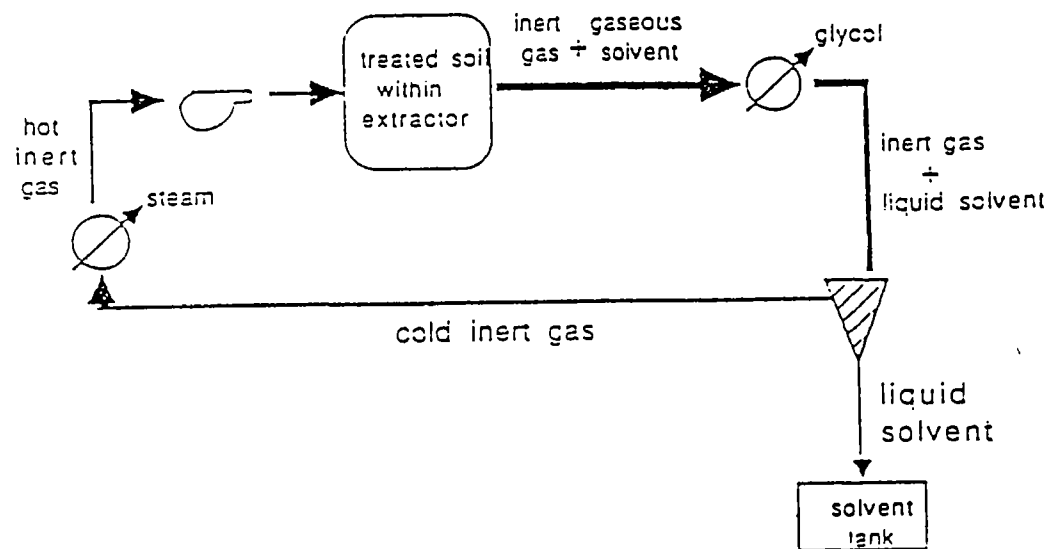
i) Process Description

The ExtraksoTM process was originally developed in Canada to treat PCB contaminated soil, but the process has been expanded to treat a wide range of organic contaminants.

ExtraksoTM is a batch process which utilizes a proprietary solvent, and operates as a closed system in an extraction mode and a drying mode. During extraction, contaminated soil, sediment or sludge is loaded into a slowly rotating extractor and clean solvent is continuously pumped into and withdrawn from the extractor. Contaminants are removed from the matrix by desorption/dissolution processes and are carried by the solvent to a holding tank where the solvent is regenerated and separated from the contaminants using distillation and condensation, leaving a contaminated residue and a cleaned solvent. The cleaned solvent is transferred to a solvent tank for recycling and the contaminated residue is removed for final disposal or recycling. The extraction mode is illustrated in Figure 2.20(a).

In the drying mode, the treated soil within the reactor is subjected to a stream of hot inert gas which volatilizes and strips any residual solvent from the treated soil. The inert gas and solvent vapour are cooled and the solvent is condensed into a clean solvent tank for recycling, while the cooled inert gas is heated and recycled into the extractor until the treated soil is dry. The treated soil is then removed from the extractor for on-site emplacement. Figure 2.20(b) illustrates the drying or stripping mode.





For the treatment of non-volatile organics the process is run using both extraction and stripping modes. However during the treatment of volatile organics, the process may be run in the stripping mode only.

ii) Waste Treated

The Extraksol™ process has been subject to testing by the developer on a wide range of solid matrix types and contaminants.

Treated matrices include coarse and fine grained soils (including clay bearing soils), Fuller's earth, oily sludge, and activated carbon. Contaminants which have been extracted with greater than 80-90% efficiency include PCB's, oil and grease, PAH's, and PCP (Pacquin and Mourato, undated). Reduced extraction efficiencies of 50-60% were obtained for PCP and oil and grease on contaminated gravels where individual gravel fragments had some matrix porosity. Extraction efficiencies with these porous matrix materials could perhaps be improved by allowing a soaking period of the solvent with the contaminated materials prior to active solvent circulation and mixing (Pacquin and Mourato, undated).

iii) Applications/Demonstrations

A mobile unit requiring two operators, three days set up time, and capable of processing 0.9-1.4 tonnes/hour of contaminated soil has been used to provide full-scale demonstrations for the above listed contaminants and matrices. These demonstrations have been carried out by the vendor. Further information on this process is described in Case Study 15 in Appendix B.

iv) Need for Additional Research

A third party critical evaluation of the process is required as well as further evaluation of treatability of waste feed types. Construction of a larger mobile unit capable of processing 5-7 tonnes/hour is planned by the vendor.

2.3.1.3 Low Energy Extraction Process (LEEP)

i) Process Description

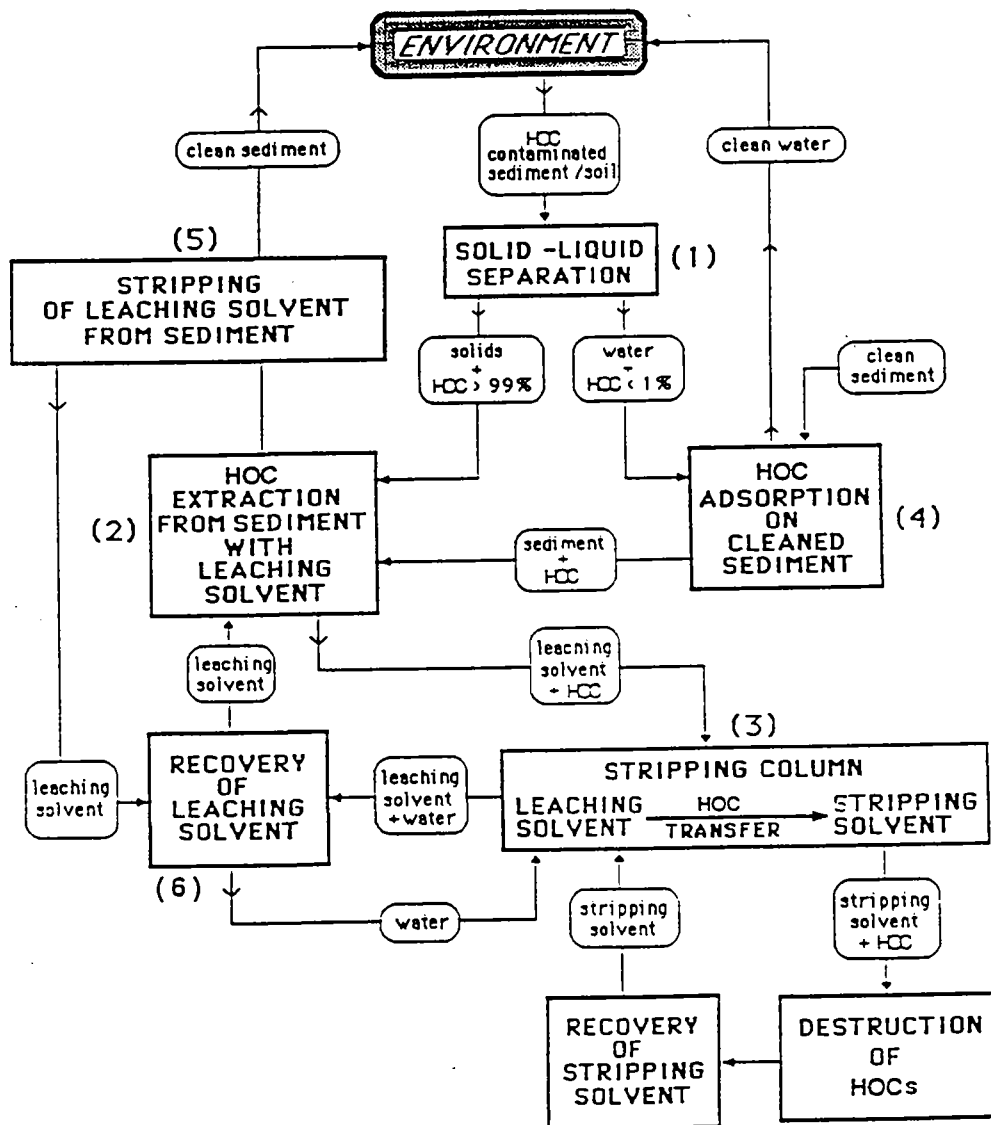
LEEP technology was developed to remove PCB's and organic compounds from contaminated soil. Water miscible contaminants are extracted using acetone while kerosene is used to extract contaminants which are immiscible with water.

The technology consists of six operations: solid-liquid separation, extraction, distillation, adsorption, air stripping, and liquid-liquid extraction (Hall et al., 1989). A flow diagram of the LEEP technology process showing the six process operations is given in Figure 2.21.

Process feed is first separated into liquid and solid fractions by filtration or centrifugation. The solid component must be sized to less than 1.25 cm diameter.

The solid component is transferred to a counter current paddle washer where it is leached with acetone to produce two streams; (i) an acetone/water mixture containing organic contaminants and (ii) an uncontaminated soil/acetone slurry. The uncontaminated slurry is discharged to the environment following solvent recovery by stream stripping.

The acetone/water mixture containing organic contaminants is fed to a counter current centrifugal liquid-liquid extractor where it is contacted with kerosene and potassium sulphate, which allows the organic contaminants to partition into the kerosene. Two product streams are discharged; (i) contaminated kerosene and (ii) acetone/water mixture which contains trace amounts of organic contaminants. The contaminated kerosene is disposed using destructive technology, while the acetone/water stream is distilled to recover acetone for recycling, leaving a contaminated water which is redirected to the liquid-liquid extractor.



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Revisions	Date

LOW ENERGY EXTRACTION PROCESS (LEEP)
(Applied Remediation Technology, Inc. undated)

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Figure 2.21

Water separated during step 1 is passed through an adsorption bed consisting of cleaned soil, to remove trace levels of organic contaminants. The decontaminated water is released to the environment, while the adsorption bed material is circulated back to the raw waste stream. The system is limited by particle size requiring a waste stream particle size of <1.25 cm. The system is not yet available commercially for full field-scale application.

System capacity is restricted to bench-scale testing. Costs are not available at this time.

ii) Waste Treated

LEEP technology has been used to treat PCB contaminated sediments and volatile and semi-volatile priority pollutants in refinery sludges. The process also treats metals.

iii) Applications/Demonstrations

LEEP technology is patented and is being developed and commercialized by Remediation Technology (REMTECH) Inc. A skid mounted pilot-scale unit is currently under construction. Bench-scale studies of PCB contaminated sediment from Waukegan Harbour in Illinois have been completed along with bench-scale studies of refinery sludge from two refineries, but results were not available for this study.

iv) Need for Additional Research

Evaluation of pilot-scale and full-scale treatment required. Development of mobile unit to be completed. Further evaluation of treatability of different waste feeds and contaminant types required.

2.3.1.4 BP Oil Solvent Extraction Process

i) Process Description

The BP Oil Solvent Extraction Process is an advancement of a solvent extraction process developed by Standard Oil of Ohio for the treatment of oil refinery waste sludges. This proprietary technology consists of three operations: solid-liquid separation, solvent extraction, and chemical fixation (Hall et al., 1989). A flow diagram of the treatment process is shown in Figure 2.22.

The waste sludge is initially filtered using a filtration aid and a recessed plate filter. The solid fraction is sent to the extraction unit, while the liquid fraction, consisting of oil and water is separated. The soil is recovered and the water is re-directed elsewhere for further treatment.

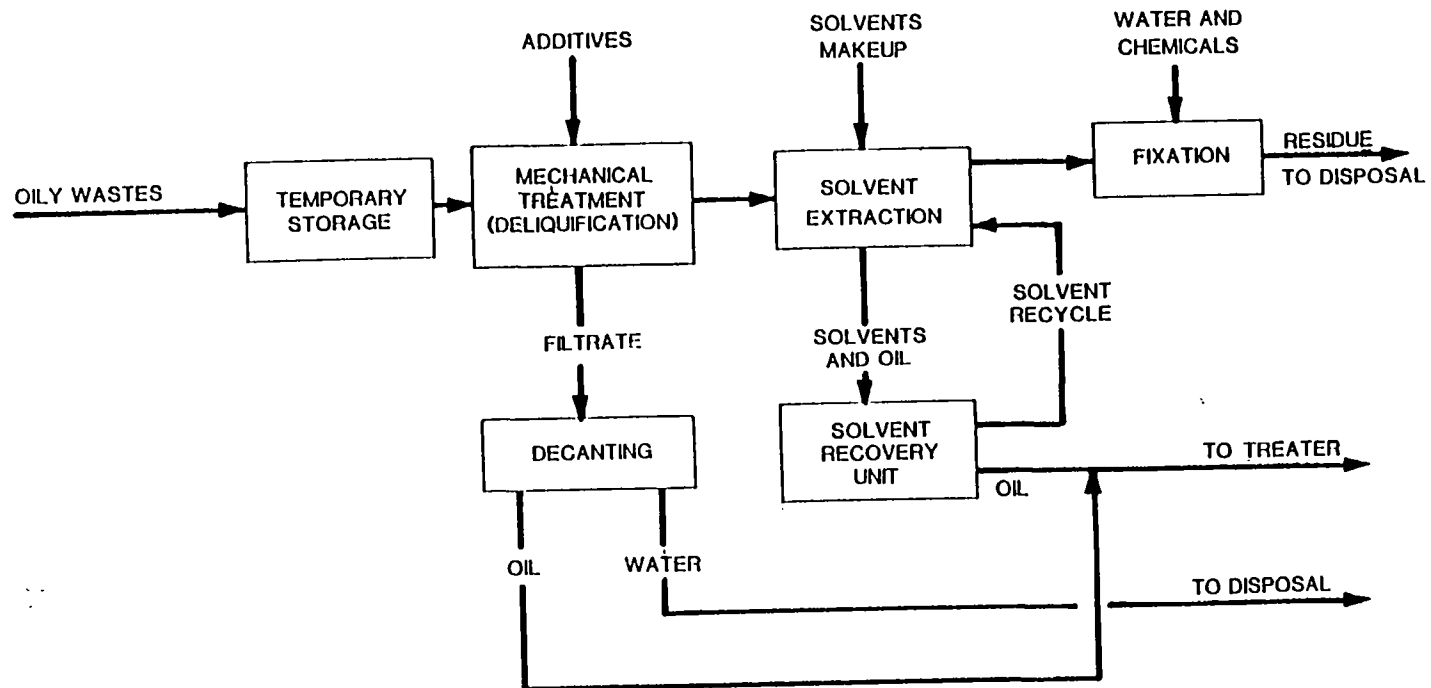
The extraction unit operates in a batch rather than continuous operation, in single or in multiple cycles. Single cycles are used to remove lighter fraction aromatic hydrocarbons. Solvents are recycled.

The extraction step produces two process streams; (i) cleaned "coarse grained" solids which are washed from the extractor using a water stream and (ii) a contaminated sludge which is dewatered in a filter press and fixed using additives that induce pozzolanic reactions (Hall et al., 1989).

The process recovers petroleum product, and produces no air emissions. The capacity of a proposed full-scale commercial unit is reported to be 13.5 tonnes/day producing 6 tonnes of recycled petroleum feedstock. Costs are competitive with incineration but details were not reported.

ii) Waste Treated

The process has been used specifically to treat petroleum refinery wastes.



iii) Applications/Demonstrations

The BP Oil Extraction Process is commercially available from BP Oil. Pilot-scale studies have been completed on sludges from two Standard Oil refineries and a full-scale demonstration at the Alhama Refinery in Belle Chase, Louisiana was reported to the EPA. Results were not available at the time of this report.

iv) Need for Additional Research

Assess treatment potential for other organic contaminants such as chlorinated phenols and chlorinated solvents.

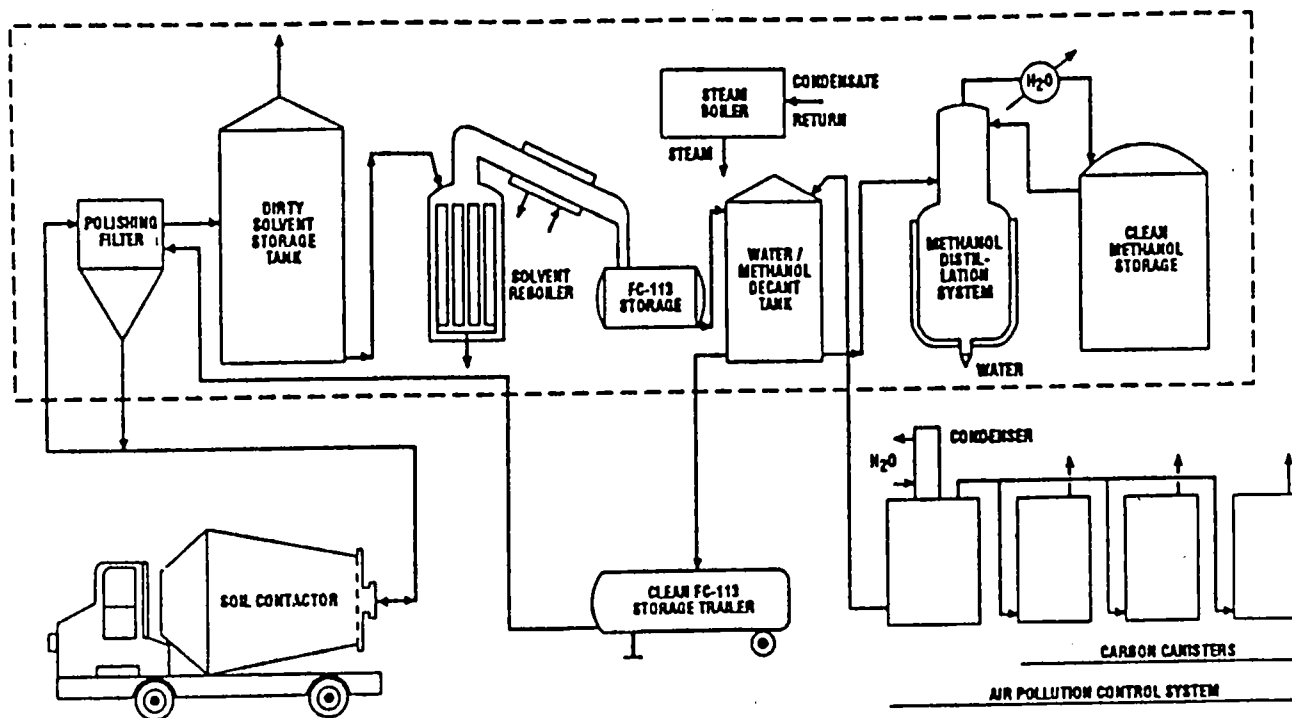
2.3.1.5 Accurex Solvent Extraction Process

i) Process Description

The Accurex process was developed by the Electric Power Research Institute (EPRI) for the cleanup of PCB contaminated soils and was further developed and modified by Envirote Field Services Inc. and Harmon Environmental Services. The process utilizes a proprietary solvent mixture which includes Fluorocarbon-113 (FC-113) and methanol. The process treatment train configuration is shown in Figure 2.23.

PCB contaminated soil is fed to a reactor where it is mixed with successive treatments of proprietary solvents to remove water and reduce PCB concentrations to acceptable levels. Washed solids are redirected to a steam stripper to remove residual solvent and the cleaned solids are disposed of on site.

The liquid waste stream consists of the original water which was present in the soil, and the solvent. The waste water stream is filtered to remove very fine suspended material prior to discharge to the environment. The fine grained filtrate, which may contain adsorbed PCB's, is returned for reprocessing or destruction.



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ACCUREX SOLVENT EXTRACTION PROCESS
(Hall et al., 1989)

Figure 2.23

The solvent waste stream is distilled to recover cleaned solvent while the contaminated still bottom is returned for reprocessing or destruction.

Volatile emissions are vented to a condenser where residual solvents are recovered, and the final air stream is passed through a series of activated carbon adsorbers before venting to the atmosphere.

ii) Waste Treated

The process was originally designed to treat PCB contaminated soil, but has also been used to treat soils contaminated with fuel oil.

iii) Applications/Demonstrations

The Accurex process has been completed at bench-scale for the treatment of soils contaminated with fuel oil, and design of a pilot plant is being considered.

iv) Need for Additional Research

Treatment at pilot-scale and full-scale needed. Assessment of treatability for a range of organic contaminants and waste feed.

2.3.1.6 Soilex Process

i) Process Description

The Soilex process involves the use of two immiscible liquids, water (a polar liquid) and kerosene (a non-polar liquid), to produce a solvent mixture to remove organic contaminants. The process is currently at the pilot-scale and is briefly described by Raghaven et al., (1989) with further reference to Saunders (1985).

The process consists of three mixing stages operated in counter current mode. Soil and water are mixed together using an air driven agitator in a 200

litre capacity tank. Kerosene is added later at a ratio of 3:1 kerosene to soil. Solid-liquid separation occurs by settling and decantation while kerosene is recovered by batch distillation.

ii) Waste Treated

The Soilex process has been used to treat PCB contaminated soil.

iii) Applications/Demonstrations

The reader is referred to the reference by Saunders (1985) for a description of the pilot-scale study.

iv) Need for Additional Research

Evaluation of pilot-scale treatment required.

2.3.1.7 EETD Solvent Extraction Project

i) Process Description

Environment Canada's Environmental Emergencies Technology Division (EETD) is investigating the use of solvent extraction using natural gas condensates to clean up soils contaminated with oily hydrocarbons in the vicinity of oil refineries and oil pipelines. The proposed work will include bench-scale testing of three soil types (clay-rich, humus-rich and sandy) contaminated with three types of oil using the following five solvents:

- 2 raw natural gas condensates
- 2 pre-distilled natural gas condensates
- hexane

The process will involve solvent extraction of a contaminated soil in a mixing chamber followed by solid-liquid extraction by centrifuging and solvent contaminant separation and recovery by distillation. The project will

investigate effects of mixing chamber retention time, centrifuge retention time and distillation temperatures (Punt, 1990). A schematic of the proposed process is given in Figure 2.24.

This work is at the research stage, and no further information is available at this time.

2.3.2 Solvent Extraction Using Critical Fluid Solvents

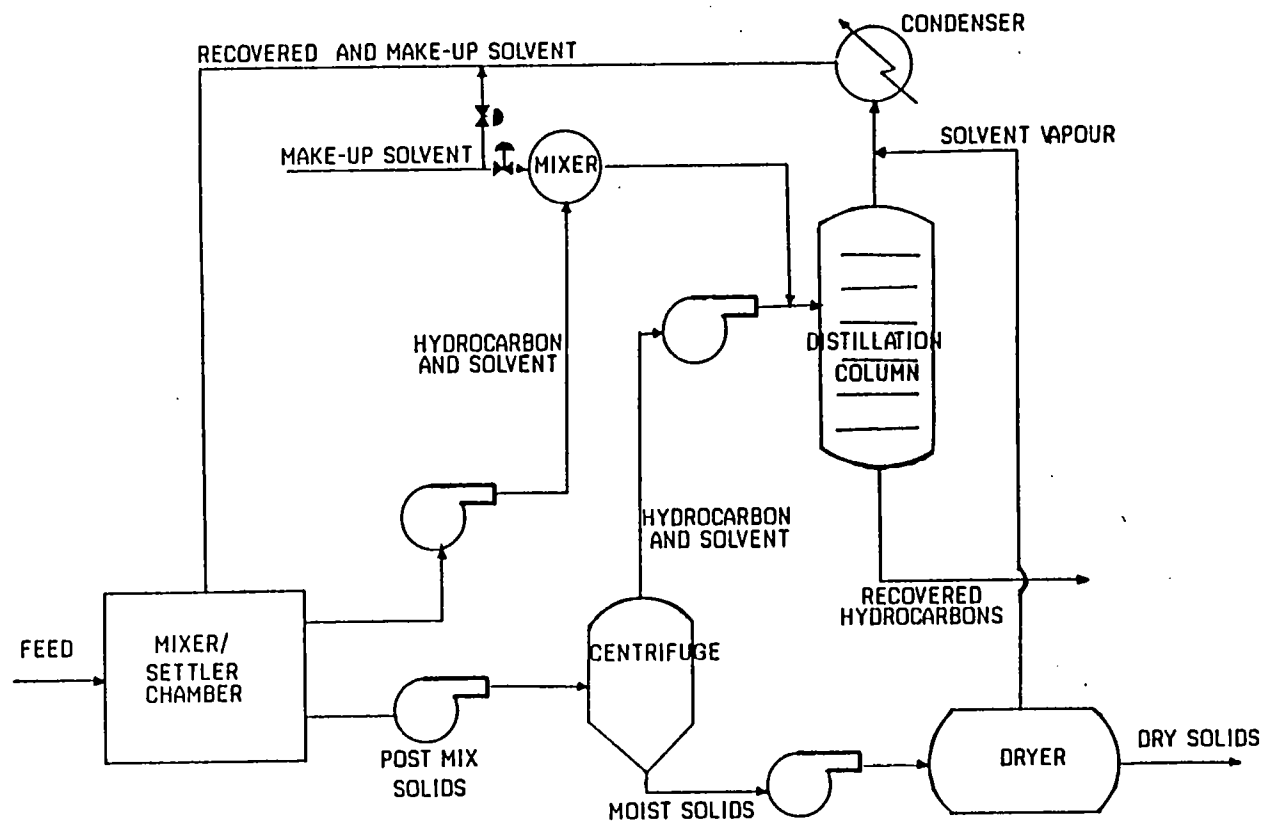
Solvent extraction using inert gases such as carbon dioxide or light hydrocarbons such as propane, in a state at or above critical pressures and temperatures, has been found to be an effective process for the removal of organic compounds from contaminated soil and water.

Carbon dioxide is commonly used as a solvent to treat waste water because of CO_2 's non-toxicity, non-flammability, low cost and low critical point (Irvin et al., 1987) while light hydrocarbon gases are used as critical fluid solvents for the treatment of contaminated soils.

Critical fluids are fluids at or above their thermodynamic critical temperatures and pressures. Properties such as density, viscosity, dielectric constant and diffusivity are intermediate between those values of the fluid as a gas and as a liquid. Under these conditions, variations in temperature and pressure can cause great increases in the solubility of organic compounds in the solvent (Dooley et al., 1987, Moses and Abrishamian, 1988).

Reducing the temperature or pressure of the solvent/contaminant mixture following extraction results in phase separation of the solvent gas and the contaminant liquid or solid, and allows the solvent gas to be recycled.

The use of polar entrainers such as methanol or toluene in concentrations of a few weight percent can greatly increase the solubility of organic compounds when carbon dioxide is used as the solvent.



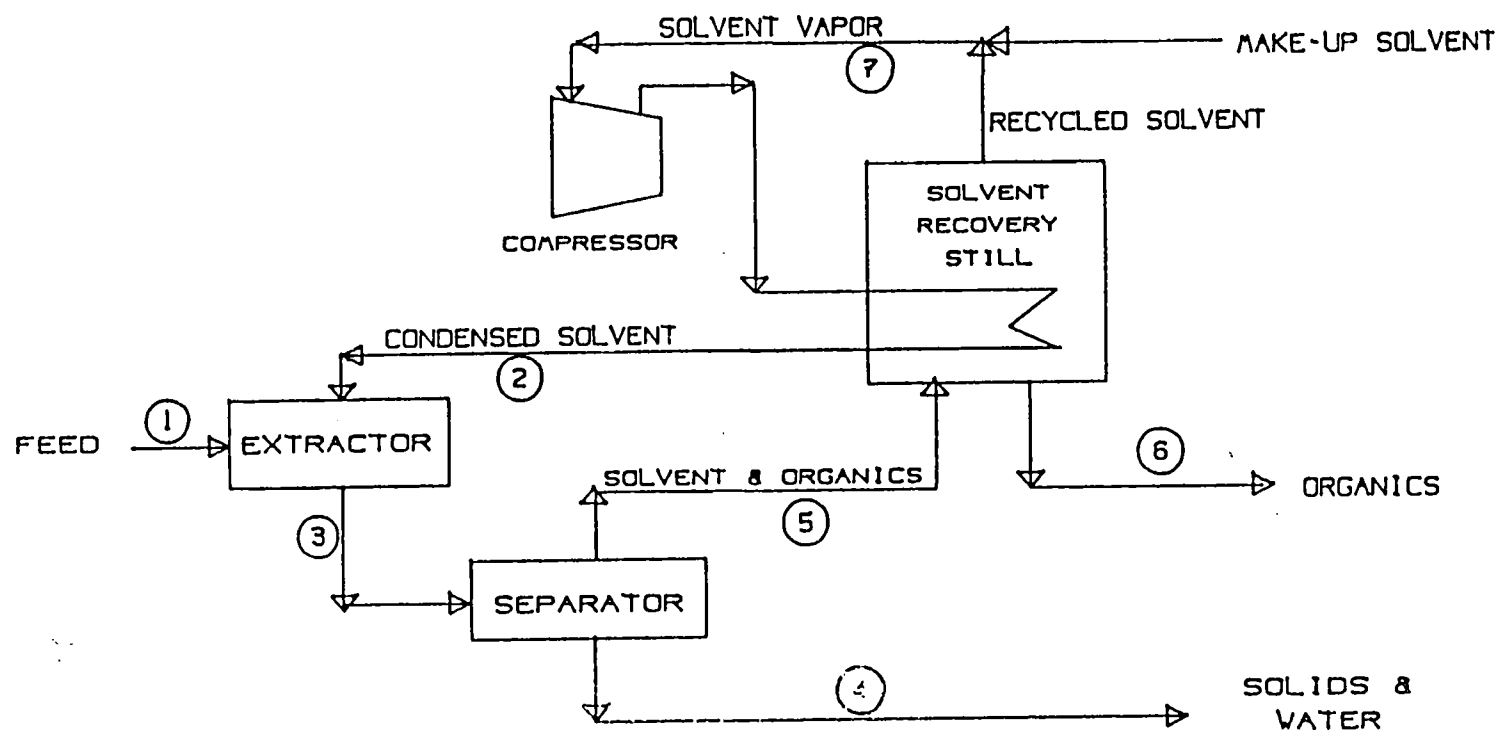
Research is currently addressing the treatment of the waste stream by catalyzing the oxidation of the organic contaminant mixture following extraction while the system is still at critical pressure (Dooley et al., 1987).

2.3.2.1 CF Systems Process

i) Process Description

CF Systems Corporation has developed a critical fluid solvent extraction process for extracting volatile and non-volatile organic contaminants from soil materials with a wide range of soil matrix properties, by utilizing liquified propane and butane as the solvent.

The process consists of four basic unit operations including extraction, phase separation, solvent recovery and filtration (Hall et al., 1989). A schematic of the process is given in Figure 2.25. The waste feed is screened for particle size to enable the waste to be slurried, is mixed with water and pumped on a continuous basis into the top of the first of a number of extraction units. The number of extraction units or stages will vary according to the type of feed material and the degree of contamination. Propane or butane close to the critical point is used as the solvent and is directed to the extraction unit so that the solvent feed direction is countercurrent to the waste feed. This configuration maximizes extraction efficiency. The waste is pumped into a decanter which is paired with each extractor, and the solvent/organic solution is separated from the water/solid residue. Following the extraction process, the water/solids residue is sent to a dewatering system where a portion of the recovered water is returned and used to slurry the waste feed. Waste water is treated as required and discharged. Cleaned soil material is removed from the dewatering unit and discharged. The solvent/organics solution is treated to remove entrained water and directed to a solvent-recovery still where the organics and solvent are separated by vaporization of the solvent as the pressure is decreased. The liquid organic contaminant fraction is removed and treated. The vaporized solvent is compressed and recycled to the extraction system.



A mobile full-scale commercial system capable of processing 45 tonnes/day has been developed. Processing costs based on pilot-scale testing are estimated at \$190-580/tonne for PCB contaminated soils. Costs will vary depending upon waste characteristics, amount of waste, the amount of time the system operates, material handling, and pre- and post-treatment requirements. Since the waste is slurried during the process, coarser grained material may not be suitable for treatment and will need to be removed during the screening process. Treatment of this material will add to costs. Likewise, the post-treatment costs associated with dewatering of the contaminant stream will vary according to the treatment method. Pre- and post-treatment costs account for approximately 33% of estimated costs (Davidson et al., undated). Feeds with low ambient temperatures need to be heated to a minimum of 15.5°C.

ii) Wastes Treated

The CF Systems process has treated harbour sediments, API separator sludges and soils. Contaminants which have been treated include PCB's, PCP and creosote wastes, alcohols, gasoline, phenol, oils and grease, organic acids, and chlorinated solvents (Kaleri et al., 1990, U.S. EPA, 1989(f), Davidson et al., undated). PCB concentration ranging up to 2600 ppm and total PAH's ranging up to 4200 ppm have been treated.

iii) Applications/Demonstrations

The CF Systems process was used to clean up PCB contaminated harbour sediments at New Bedford Harbour in Massachusetts in 1988. Extraction efficiencies ranged from 70% after three extraction stages on sediments with an initial PCB concentration of 288 ppm, to 92% after six stages on sediments with an initial PCB concentration of 2575 ppm (U.S. EPA, 1989(b)). Kaleri et al (1990) report on treatability studies at the United Creosoting site at Conroe Texas. Total PAH concentrations in two samples were 1973 ppm and 4169 ppm, and removal efficiency was reported as 98% after four extraction stages and 94% after three extraction stages respectively. Low levels (<1 ppm) of PCP, dioxins and

furans showed removal efficiencies of 91%, 70-83% and 66-73% respectively. Further information is provided in Case Study 16 in Appendix B.

Efficiencies of 80 to 99.9% have been obtained in laboratory studies for volatile and semivolatile organic compounds ranging in concentrations from <0.3 ppm to 1930 ppm (Davidson et al., undated).

In addition to field demonstrations and treatability studies at the two superfund sites, the CF Systems process has been demonstrated at the following locations:

- Texaco refinery, Port Arthur, Texas. During September to October 1987 various feed types including ditch skimmer sludge and tank bottom wastes were processed. The process met or bettered existing best demonstrated available technology (BDAT) standards for VOC's and PAH's. CF systems is currently operating their 45 tonne/day unit to treat 15,000m³ of refinery waste.
- Petro-Canada refinery, Montreal, Quebec. Over a six week period, 14 different feed types including API separator sludges and contaminated solids were run.
- Tricil waste treatment facility near Sarnia, Ontario. Process feeds included API separator sludges, paint waste, coal tar waste and synthetic rubber process waste.
- BASF plant, Kearny, New Jersey. One of the waste streams treated included emulsified di-octyl phthalate water and other organic compounds.
- Unocal refinery, Parachute Creek, Colorado. Waste feeds included shale-oil wastes and drilling muds. The process recovered oil from shale-oil waste (Davidson et al., undated).

iv) Need for Additional Research

Operational problems reported during pilot-scale testing included fluctuations in solvent flow which varied the solvent-to-feed ratio, retention of solids in process hardware, and foaming of treated sediments. These problems relate to waste feed pre-treatment and handling, treatment configuration, general maintenance and mechanical problems, and are thought to be solvable in a full-scale commercial unit.

A summary of solvent extraction applications is given in Table 2.12.

2.3.3 Substitution and Reduction-Oxidation Technologies

Substitution and reduction-oxidation technologies are destructive techniques which utilize chemical processes and reagents to change the structure of toxic compounds to less toxic or non-toxic transformation products.

Chlorinated organic compounds are among the most toxic organic compounds produced by industry. Chlorinated compounds such as PCB's are often incinerated, but burning at less than optimum temperatures can produce highly toxic compounds such as chlorinated dioxins and furans. Removal of chlorine atoms from the structure of a contaminant compound can significantly reduce the toxicity of the product compound making dehalogenation processes an important alternative to thermal destruction.

In this section the following substitution and reduction-oxidation technologies will be discussed:

- dechlorination
- oxidation

Table 2.12 Summary of Solvent Extraction Applications

Date	Site	Customer	Contractor	Contaminants	Initial Concentration (ppm)	Final Concentration (ppm)	Initial Quantity Contaminated Soil (tonnes)	Reference
1988	General Refining, Savannah, Georgia	Field Demonstration	Resources Conservation Company	PCB's Oil and Grease	<1-5.0 15-20%	0.37-1.7 --	3300	Sudell (1988)
undated	not given	various cleanups/ treatability studies	Sanexen International	PCB's Oil and Grease PAH's PCP	5.3-2,055 600-447,000 240-1739 8.2-744	0.7-48.8 80-5,500 10-130 <0.82-83	-- -- -- --	Pacquin and Mourato (undated)
1988	New Bedford Harbour, Massachusetts	Field Demonstration	CF Systems	PCB's	(i) 288 (ii) 2578	23 206	-- --	USEPA (1989b)
1990	United Creosoting,	Treatability Study	CF Systems	PAH's (total)	(i) 1973 (ii) 4169	40 250	-- --	Kaleri et al., (1990)

2.3.3.1 Dechlorination

2.3.3.1.1 APEG Process

i) Process Description

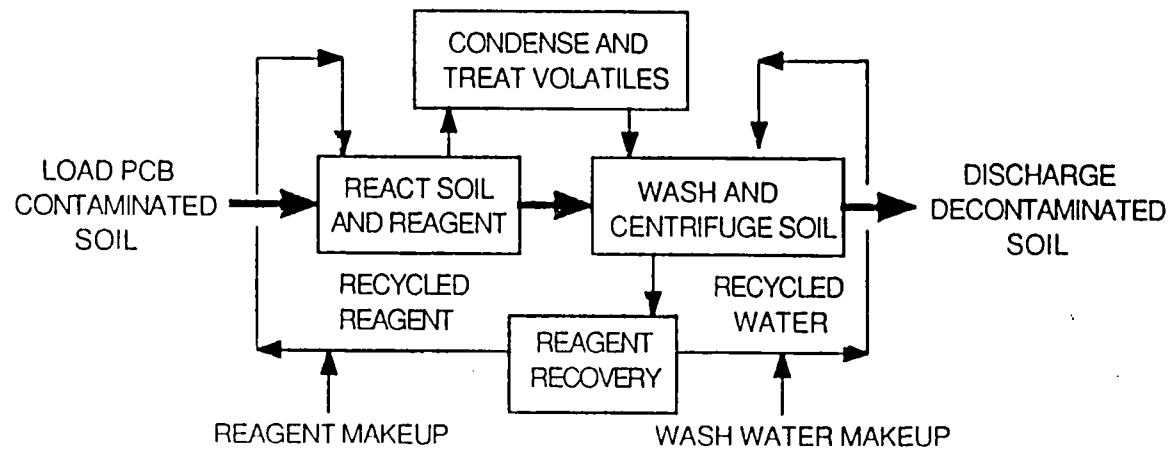
The APEG process is an alkaline dechlorination process, which utilizes an alkoxide produced from the reaction of a glycol with an alkali metal hydroxide, to dechlorinate toxic target compounds resulting in the formation of an ether and an alkali metal salt.

Specifically, an alkaline(A) solution of potassium hydroxide is reacted with polyethylene glycol (PEG) under relatively mild temperature and pressure conditions to produce a polymeric alkoxide (APEG) (Rogers et al., 1987). A catalyst such as dimethyl sulfoxide can be added to speed up the reaction by overcoming inhibitory effects of hydroxide ions (U.S. EPA, 1989(g)).

The alkoxide (APEG) substitutes for a chlorine atom on the organic contaminant to produce water soluble reaction products consisting of glycol ether, or a hydroxylated compound and an alkali metal salt.

The system processes involve reagent preparation, waste feed preparation, reagent waste feed mixing, reagent/soil separation, soil washing, soil dewatering and solvent recovery. A schematic of the process is shown in Figure 2.26.

The potassium hydroxide and polyethylene glycol reagents are mixed in a reagent tank to form a polymeric alkoxide. Waste feed is screened (0.64cm) to remove coarse particles and debris, and is directed to a closed reactor where it is mixed with reagents to form a slurry. The slurry is heated to between 100-160°C and is retained in the reactor for 2-8 hours depending on the nature of the matrix and the type and concentration of the contaminant (Cleary and Granger, 1988, U.S. EPA, 1989(g)). Following reagent and soil reaction, unreacted reagent is separated from the soil by centrifugation, filtration or sedimentation and the



cleaned soil is water washed. Water vapour and volatiles generated from the reaction are condensed and the air stream is discharged after separation of volatiles. Cleaned soil is returned to the site. Soil wash water and used reagents are mixed, and reagents are separated and returned to the reagent tank.

Advantages of the process include:

- reagents are non-toxic
- toxic chlorinated compounds degrade to dechlorinated species
- process units are mobile

Disadvantages of the process include:

- storage of caustic reagents on site
- pH of treated soil may have to be neutralized if reagent residual is retained
- effectiveness of process is reduced by clay-rich and organic-rich soils due to increased adsorption of organic contaminant

Costs for treatment vary according to waste feed type, contaminant type and concentrations and required clean up levels, and costs range between \$195-400/tonne (Galson Remediation Corp., undated (a)).

ii) Wastes Treated

This process can be used in the treatment of soils, sediments, sludges and oils (Rogers et al., 1987, Cleary and Granger, 1988, U.S. EPA, 1988). The process is designed specifically for treating halogenated compounds including PCB's, dioxins and furans, and should be capable of treating halogenated solvents and halogenated pesticides. However, Esposito et al., (1989) reported that KPEG reagent was not successful in dechlorinating volatile and semi-volatile organic compounds with the exception of 1,2-dichloroethane and tetrachloroethylene. They attributed organic losses to volatilization.

iii) Applications/Demonstrations

The APEG process has been demonstrated in the treatment of oils and soils contaminated with dioxins, furans and PCB's. Rogers et al., (1987) describe the treatment of approximately 34,000L of PCDD- and PCDF-contaminated oil at Butte, Montana. All PCDD's and PCDF's were destroyed to below the 1 ppb limit of detection.

At the Wide Beach Superfund Site at Brant, New York, the APEG process was used to treat approximately 22,000 tonnes of clay silt soil in a residential area in yards, driveways, and drainage ditches. PCB concentrations varied up to 1026 mg/kg. Under pilot-scale testing, PCB concentrations were reduced from initial concentrations in the range of 30-260 ppm to concentrations in the range of 0.7-1.7 ppm. Further information is provided in Case Study 17 in Appendix B.

Other applications of APEG are listed in Galson Remediation Group (undated (b)).

iv) Need for Additional Research

Further research is needed to investigate the inhibitory effects of clays and organic materials in various waste feeds due to the adsorption of contaminant compounds. The use of solvents to solubilize contaminants and speed up reaction rates is being investigated.

Identification of transformation products and toxicity evaluation should be carried out for those waste types and soil types where this information is lacking.

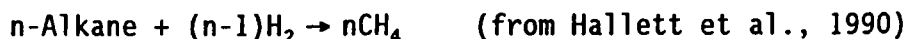
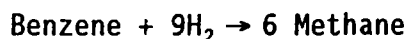
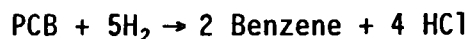
2.3.3.1.2 Eco Logic Process

i) Process Description

The Eco Logic process utilizes hydrogen to dechlorinate organic compounds at elevated temperatures in excess of 850°C, producing end products of



hydrogen chloride, methane and ethylene. The dechlorination process for PCB, for example, can be described in terms of three chemical reactions:



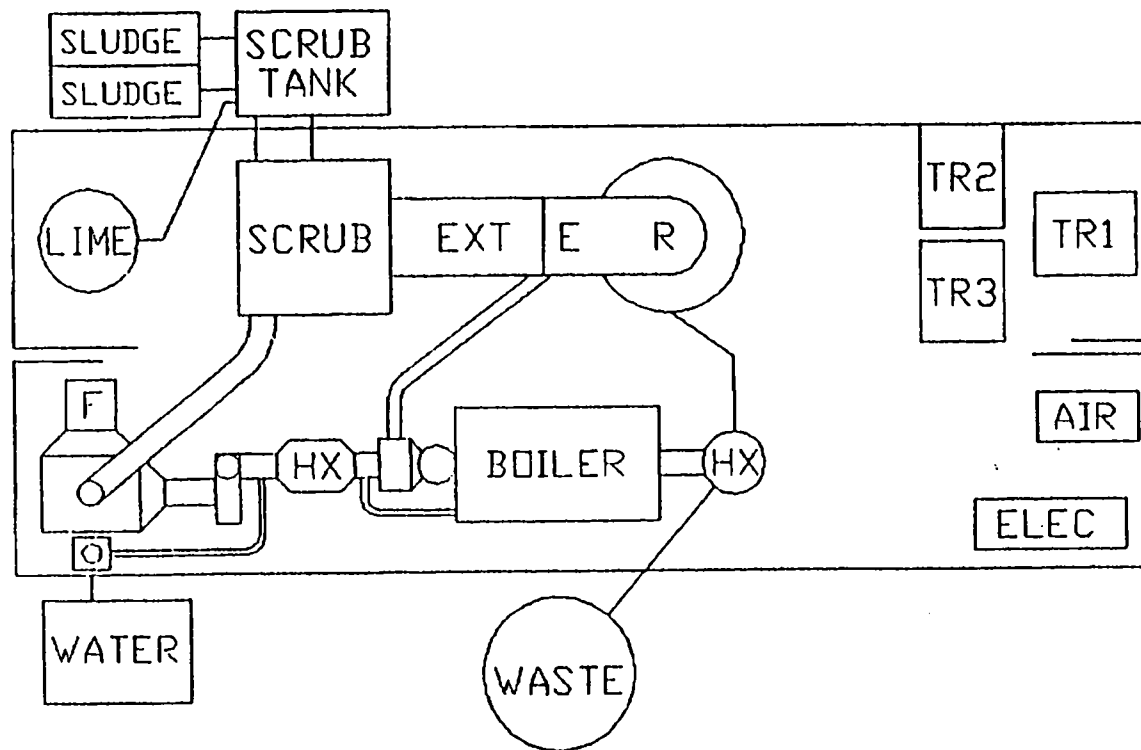
The process is described by Hallett et al., (1990) and involves preheating the waste stream using boiler steam and a heat exchanger, and injecting the waste and hydrogen into the top of the reactor. The mixture is heated to 850°C. Coarse material passes the heater where organic material is volatilized and the coarse fraction passes through the bottom of the reactor to a quench tank. Finer material is entrained in a gas stream and remains within the reactor for a longer period of time to ensure complete dechlorination. The waste stream consists of hydrogen, methane, ethylene and carbon monoxide. Ninety percent of the waste gases are recycled to the reactor while the remaining 10 percent are used as supplementary boiler fuel. Residues from the process include coarse particles exiting at the base of the reactor, calcium chloride, scrubber sludge and condensed water sludge. A process schematic is shown in Figure 2.27.

The process operates on a continuous feed basis and the waste stream is monitored to provide a continuous readout of destruction efficiency. The process is completely mobile and can be transported on two tractor trailers. Set up time is several days. Capital costs are roughly 5-10 times less expensive than incineration, and operating costs are predicted to be 3-5 times lower than for incineration.

Since the chlorinated compounds are treated in a reducing environment, dioxins or furans are not produced.

ii) Wastes Treated

The Eco Logic process is designed to process PCB's, chlorinated solvents and chlorinated dioxins in a variety of aqueous and solid matrices.



iii) Applications/Demonstrations

No specific tests were described, but approximately 100 bench-scale tests have been undertaken, with destruction efficiencies of 99.9999% or better (Hallett, 1990).

iv) Need for Additional Research

A test program of the process will be undertaken during 1990 for the Canadian Department of National Defense.

2.3.3.2 Chemical Oxidation

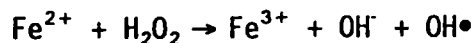
i) Process Description

Oxidation of a chemical compound is an electron transfer process whereby the compound loses electrons. Organic compounds can be oxidized by gaining an electronegative element such as oxygen or chlorine, or by losing hydrogen, however oxidation through the addition of chlorine is not a viable alternative because the reaction can produce toxic compounds.

Oxidation processes have been used in the treatment of water and waste water streams and provide an alternative to the treatment of soil contaminated with recalcitrant organic compounds (Ravikuma and Gurol, 1990).

Hydrogen peroxide and ozone produce powerful oxidants and have already been applied to pilot-scale and full-scale treatment of contaminated soil, although process application is still in the development stage.

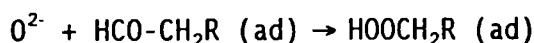
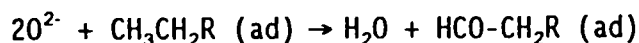
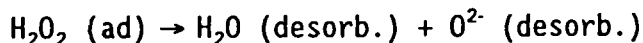
Hydrogen peroxide in soil can be broken down to hydroxyl radicals which are more powerful oxidants than hydrogen peroxide. Ferrous and ferric ions catalyze the following breakdown reactions:



(from Ravikumar and Guroi, 1990)

The LANDTREAT Process is another treatment process that utilizes hydrogen peroxide as an oxidizing agent. LANDTREAT is a patented process which utilizes defects in the matrix of a synthetic polysilicate as adsorption sites for hydrogen peroxide and organic compounds. At these sites, hydrogen peroxide decomposes to water and a highly reactive singlet oxygen. The singlet oxygen oxidizes the organic compound to intermediate products which are adsorbed at the defect sites and the oxidation process is continued. Complete oxidation results in the formation of carbon dioxide and water. The reaction is catalyzed by ultra violet light (Smith and Sabherwal, 1987).

The process sequence can be written as the following series of chemical reactions for an aliphatic hydrocarbon:



(from Smith and Sabherwal, 1987)

At the field site, the treatment area is bermed to control surface runoff. Contaminated soil is spread uniformly over the treatment area and the LANDTREAT polysilicate is mixed into the soil using a backhoe or front-end loader. Hydrogen peroxide is mixed with water in a mix tank. A spray gun attached to a gasoline powered compressor is used to spray the hydrogen peroxide/water mixture onto the soil. On-site testing, using a photoionization



detector, is used to monitor organic contaminant levels in the treatment area and ambient air quality.

Advantages of hydrogen peroxide treatment are:

- readily available and inexpensive
- rapid reaction

Disadvantages of hydrogen peroxide treatment are:

- direct hydrogen peroxide can produce a highly exothermic reaction which volatilizes hydrocarbons before they can be oxidized by the process
- intermediate breakdown products such as thiols can produce noxious odours
- no control of volatilization and biotic losses

Treatment costs for LANDTREAT range from \$70-125/tonne (Smith and Sabherwal, 1987). Treatment of 200-1,200m³ of contaminated soil is common and actual on-site work takes from three to seven days.

Treatment by ozone is another application of an oxidation process. Ozone is produced commercially by the action of an electrical discharge on molecular oxygen. Ozone oxidizes organic compounds to alcohols, aldehydes, ketones and carboxylic acids, all of which are highly biodegradable (Ruhoff, 1990). In PAH treatment, the ozone demand is roughly 3 mg of ozone per mg of PAH. Laboratory studies of oxidation products of selected PAH's indicate that oxalic acid is produced as an intermediate product prior to mineralization to carbon dioxide and water.

Advantages of ozone treatment are:

- rapid reaction rate
- produces biodegradable intermediates

Disadvantages of ozone treatment include:

- expense of producing ozone
- ozone is toxic to microorganisms and soil has to be amended with sewage sludge or commercial microbes for biodegradation to be effective as a polishing step

ii) Wastes Treated

Wastes treated by oxidation methods include gasoline and mineral oils. Specific contaminant groups include aliphatic hydrocarbons, aromatic hydrocarbons, PAH's (molecular weight not specified) and PCP.

iii) Applications/Demonstrations

Hydrogen peroxide was used in bench-scale soil column studies to treat coarse grained sand with low (<0.4%) organic matter contaminated with a one molar solution of PCP. Hydrogen peroxide was leached through the soil column and PCP concentrations were measured in the effluent. Results of the study indicated that at concentrations of 59 mg/kg PCP in the soil, 1.55 mmols of hydrogen peroxide were able to oxidize 27% of the PCP. Sixty-seven percent of the PCP was removed through desorption and washing (Ravikumar and Gurol, 1990)

Smith and Sabherwal (1987) report on the use of the LANDTREAT process to treat gasoline contaminated soils. Initial concentrations in soil for total petroleum hydrocarbons ranged from 9.5 to 40,000 (units not given). Following treatment, total hydrocarbon concentrations ranged from <2.0 - 360 (units not given).

Ozone treatment is described by Ruhoff (1990) for laboratory studies of 2 kg quantities of contaminated sandy soils located at bulk fuel storage facilities and refineries. PAH's with an initial concentration of 2,300 mg/kg were reduced by nearly 98% to a level of 50 mg/kg in a period of 20 days, while total hydrocarbon concentrations were decreased from 12,000 mg/kg to 150 mg/kg within 2.5 days, a reduction of 99%.

iv) Need for Additional Work

Further work is needed to evaluate losses particularly from biodegradation since oxidizing agents can improve conditions for microbial growth. Other losses include volatilization, photolytic degradation and leaching.

Third party evaluations of pilot-scale and field treatment demonstrations should be undertaken to provide a critical review of technologies.

Further understanding of basic processes and identification of transformation products for a variety of soil and contaminant types is required.

2.4 BIOLOGICAL TREATMENT TECHNOLOGIES

The subsurface contains large populations of diverse microbial communities including bacteria, algae, and fungi which are capable of partially transforming or completely mineralizing toxic organic compounds. Microorganisms derive energy to maintain cell respiration and to produce biomass from the oxidation of organic and inorganic substrates.

Microbial metabolic processes involve three types of respiration: aerobic, anaerobic and fermentation, during which electron transfer takes place. Under aerobic conditions, microorganisms utilize molecular oxygen as the terminal electron acceptor. Metabolic and growth processes which utilize organic compounds as a primary substrate, are catalyzed by enzymes secreted by the microorganism, leading to the mineralization of the organic compound ultimately to water and carbon dioxide. In some reactions, the microorganism may utilize another substrate as the primary energy source, and in the process, the organic contaminant compound is partially degraded or transformed. This process is termed cometabolism and may perhaps be a necessary step in the mineralization of recalcitrant compounds such as PAH's (Kech et al., 1989, Sims et al., 1989).

Under anaerobic or reducing conditions, microorganisms utilize other electron acceptors such as nitrate, sulphate, organic acids and carbon dioxide, and under these conditions, organic compounds are only partially degraded or oxidized, and energy conversions are as much as 20 times less than under aerobic conditions (Torpy et al., 1989). Under extreme reducing conditions, microorganisms involved in fermentation remove excess electrons by secreting reduced organic compounds.

Biological treatment methods currently being applied by industry utilize aerobic processes while anaerobic processes remain much within the realm of research.

The rate and extent of the biodegradation of organic contaminants are dependent on the activity and growth of microorganisms, the latter of which are determined by environmental factors such as:

- redox potential
- availability of nutrients
- pH
- temperature
- soil moisture
- nature and concentration of contaminants

Redox potential in the soil will determine whether biodegradation will take place under aerobic or anaerobic conditions. During aerobic biodegradation of hydrocarbons, approximately 3 mg of oxygen are required for the oxidation of 1 mg of hydrocarbons, (Werner, 1989) and under conditions of high concentrations of hydrocarbons, oxygen availability may be the growth limiting factor. Oxygen distribution and availability can be improved by turning over the soil by tilling or using methods such as forced aeration, or hydrogen peroxide additions.

Besides a source of carbon, microorganisms require nutrients including nitrogen and phosphorus to carry out metabolic and growth processes. These nutrients are added as fertilizers to soil so that carbon/nitrogen ratios are maintained in the range of 20-30 to 1 and nitrogen/phosphorus ratios are

maintained at approximately 10 to 1 (Pope, 1989). Microorganisms function well within a pH range of 3 to 9 with most bioremediation processes taking place within a pH range of 5 - 8 (Pope, 1989).

Temperature influences the rate of metabolic processes. The optimum temperature for bioremediation falls within the range of 18 - 30°C, and at lower temperatures enzyme activity is significantly reduced. Under cold climate conditions, bioremediation ceases as the temperature approaches 0°C.

Bioremediation processes in soil take place within the sheath of water which surrounds individual soil grains, and optimal soil moisture levels for microbial growth occur at 75 to 85% of water holding capacity (Flatham et al., 1983, Sims et al., 1989). Too much water in the site can impede oxygen diffusion.

Contaminant type and concentration will also affect the rate of biodegradation. Aliphatic and simple aromatic hydrocarbons are readily degraded aerobically. More complex compounds such as PAH's which consist of fused benzene rings become more difficult to degrade aerobically as the number of rings and the molecular weight increases. The addition of chlorine atoms to the organic molecule further inhibits the rate of aerobic degradation. Pentachlorophenol, which contains five chlorine atoms and is a biocide, is still capable of being degraded cometabolically by several types of bacteria and fungi (Hoffmann and Hrudey, 1990). High concentrations of contaminants may have a toxic effect on microorganisms.

Soil type plays an important role in the biodegradation of organic contaminants. Hydrophobic organic contaminants will partition onto soil organic matter and clay grains. Under conditions of strong adsorption, microbes are unable to utilize the contaminant as a carbon source since carbon utilization takes place within the soil water phase.

Models describing the fate and transport of organic contaminants in soil subject to biodegradation are discussed in Stevens et al., (1989) and Symons et al., (1988).

2.4.1 Treatability Studies

Treatability studies are required to determine whether, under a given set of conditions of soil type, contaminant type and concentration, bioremediation will proceed in a cost effective manner. Treatability studies can include a mass balance approach to the degradation and transformation of organic compounds, and a calculation of the degradation rate thorough measurements of carbon dioxide produced as a result of mineralization of the parent compound (Sims et al., 1989).

Degradation kinetics are often described using the power rate law and first-order reaction kinetics as described in the following equation:

$$\text{degradation rate} = k[S]^n, (1) \quad \text{Walton et al., (1989)}$$

where k = degradation rate constant

$[S]$ = substrate concentration

$n = 1$

A half life of the substrate or organic compound can then be calculated from the following equation:

$$t_{\frac{1}{2}} = 0.693/k, (2)$$

where $t_{\frac{1}{2}}$ is the amount of time required to degrade a compound to one half its original mass in the soil.

Treatability studies are described more fully in Aprill et al., (1990), Sims et al., (1989), Walton et al., (1989), Loehr (1989) and McGinnis et al., (1988).

Biodegradation studies and bioremediation have been conducted on a number of waste types including industrial wastes from petroleum refining, wood preserving, organic chemical and pesticide manufacturing and coal gasification. Contaminant groups include aliphatic and aromatic hydrocarbons, PAH's, chlorinated aliphatic compounds, chlorinated aromatic compounds and chlorinated and non-chlorinated phenols.

While biodegradation has been shown to be applicable for a wide range of compounds, it may be limited at any one particular site by one or a combination of environmental conditions discussed in section 2.4.1 and biodegradation may not proceed at a rate which is cost effective. In some cases, transformation products may be more toxic than the parent compound, for example, the partial degradation of trichloroethane to vinyl chloride. Heavy metals which may be associated with the organic contamination may be at concentrations toxic to the microorganism and other carbon containing compounds may compete with the organic contaminant as primary substrate.

Sims (1990) and Sims et al., (1990) provide a critical review of the use of soil remediation techniques at hazardous waste sites.

2.4.2 Landfarming

i) Process Description

Landfarming in its simplest form involves the spreading of contaminated soil onto the existing ground surface using construction or agricultural machinery followed by regular tilling of the soil to promote aeration and aerobic degradation. The addition of nutrients, phosphorus and nitrogen, optimizes rates of biodegradation.

To prevent the leaching of infiltrating fluids deeper within the soil profile, or to the water table, a liner constructed of 0.5 mm PVC material is placed beneath the treatment area. This technique is commonly used in The Netherlands where a bed of sand and a drainage system are placed over the liner, prior to emplacement of contaminated soil to collect leachate which is recycled back to the landfarm treatment area (Staps, 1990). Leachate containing nitrate levels of up to 150 to 250 mg/L have been reported (Soczo et al., 1988).

In cases where leaching is a major concern, a double liner may be employed. In this case, a leak detection system consisting of a clay liner overlain by sand and drainage piping is constructed beneath the PVC liner (Christiansen et al., 1989). An example of a double-lined configuration is given

in Figure 2.28. Berming or drainage around the treatment area may be required to control surface runoff.

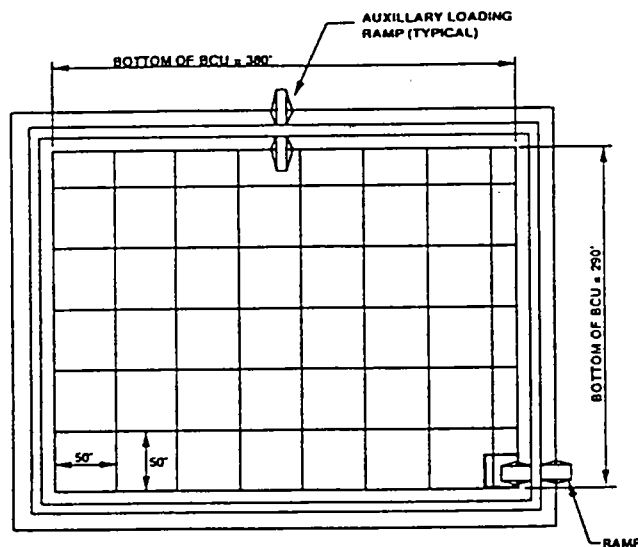
Since biodegradation rates are temperature dependent, cool climate conditions impose restrictions on the time period where landfarming is practical, and soil cleanups may take several seasons to reach target levels.

An overview of landspreading of petroleum industry sludges in Canada is given in Beak Consultants Limited (1981a, b). Oily sludges containing up to 20-40% oil by weight can be landspread, once soil microorganisms are acclimatized to the sludge substrate, providing that the sludge is applied in layers generally less than 8cm to allow for adequate drying. Once the sludge is dried, it is mixed into the upper 15-20cm of soil and the soil is tilled at frequencies of about once every two weeks. Major landspreading operations include the following:

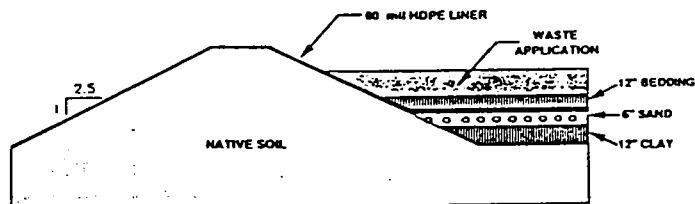
- overapplication of sludges
- soil compaction
- contaminant leaching
- surface runoff of sludge components

Other problems relate to the evaluation of the effectiveness of landfarming techniques including:

- (i) Contaminant losses from abiotic processes such as volatilization, photolytic degradation and leaching. Such processes may be difficult to monitor, and prevent the calculation of material and contaminant mass balances. Losses of between 20-40% from the photo-oxidation and volatilization of hydrocarbons have been estimated (Beak Consultants Limited, 1981). Park et al., (1990) calculated volatilization losses of PAH's from two soils in laboratory experiments. They estimated losses of 30% and 15% for naphthalene and 1-methylnaphthalene by volatilization. Losses of other PAH compound by volatilization were negligible.



BIODEGRADATION CLOSURE UNIT, GRID
PLAN VIEW



CROSS SECTION DETAIL

Drawn by	Date	BIODEGRADATION CLOSURE UNIT, PLAN VIEW AND DETAILED CROSS SECTION (Christiansen et al., 1989)
Checked by	Date	
Revisions	Date	
INTERA KENTING		Figure 2.28

- (ii) Apparent decreases in contaminant concentrations may be due to more complete mixing of a heterogeneously contaminated soil during tilling operations.

Landfarming costs in Canada, based on data from 15 refinery sites and corrected for inflation, indicated that operational costs varied from \$17/tonne on a wet basis to \$64/tonne on a dry basis (Beak Consultants Limited, 1981a).

Landfarming costs in The Netherlands are estimated at \$30-50/tonne (Staps, 1990) but estimates from projects in the United States indicate higher costs in the range of \$80-160/tonne (Olsen et al., 1986, Flatham et al., 1983).

ii) Wastes Treated

Landfarming techniques have been applied to treat oily wastes and sludges associated with the petroleum refinery industry and wood treating plant wastes containing creosote and pentachlorophenol (PCP).

A significant number of compounds in the following contaminant groups can be treated by landfarming:

- aliphatic hydrocarbons
- aromatic hydrocarbons
- light molecular weight (2-3 ringed) PAH's
- phenolic compounds

but there are some compounds in each group which cannot be treated by landfarming alone.

(iii) Applications/Demonstrations

Landfarming techniques have been applied at a number of sites with projects ranging in scale from laboratory-scale feasibility studies to full-scale site remediation. Projects are summarized in Table 2.13 and selected projects are reported below.

Table 2.13 Summary of Landfarming Projects

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1982-1989	Drayton Valley, Lloydminster, Grande Prairie, Brooks, Alberta	Field studies	University of Calgary	oil field wastes (tank bottom waste, separator sludges, slop oils)	aliphatics: 38-74% aromatics: 10-20% asphaltenes: 4-17%	19-81 19-81 14-17/year	8 plots/site @ 270m ²	Peake et al. (1985) Peake and Connery (1986), Danielson et al. (1987) Danielson et al. (1988), Danielson et al. (1989)
1982-1983	Tompkins County New York	Field study	Cornell University USEPA	Oklahoma Petroleum Refinery Wastes (Aliphatic C-12toC-26) (PAH's)	0.09-5.25% oil and grease	--	20x16m ² plots	Loehr et al. (1987)
1983	Picillo Farm Superfund Coventry, Rhode Is.	Remediation	O.H. Materials Co.	Phenolics PCB's	3,000 ppm 875 ppm <180 ppm	-- 81 --	1,000 yds ³ 2,000 yds ³ 3,500 yds ³	Flatham et al. (1983) GCA Corp. (1985)
1984-1985	3 refinery sites (A,B,C) Ontario	Field study	Environment Canada	Petroleum Refinery Wastes PAH's	0.3-6% oil A: 1-69 ppm B: 0.5-58 ppm C: 0.2-92 ppm	17-35 -- -- --	-- -- --	Bulman et al. (1988)
1985	not given	Remediation	Hooghwerff, The Netherlands	oils	2,000-22,000 ppm	--	5,400 tonnes	DeKreuk (1986)
1986	Burlington Northern Brainard MN	Remediation underway	Remediation Technology	creosote (PAH's)	20,000 ppm	95	--	Sims (1989)
1986	Burlington Northern Somers, MT	Site demonstration completed		creosote (PAH's)	not given	--	18,500 yds ³	Sims (1989)
1986	Rocky Mountain foothills, Alberta	Field study	Norwest Soil Research Environment Canada Canterra Energy Ltd.	diesel invert cuttings (PAH's)	hydrocarbons: 11.4%	61-92	3x22m ² plots	Ashworth et al. (1988)
1986	The Netherlands	Remediation	BSN, DSM	mineral oil	1,100 ppm	64		Soczo et al. (1988)
1987	Rijswijk, The Netherlands	Field study (pilot-scale)	DeRuiter, IWACO	crude oil	35,000 ppm	--	1,800 tonnes	Soczo et al. (1988)

Table 2.13 Summary of Landfarming Projects (Cont'd)

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1987	The Netherlands	Remediation	Drenthe, KW/VAM	crude oil	8,000 ppm	--		Soczo et al.(1988)
1987	The Netherlands	Field study pilot-scale	N.-B., Grontmij	fuel oil	6,800 ppm	96	--	Soczo et al.(1988)
1987	Greenbank Gas Works, Blackburn, U.K.	Remediation	Biotreatment Ltd. Cardiff, U.K.	coal tars (PAH's)	12,500 ppm	40	12,000m ³	Bewley et al.(1989) Bewley and Thiele (1988a) Bewley, Thiele (1988b) Bewley (1987) (see Case Study 18)
1988	Brown Wood Preserving, Live Oak, Florida	Proposed remediation	Remediation Technology	creosote (PAH's)	<1,000 ppm	--	6,000 yds ³	Sims (1989)
1988	United Creosoting Co. Conroe, Texas	Feasibility study completed	Roy F. Weston	creosote, PCP, dioxins	not given	--	70,000 yds ³	Sims (1989)
1988	Libby Ground-water, Libby MT	Proposed remediation	Woodward Clyde, MOTEC	creosote, PCP, dioxins, VOC's	not given	--	30,000 yds ³	Sims (1989)
1988	Old Inger, Darrow, Louisiana	Remediation	Louisiana State University	aliphatic C-12 to C-31 PAH's	300-5000 ppm 60-6000 ppm	91 97		(i) Bianchini et al.(1988) (ii) Portier et al.(1988)
1988-1989	Oil gas plant, Port Stanley, Ontario	Remediation	Waste Stream Technology Inc.	PAH's VOC's oil and grease	340 ppm 13 ppm 1,500 ppm	67-92 -- 36		Barnhart and Myers (1989) Sevenson Environment and Waste Stream Technology (1989)
1988	Hazardous waste site, California	Remediation	Ecova Corp.	petroleum hydrocarbons	2,800 ppm	90	15,000 yds ³	Ross et al.(1988)
1989	California	Remediation at 6 industrial sites	Solmar Corporation	petroleum hydrocarbons	1500-30,000 ppm	68-99	1500-25,000 yds ³	Molnaa and Grubbs (1989)

Table 2.13 Summary of Landfarming Projects (Cont'd)

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1989	(i) Grenada, Mississippi	Feasibility study	Mississippi Forest Products Laboratory	wood-treating plant sludge creosote (PAH's) PCP oil and grease	96,000 ppm 7,000 ppm 9.7%	4-NT** 289 --	100 acre site	McGinnis et al. (1988) Borazjani et al. (1989)
	(ii) Gulfport, Mississippi	"	"	wood treating plant sludge creosote (PAH's) PCP oil and grease	101,000 ppm 5,600 ppm 44%	4-1155 64 --	100 acre site	"
	(iii) Wiggins, Mississippi	"	"	wood-treating plant sludge creosote (PAH's) PCP oil and grease	20,000-114,000ppm 2,000-30,000 ppm 16-23%	2-82 NT --	100 acre site	"
	(iv) Columbus, Mississippi	"	"	wood-treating plant sludge creosote (PAH's) oil and grease	475,000 ppm 45%	2-NT --		"
	(v) Atlanta, Georgia	"	"	wood-treating plant sludge creosote (PAH's) PCP oil and grease	120,000 ppm 52,000 ppm 14%	4-NT NT --	15 acre site	"
	(vi) Wilmington North Carolina	"	"	wood-treating plant sludge creosote (PAH's)	10,000 ppm	4-NT		"
	(vii) Meridian, Mississippi	"	"	wood-treating plant sludge creosote (PAH's) PCP oil and grease	119,000 ppm 14,000 ppm 35.3%	3-NT 815 --	125 acre site	"
	(viii) Chattanooga Tennessee	"	"	wood-treating plant sludge creosote (PAH's) oil and grease	72,000 ppm 3.68%	4-NT --	76 acre site	"
1989	J.H. Baxter/ International Paper/Roseburg Superfund site, Weed, California	Feasibility study	Mississippi Forest Products Laboratory	creosote (PAH's) PCP and other preservatives and flame retardants	62-15,000 ppm 68-2,200 ppm	33-91 91-100		McGinnis et al. (1989)

Table 2.13 Summary of Landfarming Projects (Cont'd)

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1989	Chemical Company Site, Plaquemine, Louisiana	Remediation	Environmental Remediation Inc., Baton Rouge, La	phenol tars benzene	10-3,600 ppm 500-2,500 ppm <16 ppm	>99 >80-96 >50-97	30,000 yds ³	Christiansen et al.(1989)

* Degradation losses calculated as the percentage of the initial concentration lost during the test period.

** Degradation losses for the following sites: (i) Grenada, (ii) Aulport, (iii) Wiggins, (iv) Columbus, (v) Atlanta, (vi) Wilmington, (vii) Meridian, (viii) Chattanooga given as half life in days.

NT = no transformation detected

A major landfarming study was carried out by the Kananaskis Centre for Environmental Research at the University of Calgary during the period 1982 to 1989 and the results have been reported by Peake et al., (1985), Peak and Connery (1986), and Danielson et al., (1987, 1988, 1989, 1990). Sludges were taken from four sludge reclamation plants containing from 9-32% oil and variable amounts of water and solids. Asphaltene content in the oils varied from 4-17% while aliphatic hydrocarbon content ranged from 38-74% and aromatic content ranged from 10-20%. In laboratory studies, various textured soils from each proposed landfarm site were mixed in various ratios of oil to solid. Percent degradation of oil ranged from 19.9 to 69.4% over a six month period with a 95% confidence interval. Losses of volatile aromatic compounds due to volatilization were considered to be dominant over losses from biodegradation. In field trials, eight plots 30m long by 9.1m wide were established at each of four field sites. Sludge was applied to provide oil concentrations in the soil of 2 and 4% and various fertilizer application rates and cultivation rates were maintained. Degradation rates ranged from 42-81% over a two year period with most of the degradation occurring during summer months. Three PAH compounds, pyrene, chrysene and benzo(e)pyrene at initial concentrations ranging from 7.5 to 21.8 ppm, showed percent reductions ranging from 80-85% over a three year period. Losses of these heavier weight molecular compounds would not be considered to be dominated by volatilization processes and were therefore thought to have been biodegraded. The highly recalcitrant asphaltene component of the oily waste showed degradation rates of 14%, 15% and 17% in each of the last three years of the project. Good growth of gram and forage crops was attained where soil oil concentrations were less than 2.5-4%. There was no indication of the uptake of toxic compounds by crops grown in these soils.

At the Picillo Farm Superfund site in Coventry, Rhode Island, soil contaminated with an average 875 ppm total recoverable phenolics including phenols, chlorophenols and nitrophenols, was biodegraded in laboratory bench-scale tests against an abiotic control (Flatham et al., 1983). Replicate tests indicated 36% and 66% reductions in phenolics after 65 days. Full scale remediation of 1300 m³ of contaminated sandy loam soil was carried out in a double lined 0.28 ha landfarm facility. A drainage system was constructed to feed leachate from the field to a bioreactor for treatment and recirculated to the treated area for soil moisture control. Soil was tilled and amended with

nitrogen, phosphorus and commercially available microbes. A cosubstrate was added after day 13 to facilitate cometabolism after degradation decreased dramatically. On day 70, total recoverable phenolics were at a concentration of 168 ppm and further biodegradation was inhibited by freezing temperatures. Levels of total recoverable phenolics were measured at 61 ppm 304 days after the start of landfarming.

Bulman et al., (1988) studied PAH persistence and degradation in oil refinery wastes containing from 0.3-6% oil in both laboratory and field studies at three sites. Soils were analyzed for oil and grease and 16 target PAH's. Field losses of oil and grease over the 120 day field season (May to September) showed reductions of 17-35% from initial concentrations. Heavy molecular weight PAH's tended to remain in the soil but analytical variability hindered quantification of their loss.

Landfarming was applied to the cleanup of 4800 m³ of soil contaminated with oil tar at a former oil gasification site in Port Stanley, Ontario (Barnhard and Myers, 1989; Severson Environmental and Waste Stream Technology, 1989). The treatment area was lined with clay to prevent leachate migration to below the treatment area. Soil was conditioned and applications of nutrient and acclimated bacteria were made. Soil was tilled to a depth of 0.7m. The vendor reported the following percent reductions for PAH compounds:

2 and 3 ring PAH	92% reduction
4 ring PAH	80% reduction
5 ring PAH	67% reduction

Most of the PAH reduction was observed in the first 14 days with very little reduction observed during the following 37 days. A critical review of the above project by Waterloo Hydrogeology Advisors (1989) indicated that PAH reduction by biodegradation could not be substantiated by the field data because of a lack of control experiments during the pilot-scale studies. PAH losses could be attributed to other mechanisms such as volatilization for light PAH's (eg. naphthalene), homogenization of previously heterogeneously distributed contamination through tilling, leaching of contaminants during surfactant addition, and photolytic degradation.

In the United Kingdom, landfarming techniques were used to clean up soil at a gas-works plant contaminated with phenol and PAH's. Approximately 30,500 m³ of contaminated soil with a mean total PAH concentration of 22,000 mg/kg were treated over a 14 month period following extensive lab-scale treatability and pilot-scale testing. At this site, surfactants were added to solubilize PAH compounds. Pilot-scale testing indicated losses of fluoranthene, pyrene and benzo(a)pyrene (Bewley et al., 1989; Bewley and Thiele, 1988(a), (b); Bewley, 1987). Further information is provided in Case Study 18 in Appendix B.

At the Old Inger Superfund Site at Darrow, Louisiana, soils and lagoon sludges at the abandoned oil reclamation facility were contaminated with benzene, toluene, aliphatic hydrocarbons and PAH's. Levels of individual PAH's ranged from <100 ppm for benzo(a)pyrene to 5757 ppm for phenanthrene (Bianchini et al., 1988; Portier et al., 1988). Laboratory-scale feasibility studies were undertaken to study effects of nutrient additives and commercial microbes on PAH contaminant transformation. Field pilot-scale tests were done on five small field plots. Commercial microbes appeared to provide some advantage at this site in being able to degrade individual PAH's at a faster rate than indigenous microbes which had to undergo a period of acclimation. Abiotic losses were suggested but not defined. Transformation products of PAH's were identified as methyl substituted homologs with generally lower toxicity than the parent compounds. Half lives for acenaphthalene, anthracene and phenanthrene were similar to one another and ranged from 4.67 to 19.72 days in different experiments.

Transformation studies of wood treating plant waste sludges at eight sites in the southeastern United States indicated that half lives of selected 2 and 3 ring PAH's were ten days or less while other selected 2 and 3 ring PAH's had half lives ranging from 10 to 100 days. Some PAH's consisting of 4 rings and greater showed essentially no transformation within the time frame of the experiment while other heavy molecular weight PAH's (including benzo(a)pyrene) showed an ability to be degraded under certain conditions (Borazjani et al., 1989).

Aprill and Sims (1990) found that the breakdown of four and five-ringed PAH's was significantly greater for soil that was vegetated with prairie grasses than for soil that was unvegetated.

(iv) Need for Additional Research

Landfarming studies often fail to identify or monitor abiotic contaminant losses through volatilization and photolytic transformation and these contaminant loss pathways need to be better understood.

While light molecular weight PAH's are readily biodegraded, heavy molecular weight PAH's are more recalcitrant although some studies have suggested under certain conditions these compounds are also biodegradable. Continued research is required to more fully understand transformation processes. Very little data are available which identify intermediate products of biodegradation.

2.4.3 Enhanced Landfarming

(i) Process Description

Enhanced landfarming techniques are applied to increase rates of biodegradation and for the purposes of this report include those techniques that involve the use of one or more of the following: (i) forced soil aeration (ii) soil heating (iii) composting and (iv) soil enclosure.

Typically, soil is heaped into long windrows on an underdrained pad. Aeration pipes are installed at various levels and contaminated soil is placed in lifts in the windrow. Amendments are added as the soil is piled. A pump is placed on the pipe system and air is forced into the pile maintaining aerobic conditions throughout the pile. Heated air maintains higher temperatures in the soil pile and increases rates of biodegradation. In other configurations air is drawn into the pile by maintaining a vacuum in the pipe system. This technique is being investigated in Alberta (Callow and Danielson, 1990).

At some sites, impermeable membranes, similar to greenhouse structures, are erected over the soil mound to trap volatiles and to maintain soil

temperatures above ambient and in-ground temperatures (Yare et al., undated; Ross et al, 1988; Hater, 1988; Staps, 1989; Land Restoration Systems Ltd., 1990).

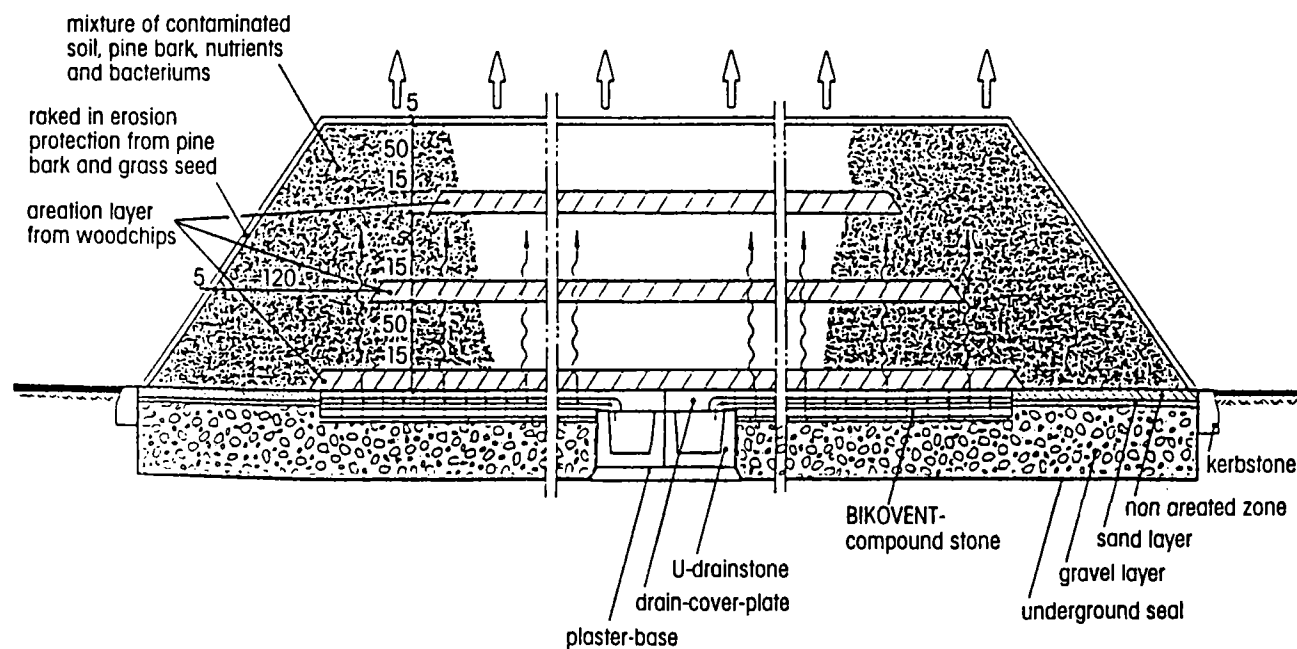
Composting is an enhancement technique and is well established in Germany, where bark is often mixed with the contaminated soil to provide a supplementary carbon source to enhance biological activity. A process developed by Shell in West Germany, known as BIOREG[®] involves composting contaminated soil, forced aeration, nutrient addition through sprinkling and recirculation of leachate. Figure 2.29 shows a section through a BIOREG[®] treatment pile (Este, 1990).

Advantages of enhanced landfarming over conventional landfarming include:

- better control of system parameters such as aeration, temperature, nutrient addition, leachate control, which results in faster rates of degradation
- volatilization can be quantified, and volatiles treated
- soil can be treated to greater depths with the use of forced aeration
- reduced maintenance costs
- requires less area to operate

Costs of enhanced landfarming techniques are within the range of \$75 - 125/tonne (Staps, 1990).

Other amendments include wheat straw, legumes, mushroom compost, green manure, sawdust and wood chips (Dearborn Environmental Consulting Group, 1990; Callow and Danielson, 1990).



(ii) Wastes Treated

Treated wastes include the same wastes which are treated by conventional landfarming except that degradation rates are much faster for enhanced techniques. As well, more recalcitrant hydrocarbon mixtures such as heavy crude oil and waxy lube oils are treatable (Land Restoration Systems Ltd., 1990) and pentachlorophenol biodegradation is reported to be significantly enhanced (Dearborn Environmental Consulting Group, 1990). Treatment of clayey soil and filter clays as well as sandy soils has been carried out using enhanced techniques. An enhanced landfarming technique is proposed to treat 6000m³ of soil contaminated with chlorinated solvents including trichloroethane and trichloroethylene, under anaerobic conditions (NATO/CCMS, 1987). Anaerobic conditions would be maintained by sprinkling nutrients and preventing air circulation in the soil mound by tightly covering the soil with an impermeable membrane.

(iii) Applications/Demonstrations

A summary of some projects which have utilized enhanced landfarming techniques is provided in Table 2.14.

At the Brio Refining Superfund Site at Friendswood, Texas, phenanthrene and volatile organic compounds including ethylbenzene (<4,400 ppm), toluene (<510 ppm), methylene chloride (0.53-20 ppm) and 1,1,2-trichloroethane (0.52-110 ppm) were monitored during enhanced landfarming (Yare et al., undated, Ross et al., 1988). Volatile losses of 99% were achieved through forced aeration over the 94 day treatment period, with most of the loss occurring within the first 21 days, principally by volatilization. Phenanthrene degradation indicated a half life of 33 days in the study compared to half lives of 69-398 days reported in the literature (Yare et al., undated).

De Kreuk (1986) provides an example of enhanced treatment of 900 tonnes of loamy, gasoline-contaminated soil, containing 1500 ppm total hydrocarbons. After 7 to 8 weeks under conditions of forced aeration, composting, and soil temperatures ranging from 22-25°C, total hydrocarbons in soil had been reduced

Table 2.14 Summary of Enhanced Landfarming Projects

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1988	Skrydstrup Chemical Waste Disposal Site, Skrydstrup, Denmark	Bench test	Technical University of Denmark	Trichloroethylene 1,1,1-Trichloroethane Tetrachloroethylene	0.5-25 ppm 1.1-190 ppm 1.1-19 ppm	-- -- --	6,000m ³	Broholm (1988) Anon. (1988)
1986	The Netherlands	Remediation	Mourik Groot Ammers Netherlands	Gasoline	1500 ppm	67-77	900 tonnes	DeKreuk (1986)
1984-1987	Brio Refining Superfund Site, Friendswood, Texas	Feasibility Study	Ecova Corp. Redmond, Washington	Still bottom tars Phenanthrene Chlorinated solvents	24,000 ppm 100,000 ppm	-- 78 --	200 yds ³	Ross et al. (1988) Yare et al. (no date)
1989	Refinery Site West Germany	Remediation	Land Restoration Systems Slough, U.K.	Refinery clay and filter cake total hydrocarbons	40,000 ppm	95	5,500m ³	Land Restoration Systems (1990) Lapinskas (1989)
1987	Manheim, West Germany	Remediation	Este, Hamburg, West Germany	Lubricants and Greases	45,000 ppm	82	7,000 m ³	Este (1990)
Not Given	United States	Remediation	Cambridge Analytical Associates Bioremediation Systems	Diesel fuel total petroleum hydrocarbons	2,800 ppm	71	3,000 yds ³	Fogel et al.

* Degradation losses calculated as the percentage of the initial concentration lost during the test period.

to 350-500 ppm. Based on air monitoring, hydrocarbon losses due to volatilization were calculated to be roughly 15%.

Land Restoration Systems (1990) provide several case studies including enhanced treatment at a former refinery site in Hannover, West Germany where 320m³ of clay soil contaminated with gasoline, light diesel fuel, and oils ranging from gas oil to heavier crude and waxy lube oils were treated. Average initial concentration of total hydrocarbon was 34,500 mg/kg. Fifty-two weeks of treatment led to a 75-80% reduction in total hydrocarbon concentration.

(iv) Need for Additional Research

Enhanced landfarming techniques have the advantage that the operator can control system conditions more readily than in conventional landfarming. However, there appears to be very little critical evaluation of the biotic and abiotic transformation processes or possible loss mechanisms (e.g. volatilization).

Research should continue into the processes and conditions which optimize biodegradation of more recalcitrant organic compounds.

2.4.4 Bioreactors

i) Process Description

Bioreactors are an important application of biotechnology to the problem of soil remediation, and offer the following advantages over conventional landfarming techniques:

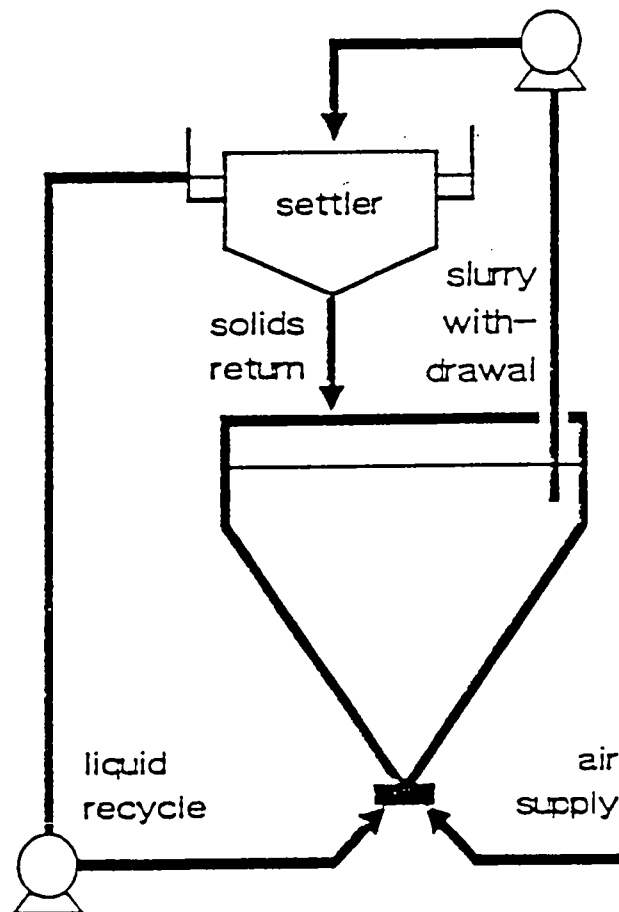
- operator maintains greater process control
- improved mixing increases contaminant availability to microorganisms
- biodegradation is faster and more effective
- treatment of complex organic compounds is possible
- treatment of clay soil and sludges is possible
- space requirements for treatment are considerably less

For the purposes of this report, bioreactors will include both vessel or tank type reactors and aeration lagoons. In the case of tank type bioreactors, preparation of waste feed may be required to reduce particle size to less than about 6.4mm ($\frac{1}{4}$ ") to prevent settling problems during mixing. The sized waste feed is then directed to a mixing tank or immediately to the bioreactor where it is slurried with water so that the solids concentrations are within the range of 10-20 wt percent to maintain particle suspension (Brox and Hanify, 1989). Nutrients and other additives such as commercially available microbes are added to optimize microbial growth. Surfactants can also be added to solubilize organic contaminants and improve the availability of the carbon source to microorganisms. The reactor is aerated to maintain aerobic conditions. Single stage bioreactors are often operated in batch mode since the operation is more easily controlled but continuous mode operation in multiple stage bioreactors is possible. The residence time of contaminated material in the bioreactor varies according to soil and contaminant type.

On completion of biodegradation, the slurry is dewatered by filtration or centrifugation. The dewatered solids are removed for final disposal. Liquid effluent can be treated and discharged or redirected back to the mixing cycle and used to slurry the next batch of waste feed. Likewise volatile emissions can be treated in-line or recirculated into the bioreactor to be biodegraded. A process schematic for bioreactors is shown in Figure 2.30.

In The Netherlands, research is being carried out using dry bioreactors, in which ambient moisture levels are maintained at 15-20%. The advantage of dry bioreactors is in the elimination of the dewatering step (U.S. EPA, 1988(c)).

Aeration lagoons have been used in The Netherlands to treat the fine fraction of large scale soil and sediment clean ups where the waste has been size separated using a hydrocyclone. The lagoon is lined with earth or an impermeable membrane and this system is mechanically aerated. Treatment times are similar to those for landfarming (Annokkee, 1989). Aeration lagoons can be set up as a



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PROCESS SCHEMATIC OF 3-PHASE SLURRY BIOREACTOR
(Kleijntjens and Luyben, 1988)

INTERA KENTING

Figure 2.30

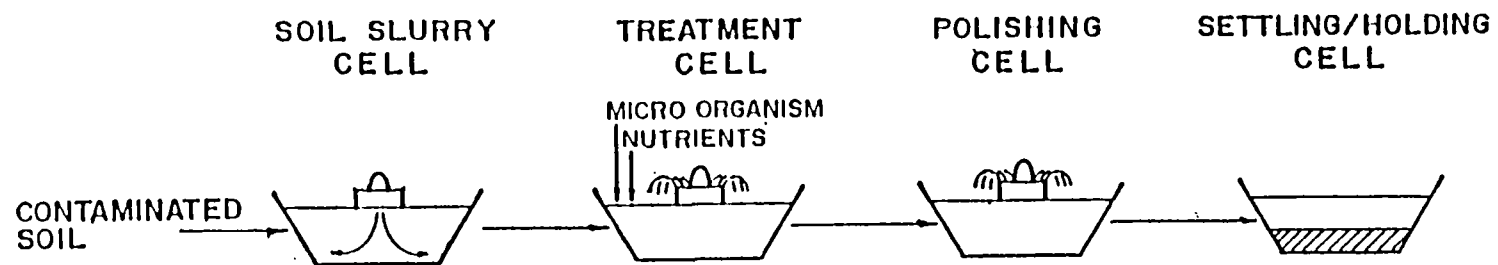
series of cells to treat large volumes of sludge waste. The first cell breaks down readily biodegradable contaminants, and after a period of about one week, sludge is transferred to a second polishing cell where more recalcitrant contaminants are treated. A third cell is used as a settling and holding cell for the treated soil prior to final discharge (Shack et al., 1989). A schematic of this treatment process is given in Figure 2.31.

TNO in The Netherlands has developed a pilot-scale bioreactor with a throughput of 10 tonnes/day. Commercial units with a capacity of 100-1100m³ and a treatment time of 10-14 days are proposed (U.S. EPA, 1988; Brox and Hanify, 1989).

Brox and Hanify (1989) estimate operating costs for a commercial scale bioreactor of approximately \$40/tonne with capital costs of \$2-7x10⁶. U.S. EPA (1988) estimate treatment costs using TNO bioreactors of approximately \$64/tonne.

ii) Waste Treated

Treatment of aliphatic hydrocarbons and low molecular weight PAH's in bioreactors leads to biodegradation rates that are about 100 times shorter than conventional landfarming (Soczo, 1989). Wastes treated using bioreactors include oily wastes and sludges from petroleum refinery operations and wood treating plant wastes. Individual contaminant groups include all of the same groups that are treated using conventional landfarming techniques as well as some of the more recalcitrant organic compounds such as high molecular weight PAH's (benzo(e)pyrene to anthanthrene) which in some lab-scale testing have shown 30% degradation in 14 days (TNO, 1988). Cyanides have been treated under bench-scale conditions (Brenner et al., 1987).



(iii) Applications/Demonstrations

A review of the literature indicated that most applications of bioreactor techniques are at the bench-scale and pilot-scale, and are used in the treatment of petroleum hydrocarbon and wood treating plant wastes. Several projects have looked at the treatability of chlorinated hydrocarbons and cyanide, and this remains an area of active research. A summary of applications of bioreactor technology are given in Table 2.15 and selected demonstration/applications are listed below.

U.S. EPA (1988) reported results of bench-scale and pilot-scale studies in batch mode in dry and slurry bioreactors at TNO in The Netherlands. Diesel fuel and cutting oils at initial concentrations of 4200 and 3000 mg/kg in sandy soil showed 79% and 77% degradation respectively in a dry bioreactor after 14 days. Cutting oils and PAH's with initial concentrations in loam soil of 26,000-65,000 mg/kg and 3,900 mg/kg respectively were degraded by 81-95% and 92% respectively in wet reactors after 14 days. Batch experiments were also conducted to study the biodegradation of the volatile chlorinated hydrocarbon, dichloromethane. The study was conducted under closed reactor conditions to prevent volatile losses. Ninety percent of the dichloromethane at initial concentrations of 20-30 ppm was degraded within one day.

At Delft University of Technology in The Netherlands, a lab-scale, 2-stage, continuous slurry feed, bioreactor has demonstrated a 70% degradation of diesel fuel contaminated soil from initial concentrations of 10 g/kg, after 200 hours treatment (Kleijntjens, 1989). Further information is provided in Case Study 19 in Appendix B.

Brox and Hanify (1989) report 60 wt % reduction in oil and grease from refinery sludges after 39 days and 90-95% removal for PAH's and PCP in treating the fine particle stream from a soil washing operation.

Table 2.15 Summary of Bioreactor Projects

Date	Site	Project Status	Contractor	Contaminants	Initial Concentration	Degradation Losses (%)	Initial Quantity Contaminated Soil	Reference
1987	Niagara Mohawk Power Corp.'s Harbour Point Site, Utica, New York	Bench-scale	University of Notre Dame, Notre Dame, Indiana	<u>Soils</u> cyanide phenol acenaphthylene	28.6 ppm 13.1 ppb 99.5 ppb	76-91 62-99 95-96	3.85 L	Brenner et al. (1987)
1988	Apeldoorn, The Netherlands	Bench-scale Pilot-scale in preparation	TNO Division of Technology for Society Apeldoorn, The Netherlands	Cutting oils diesel fuel PAH's dichloromethane	3,000 - 65,000 ppm 4,200 ppm 3,900 ppm 20-30 ppm	77-82 79 92 --		U.S. EPA (1988c) TNO (1988)
1989	Delft, The Netherlands	Bench-scale	Delft University of Technology Delft, Netherlands	diesel fuel	10,000 ppm	70		Kleijntjens et al. (1989) (see Case Study 19)
1989	Oil Refinery sludges	Bench-scale, Pilot-scale	Remediation Technologies Inc., Kent, Washington	oil and grease total PAH	not given 56,953 125,251	90-91 43-68		Stroo et al. (1989)
1989	Oil Refinery sludges	Pilot-scale	EIMCO Process Equipment Company Salt Lake City, Utah	oil and grease PAH PCP	not given not given not given	60 -- --		Brox and Hanify (1989)
1989	not given	Bench-scale	Research Institute for Nature Management (RIN), The Netherlands	Hexachlorocyclohexane	300 mg/kg	80-87		Soczko (1989)
1989	Wood Preserving Plant, Tennessee	Full-scale demonstration	Planning, Design and Research Engineers Inc. Nashville, TN	<u>Sludges</u> PCP Benzo(a)pyrene phenol <u>Soils</u> PCP Benzo(a)pyrene phenol	13,000 ppm 1,100 ppm 69 ppm 15,400 ppm 460 ppm 1,280 ppm	-- -- -- -- -- --	4,800m ³ 5,300m ³	Shack et al. (1989) (see Case Study 20)
1990	Ontario Refinery Site		Sanexen International, Burlington, Ontario	<u>Oil Sludges</u> mineral oils and greases	5.6%	89-96	400 tonnes	Sanexen International (1990)

* Degradation losses calculated as the percentage of the initial concentration lost during the test period.

Stroo et al., (1989) differentiate between oil refinery lagoon sludges and sludge pond sludges. Half lives for oil and grease in the former ranged from 2-4 weeks, while half lives for the latter ranged from 6-14 weeks.

Sanexen International has treated oily waste sludges from several sites in Canada. At a refinery site in Ontario, 400 tonnes of oily sludge with initial oil and grease concentrations of 5.6% were treated to 0.2-0.6% resulting in 89-96% degradation (Sanexen International, 1990).

Symons and Sims (1990) reported half lives for PAH's ranging from 15-17 days for fluoranthene to 173-231 days for benzo(g,h,i) perylene in batch reactors. Degradation rates decreased as loading rates increased from 2-8% initial oil and grease concentration.

At a wood preserving plant in Eastern Tennessee, 4800m³ of sludge and 5300m³ of soil contaminated with phenols, chlorinated phenols and PAH's were treated in a series of aeration lagoons. Initial concentrations for PCP were 13,000-15,400 ppm in sludge and soil and concentrations of individual PAH's ranged from 460 ppm for benzo(a)pyrene to 300,000 ppm for phenanthrene + anthracene. Maximum reductions of 98.5 to 99.8 were achieved for PCP, benzo(a)pyrene, and phenanthrene + anthracene (Shack et al., 1989). Further information is provided in Case Study 20 in Appendix B.

(iv) Need for Additional Research

Further research is required to optimize biodegradation for recalcitrant organic compounds in a variety of different soil and sludge compositions by controlling temperature, aeration, addition of acclimated microbes, nutrients and improving the transfer of contaminants to the sites of microbial adsorption through the use of surfactants, solvents, ultrasound and heat.



Process improvements such as dry reactors to eliminate the dewatering step will continue to be studied by TNO.

Further study is needed on the effects of system performance when bench and pilot-scaled systems are scaled up to full-scale.

3. SUMMARY OF TREATMENT TECHNOLOGIES

The amount and quality of available information on any one of the technologies discussed in this report varied from very detailed to very limited. Certain technologies such as thermal destruction techniques are well known processes, are available commercially and have a well documented history of application to soil cleanup, while other technologies such as solvent extraction and bioreactor technology are less well developed. Therefore comparisons of technologies and individual processes are made difficult by a lack of quality data which vary according to the degree of development of the process.

Discussions in the literature of various processes often reported the concentrations of organic contaminants as total hydrocarbons or total PAH's, so that the effectiveness of the technology on individual organic compounds was not evaluated.

A summary of treatment technologies is given in Table 3.1. Headings for comparison include:

- Contaminants treated
- Treatment rate
- Cost
- Mobility
- Advantages of process
- Disadvantages of process

For a number of the processes, information regarding treatment rate and cost were not available.

As mentioned in Section 2, treatment technologies discussed in this report can also be grouped into one of the following three broad classifications:

- Separation processes
- Destructive processes
- Immobilization processes

Table 3.1 Summary of Treatment Technologies

Process	Contaminants Treated	Treatment Rate (tonne/day)*	Cost (\$/tonne)	Mobility	Advantages	Disadvantages
THERMAL TREATMENT TECHNOLOGIES						
Rotary Kiln	PCB, Dioxin, BTX, PCP, PAH	25-600	235-1700	Mobile Units Available	<ul style="list-style-type: none"> • Technology is well known • Treats a wide range of waste feed types: sludge, slurries, solids 	<ul style="list-style-type: none"> • Treatment rates decrease with increasing moisture content • Metals in waste feed can decrease efficiency and increase particulate emissions
Circulating Bed Combustors	PCB, Hydrocarbon	70-124	118-353	Transportable Units Available	<ul style="list-style-type: none"> • Very efficient process • Proven cold weather application • Treats clay-gravel (<2.54cm waste feed) 	<ul style="list-style-type: none"> • Size limitations of waste feed • Treatment rates decrease with increasing moisture content
Plasma Arc/Torch	PCE, PAH, Phthalates	5-125	N/A	Transportable Unit not yet Developed	<ul style="list-style-type: none"> • High DRE • Treats liquids and solids (clay-gravel) 	<ul style="list-style-type: none"> • Developmental stage • Low feed rate • High energy consumption
Heat Soaking Furnace	PCB	N/A	N/A	Transportable		<ul style="list-style-type: none"> • Developmental stage • Unproven on soil waste feed
Infrared	PCB, PAH, Dioxin, PCP, Furans, Hal. Aromatics	100	<900	Mobile and Transportable Units	<ul style="list-style-type: none"> • Reduced particulate emissions • Good process control • Treats sludge and solids (5mm-5cm) 	<ul style="list-style-type: none"> • Higher maintenance costs • Some organics may remain in ash
Oxygen Enriched	Function of Original Incinerator	Increased by up to 2X	18-588 (savings)	Retrofit to Existing Incinerators	<ul style="list-style-type: none"> • Improves combustion efficiency • Substantial cost savings 	<ul style="list-style-type: none"> • Higher temperatures may cause refractory damage, slag formation
Advanced Electric Reactor	PCB, Dioxin	55-135	N/A	Transportable	<ul style="list-style-type: none"> • Waste feed <0.5mm 	<ul style="list-style-type: none"> • Developmental stage
High Temp Slagging	PCB, Chlorinated Organics	0.06	4,000	Not Transportable		<ul style="list-style-type: none"> • High cost • Low treatment rates • Limited testing to date
Molten Salt	PCB, Chlorinated Hydrocarbon	N/A	N/A	N/A	<ul style="list-style-type: none"> • Treats wide variety of lavash organic waste feed: liquid or solid 	<ul style="list-style-type: none"> • Developmental stage • Generates waste salt
Taciuk	Hydrocarbon PCB, PAH	72-600	60-140 (excludes excavation/feed prep.)	Transportable	<ul style="list-style-type: none"> • Well suited to hydrocarbon contaminated waste feed • Hydrocarbon waste feed produces combustible by-product which offsets operating costs • Treats soils and sludges 	<ul style="list-style-type: none"> • Non-destructive • Further treatment required

*Based on 24h per day operation

Table 3.1 Summary of Treatment Technologies (cont'd)

Process	Contaminants Treated	Treatment Rate (tonne/day)*	Cost (\$/tonne)	Mobility	Advantages	Disadvantages
Low Temperature Thermal	TCE, PCE, BTX, PAH	240-1200	94-176	Transportable	<ul style="list-style-type: none"> • Low Cost • High treatment rate • Recovery of saleable oil by-product • Treats soil waste feed <5-7.5cm 	<ul style="list-style-type: none"> • Possible hazardous by-products
PHYSICAL TREATMENT TECHNOLOGIES						
Portland Cement Solidification	Volatile Organics, PCBs, PAHs, BNAs Oil & Grease (?)	192-1560	125-275	Mobile	<ul style="list-style-type: none"> • Process well known • Withstands freeze/thaw cycles 	<ul style="list-style-type: none"> • Volume increase due to addition of cement • Requires additives to treat organics • High concentrations of organics and certain metals may affect integrity • Not suitable for fine grained (<0.075mm) silt and clay • some leaching of organics after treatment
Lime Based Solidification	Oil & Grease	288-720	150-200	Mobile	<ul style="list-style-type: none"> • Process well known • Can treat high concentrations of non-volatile organics 	<ul style="list-style-type: none"> • Exothermic - may volatilize volatile organics • Not evaluated under freeze/thaw cycles
Asphalt Batching	Gasoline, Tar Oil & Grease	840	100-130	Off-Site Process	<ul style="list-style-type: none"> • Low contaminant leachability • End product may be used as road bed material 	<ul style="list-style-type: none"> • High concentrations of flammable contaminants pose explosion hazard • Requires specialized equipment • Re-hydration of salts may cause fracturing • Control of air emissions • Unsuitable for heavy, wet clays • Incompatibility of many waste types
Organic Polymer Solidification	N/A	N/A	N/A	N/A	<ul style="list-style-type: none"> • Low density end product • Operates at low temperature • End product non-flammable 	<ul style="list-style-type: none"> • Not proven for organics • Contaminants may be easily leached • May produce acid leachate • May produce hazardous/noxious gases • Some polymers may be biodegradable
Silicate Solidification	BNAs, PAHs High Molecular Weight Organics	400	80	Mobile	<ul style="list-style-type: none"> • Equipment and additives readily available • Applicable to wide variety of high molecular weight organics 	<ul style="list-style-type: none"> • Slow setting times • Process water may leach contaminants • Not suitable for low molecular weight organics
Clay Stabilization	Organic Solvents, Phenols, PAHs, Alkanes, phthalates	N/A	N/A	N/A	<ul style="list-style-type: none"> • Lab-scale treatment of hydrocarbon contaminated sludge 	<ul style="list-style-type: none"> • Developmental stage
Glassification	PAHs	N/A	N/A	Transportable	<ul style="list-style-type: none"> • Very low leach rate 	<ul style="list-style-type: none"> • High energy demand • Specialized equipment and personnel

Table 3.1 Summary of Treatment Technologies (cont'd)

Process	Contaminants Treated	Treatment Rate (tonne/day)*	Cost (\$/tonne)	Mobility	Advantages	Disadvantages
Encapsulation	Oil	N/A	165-250	N/A	<ul style="list-style-type: none"> Resistant to chemical and mechanical stress Very low leaching of contaminants Materials are non-biodegradable 	<ul style="list-style-type: none"> High energy demand Skilled personnel required High cost of treatment Materials may be flammable Limited application to organic wastes
Soil Classification & Washing With Water	Volatiles, Semi-volatiles, LNAPLS	240-1440	95-132	Mobile	<ul style="list-style-type: none"> Inexpensive 	<ul style="list-style-type: none"> Problems with separating clays from solution Can generate large amount of sludge Difficulty with removing heavy molecular weight organics
Soil Washing with Acids/Bases	Volatiles, Chlorinated Hydrocarbons, Aromatics, Mineral Oil, PAHs	480	70-105	Mobile	<ul style="list-style-type: none"> Inexpensive 	<ul style="list-style-type: none"> Fine soils produce high amount of residual sludge Difficulty with removing heavy molecular weight organics
Aqueous Surfactants	Oil Distillate, PCBs, Chlorophenols, Volatile & Semi-volatile Organics	4-8	N/A	N/A	<ul style="list-style-type: none"> Contaminants separated from soil particles Can treat finer grained waste feeds 	<ul style="list-style-type: none"> Developmental stage Process waste water may be difficult to treat due to surfactant May require excessive amounts of surfactant
Chelating Agents	Metals	N/A	N/A	N/A		<ul style="list-style-type: none"> Does not treat organics
Steam Stripping	Volatile Organics	N/A	N/A	N/A	<ul style="list-style-type: none"> Can treat chlorinated hydrocarbons 	<ul style="list-style-type: none"> Developmental stage Limited to treatment of sandy soils
Agloflotation TM	Aliphatic and Aromatic Hydrocarbons, PAH	100	\$15-50	Mobile unit in development stage	<ul style="list-style-type: none"> Low cost treatment Produces combustible by-product Can treat heavy molecular weight organics 	<ul style="list-style-type: none"> Process requires coal Certain feed materials decrease process efficiency
Mosmans Method TM	Aliphatic and Aromatic Hydro-Organic Compounds	324 (fixed) 12 (mobile)	N/A	Mobile	<ul style="list-style-type: none"> High treatment capacity Can treat heavy molecular weight organics 	<ul style="list-style-type: none"> Produces large quantities of contaminated sludge which need to be disposed of
CHEMICAL TREATMENT TECHNOLOGIES						
B.E.S.T. TM	Aliphatic and Aromatic Hydrocarbons, PAH, PCB	34-90	65-132	Mobile	<ul style="list-style-type: none"> Treats a wide range of waste feed types including sludges and soils Closed system produces no volatiles 	<ul style="list-style-type: none"> TEA is a flammable solvent Waste water and solids may require treatment prior to disposal

Table 3.1 Summary of Treatment Technologies (cont'd)

Process	Contaminants Treated	Treatment Rate (tonne/day)*	Cost (\$/tonne)	Mobility	Advantages	Disadvantages
Extraksol™	Aliphatic and Hydrocarbons, PAH, PCB, PCP	0.9-1.4	90-180	Mobile	<ul style="list-style-type: none"> • Treats a wide range of waste feed types • Closed system produces no volatiles • Simplified process for volatiles 	<ul style="list-style-type: none"> • Reduced extraction efficiency on matrices with primary porosity • Third party evaluation of process required
LEEP	Aliphatic and Aromatic Hydrocarbons, PAH, PCB	N/A	N/A	Transportable pilot-scale unit under construction	<ul style="list-style-type: none"> • Has treated contaminated sediments and sludges 	<ul style="list-style-type: none"> • Developmental stage • Solids must be <1.25cm diameter
BP Oil	Aliphatic and Aromatic Hydrocarbons, PAH	13.5 (projected)	N/A	Mobile	<ul style="list-style-type: none"> • Has treated contaminated sludge 	<ul style="list-style-type: none"> • Full-scale commercial unit not yet available
Accurex	Aliphatic and Aromatic Hydrocarbons and PCB	N/A	N/A	N/A	<ul style="list-style-type: none"> • Volatile emissions are controlled and treated 	<ul style="list-style-type: none"> • Developmental stage • No pilot-scale treatment data
Soilex	PCB	N/A	N/A	N/A	<ul style="list-style-type: none"> • No data 	<ul style="list-style-type: none"> • No data
EETD	Aliphatic and Aromatic Hydrocarbons	N/A	N/A	N/A		<ul style="list-style-type: none"> • Developmental stage
CF Systems	Aliphatic and Aromatic Hydrocarbons, PAH, PCB, Phenolics and PCP, Chlorinated Solvents	45	190-580	Mobile	<ul style="list-style-type: none"> • Has treated wide range of organic contaminants and waste feed types 	<ul style="list-style-type: none"> • Operational problems at pilot-scale • Minimum temperature of waste feed is 15.5°C
APEG	Halogenated Wastes including PCB, Dioxins, Furans, Halogenated Solvents		195-400	Mobile	<ul style="list-style-type: none"> • Reaction products degrade to non-chlorinated species • Effective for halogenated non-volatile organics • Destructive technique 	<ul style="list-style-type: none"> • Requires storage of caustic reagents • Treatment of halogenated volatiles not proven • Effectiveness reduced by clay-rich and organic-rich soils
Eco Logic	Chlorinated Compounds including PCB, Dioxins, Chlorinated Solvents	N/A	N/A	Mobile	<ul style="list-style-type: none"> • Treats halogenated organic contaminants • Efficient destruction of PCB's • Considerably less expensive than incineration 	<ul style="list-style-type: none"> • Developmental stage
LANDTREAT	Aliphatic and Aromatic Hydrocarbons, PAH, PCP	100-300	70-125	Mobile	<ul style="list-style-type: none"> • Can treat small volumes of waste economically because of low mobilization costs 	<ul style="list-style-type: none"> • Contaminant loss from other processes including bioremediation, leaching, volatilization, photolytic decomposition

Table 3.1 Summary of Treatment Technologies (cont'd)

Process	Contaminants Treated	Treatment Rate (tonne/day)*	Cost (\$/tonne)	Mobility	Advantages	Disadvantages
<u>BIOLOGICAL TREATMENT TECHNOLOGIES</u>						
Landfarming	Aliphatic and Aromatic Hydrocarbons, Light Molecular Weight PAH, PCP	Variable treatment time 10's-100's of days	30-160	Set-up on site	<ul style="list-style-type: none"> • Inexpensive • Simple process 	<ul style="list-style-type: none"> • Abiotic losses not well controlled • Generally not effective for heavy molecular weight organic compounds • Produces air emissions • Requires large land area for large quantities of waste • Less effective in finer grained soils
Enhanced Landfarming	Aliphatic and Aromatic Hydrocarbons	Variable treatment time 10's of days	75-125	Set-up on site	<ul style="list-style-type: none"> • Can treat finer grained soils than conventional landfarming • Biodegradation rates are faster • More control over process conditions 	<ul style="list-style-type: none"> • Possibility of abiotic losses if system not completely closed • Slow degradation rates for heavy molecular weight organics
Bioreactors	Aliphatic and Aromatic Hydrocarbons, Low-Heavy Molecular Weight PAH's, PCP, Cyanides	10	40-70	Mobile	<ul style="list-style-type: none"> • Environmental conditions can be completely controlled • Can treat wide variety of aliphatic and aromatic hydrocarbons and chlorinated phenolics • Can treat sludges and fine grained soils 	<ul style="list-style-type: none"> • Waste feed may contain contaminants which are toxic to microorganisms • Considerable research still needed to optimize treatment rates

3.1 SEPARATION PROCESSES

Separation processes include:

- Non destructive thermal
- Flotation processes
- Soil washing
- Solvent extraction

These processes are used to reduce the volume of treatable waste by separating the waste from the soil matrix. The non-destructive thermal processes, solvent extraction and Agloflotation processes provide advantages over other flotation techniques and soil washing because they process the contaminant into a separate phase which may have economic value as a combustible product or a reusable oil or solvent. In the event that the product is not saleable, the contaminant phase produced can be disposed of by incineration. Other flotation processes and soil washing techniques do not concentrate the contaminant to the same extent, and the waste can include a substantial amount of the fine grained soil fraction leaving a higher volume of contaminated sludge which has no economic value.

The Agloflotation process appears to be very cost effective provided that a coal source exists nearby. It remains to be seen if the costs quoted for pilot-scale remediation can be maintained for a full-scale, mobile, commercial unit.

The difference in treatment between solvent extraction and non-destructive thermal techniques are not significantly different.

3.2 DESTRUCTIVE TECHNOLOGIES

Destructive technologies include the following:

- Destructive thermal technologies
- Substitution and reduction-oxidation technologies
- Biological

Destructive thermal technologies are generally well understood and well developed. They are, however, a very expensive treatment option.

Substitution and reduction-oxidation processes, on the other hand, are still, with a few exceptions, very much in the developmental stages or unproven, so that costs and performance have not been critically assessed. The APEG process has been field demonstrated. Both the APEG and Eco Logic process are designed to treat halogenated compounds. The APEG process is cost competitive with thermal destructive technologies but clay-rich and organic-rich soils may cause problems. The Eco Logic process is claimed to be significantly more cost effective than incineration and can handle a variable waste feed. A demonstration of this technology will be undertaken during 1990.

Biological techniques are destructive techniques for those contaminants which can be completely mineralized. However biological techniques can be slow and treatment effectiveness is dependent on a large number of environmental conditions. Enhanced landfarming and bioreactor techniques are more efficient techniques than landfarming, since environmental conditions can be more readily controlled. Of the biological techniques, bioreactors offer the most versatility in treating finer grained waste feed and high molecular weight organic compounds. Biological methods are considerably less expensive than incineration techniques.

3.3 IMMOBILIZATION TECHNOLOGIES

Immobilization technologies are non-destructive and serve to immobilize contaminants in a relatively inert material so that the contaminants will have a minimal impact on the environment. However, most of the immobilization technologies mentioned in this report allow some leaching of the contaminant to occur.

Immobilization techniques are probably the least favourable solution as a sole technology to treat soil contamination problems because the contaminant is not destroyed or transformed and is subject to leaching over time. As well, the process requires space, usually in a landfill, for storing the treated waste. The process does provide a treatment option for residues generated from other treatment techniques. Since the residue from other techniques are likely to



contain a high proportion of fine grained residues, the ideal immobilization process should be able to treat these types of wastes.

Both the Portland cement process and asphalt batching are adversely affected by high clay content. Organic polymer solidification is not a proven process for organics and some polymers may be subject to biodegradation. Glassification is probably the most environmentally acceptable because of low leaching potential but will probably prove to be cost prohibitive. Clay stabilization is still in the developmental stage. Further evaluation of immobilization technologies particularly under repeated freeze/thaw conditions is required.

4. SUMMARY OF RESEARCH AND DEVELOPMENT NEEDS

Research needs for each process were evaluated in a somewhat subjective manner and given a priority rating for research support of high, medium or low. General criteria used to establish research priority ratings are as follows:

- | | |
|-----------------|---|
| High Priority | <ul style="list-style-type: none">● technology is capable of treating high volumes of waste at low cost● technology has been proven effective elsewhere but has not been demonstrated in North America● technology is still in the developmental stage and has potential for application |
| Low Priority | <ul style="list-style-type: none">● technology is well understood and well developed● technology is commercially well developed● technology is no longer being actively developed or pursued● technology has severe limitations (i.e. process too expensive, low treatment rates, low treatment effectiveness, technology cannot be made mobile) |
| Medium Priority | <ul style="list-style-type: none">● contains some combination of criteria found under both high and low priority ratings |

A summary of research priorities is given in Table 4.1.

A general discussion justifying the research priority ratings is provided below.

1. Destructive thermal technologies are fairly well understood processes, and research relates more to process refinements such as improving the treatment capability by increasing treatment capacity and improving waste feed handling.

Rotary kiln, circulating bed combustors, infrared and oxygen enriched processes have been well demonstrated and are all available commercially. Consequently they are ranked low in terms of research priority needs.

The advanced electric reactor process has been developed at a pilot-scale, but commercial application of this process is no longer being pursued and this process is given a low priority rating.

High temperature slagging is rated as a low priority because of its extremely high operating costs, its low treatment rate and its lack of portability.

Three processes are given a low to medium rating. These include plasma arc/torch, heat soaking furnace and molten salts. These processes are still in the developmental stage and limited bench-scale testing has been completed at this time. Each process is currently being investigated and developed by commercial interests; however, a detailed evaluation of each process under Canadian site conditions should be conducted following results of pilot-scale testing.

2. Non-destructive thermal technologies would appear to have potential as a treatment process for petroleum hydrocarbon contaminated soils; however, research into applicability to chlorinated hydrocarbons is required.

Both the Taciuk and low temperature thermal processes are available commercially, although the Taciuk process has not been evaluated during a field demonstration. Both processes are capable of treating large quantities of waste. Further evaluation of these processes should be a medium to high priority.

3. Solidification/stabilization technologies are well established commercially, however, their application results in a volume increase in treated material due to the larger amount of reagents required. This can create a problem with ultimate disposal where disposal space is limited.

Generally these technologies require further research into the treatability of fine grained wastes and variable contaminant feeds containing organic compounds. Furthermore, long term evaluation of the impact of freeze/thaw cycles prevalent under Canadian conditions, and the leaching potential of organic compounds is required.

Generally speaking, the Portland cement, lime based solidification, thermoplastic, organic polymer silicate solidification, and encapsulation processes do not offer a permanent solution to the treatment of contaminated wastes. Because of the uncertainty in their ability to treat and effectively contain organic compounds in the waste, a low research priority rating has been assigned to them.

Clay stabilization shows some potential for stabilizing organic compounds under bench-scale testing and this process has been assigned a medium priority rating.

Glassification has been evaluated under pilot-scale tests but this technique is very expensive and consumes a large amount of energy. Consequently this technique has been given a low research priority rating.

4. Soil washing technologies are well advanced in Germany, but have not been used to any great extent in Canada. Soil washing results in a volume reduction in the amount of contaminated material but leaves contaminated residue which must be disposed using other destructive or non-destructive technologies. The technology works best on coarse grained sandy materials. Demonstrations of the technology are needed

and research should focus on reducing the amount of residue and improving the recovery of heavy molecular weight organics.

Soil classification and washing with water and bases were given a medium research priority rating because commercial application of these technologies are well established in Europe, however, application to North American and Canadian conditions has not been extensively demonstrated. Soil washing using aqueous surfactants to enhance the removal of organic compounds was given a high rating because this technology is still in the developmental stage. Soil washing using chelating agents was given a low rating because it is not a practical technology for treating organic compounds.

Steam stripping was given a medium rating. This technology is currently being evaluated as an in-situ technique but no application to excavated soil was found during the review of the literature. One advantage of developing this technique in Canada is that the technology has been applied for some time to enhance crude oil recovery and could be readily applied to the cleanup of contaminated soils.

5. Flotation methods use a well established process, but their application to cleaning contaminated soil is relatively new. The Aglofloat process shows promise as an inexpensive soil treatment method, and was given a high research priority. Further assessment of its capability to process a range of feed types and its extraction efficiency for a range of organic contaminants at field-scale is required.

The Mosmans Method is a well developed commercial process although very little information was available for evaluation of the technique. As a result of its commercial success, the process was given a low to medium research priority rating pending the review of more detailed information regarding process performance and case studies.

6. Solvent extraction techniques are promising techniques for reducing the volume of waste material. Further assessment of the range of contaminants and feed types that can be processed is required. A number of processes are still at the laboratory and pilot-scale and further pilot-scale and full-scale demonstrations are required.

The B.E.S.T.TM, ExtraksolTM, BP Oil and CF Systems processes are well developed commercially and have participated in demonstration projects and field-scale cleanups. They were assigned medium research priority ratings. Research would mostly involve critical third party evaluation of demonstrations under Canadian conditions. The LEEP and Accurex processes are commercially-supported technologies but were rated as high because they are currently at a bench-scale stage of development and considerably more testing is needed before these processes can be properly evaluated.

The EETD project has just recently been initiated and very little information is available on the project at this time. Consequently a medium to high research priority has been assigned to this project to determine whether the technology is feasible.

Very little information was available on the Soilex process. Results of pilot-scale testing were not available. As a result, this process was given a low to medium research priority rating pending the review of process performance.

7. Dechlorination techniques are specific to the treatment of PCB's, dioxins and furans, and other chlorinated compounds. The APEG process requires an assessment of the affect of sorbing materials in soils such as clays and organic matter on the treatment effectiveness. The APEG process is well supported by commercial interests and has been well demonstrated. Consequently it was given a low research priority rating.

The Eco Logic process would appear to be very suitable to the treatment of halogenated organics; however the process has not been critically evaluated by a third party under field conditions. A major demonstration of the technology will be undertaken in 1990 and GASRep should evaluate the results. For the purposes of this report, based on preliminary information, this process is rated as a high research priority.

8. Oxidation techniques which are at or near commercial availability should be demonstrated under Canadian field conditions. Losses by other processes such as biodegradation, volatilization, leaching and photolytic degradation should be assessed.

The LANDTREAT process has been applied mainly to hydrocarbon spills in California, but a critical evaluation of this process by a third party was not available. Consequently this process was given a medium research priority rating.

9. Biological techniques, particularly enhanced landfarming and bioreactor processes should be evaluated to:

- optimize conditions for biodegradation of recalcitrant organic compounds
- improve contaminant transfer
- quantify contaminant losses through abiotic processes
- identify transformation products

Landfarming techniques are well established but difficulty with the quantification of abiotic losses presents a problem with evaluating the effectiveness of the process. As a result, this process is given a low research priority rating.

Enhanced landfarming techniques provide greater control of environmental conditions and have been given a medium priority rating.

Bioreactors, including slurry and dry bioreactors and aeration lagoons, are still undergoing considerable research, despite the commercial availability of some mobile units. Bioreactors allow even greater control of process conditions than enhanced landfarming techniques and allow a critical evaluation of process effectiveness. Research priority needs for bioreactors are subsequently rated as high.

10. Any program that supports technology demonstrations under Canadian conditions should attempt to provide a series of standard waste feeds so that comparisons of different technologies on the same type of waste can be made.
11. In technology demonstration programs, specific organic parameters should be included in the parameter list so that the effectiveness of technologies on specific organic compounds can be evaluated and compared with other technologies.

Table 4.1 Summary of Research Needs

Process	Research Needs	Development Stage	Research Priority
<u>THERMAL TREATMENT TECHNOLOGIES</u>			
Rotary Kiln	<ul style="list-style-type: none"> • Improve treatment rates 	Commercial	Low
Circulating Bed Combustors	<ul style="list-style-type: none"> • Better definition of interferences • Improve treatment rates 	Commercial	Low
Plasma Arc/Torch	<ul style="list-style-type: none"> • Evaluate economics of operation • Evaluate process sensitivity to system changes • Improve treatment rates 	Bench-scale	Low-Medium
Heat Soaking Furnace	<ul style="list-style-type: none"> • Constant pilot-scale unit and test 	Bench-scale	Low-Medium
Infrared	<ul style="list-style-type: none"> • Evaluate performance as a function of waste feed properties 	Commercial	Low
Oxygen Enriched	<ul style="list-style-type: none"> • Improve understanding of operating characteristics 	Commercial	Low
Advanced Electric Reactor	<ul style="list-style-type: none"> • Increase range of waste feed size 	Pilot-scale	Low
High Temp. Slagging	<ul style="list-style-type: none"> • Improve economics of operation and treatment rates 	Pilot-scale	Low
Molten Salts	<ul style="list-style-type: none"> • Construct pilot-scale unit and test 	Bench-scale	Low-Medium
Taciuk	<ul style="list-style-type: none"> • Applicability to chlorinated hydrocarbons 	Commercial	Medium-High
Low Temperature Thermal	<ul style="list-style-type: none"> • Evaluate suitability for chlorinated hydrocarbons and hazardous byproduct generation 	Commercial	Medium-High
<u>PHYSICAL TREATMENT TECHNOLOGIES</u>			
Portland Cement Solidification	<ul style="list-style-type: none"> • Evaluate suitability for treating organic compounds 	Commercial	Low
Lime Based Solidification	<ul style="list-style-type: none"> • Evaluate performance under freeze/thaw conditions • Evaluate range of suitability for organic compounds 	Commercial	Low
Thermoplastics (Asphalt Batching)	<ul style="list-style-type: none"> • Verify leaching characteristics • Evaluate air emissions 	Commercial	Low
Organic Polymer Solidification	<ul style="list-style-type: none"> • Undertake pilot-scale testing on organics 	Commercial	Low
Silicate Solidification	<ul style="list-style-type: none"> • Investigate leaching of organic compounds 	Commercial	Low
Clay Stabilization	<ul style="list-style-type: none"> • Pilot-scale testing to identify range of soil type and contaminant type that can be treated 	Bench-scale	Medium

Table 4.1 Summary of Research Needs Cont'd

Process	Research Needs	Development Stage	Research Priority
Glassification	<ul style="list-style-type: none"> • Evaluate organic leaching • Assess volatile emissions during and after treatment 	Commercial, pilot-scale	Low
Encapsulation	<ul style="list-style-type: none"> • Pilot testing to identify treatability of range of matrix types and organic contaminants 	Commercial	Low
Soil Classification and Washing with Water	<ul style="list-style-type: none"> • Assess practical range of environmental operating temperature conditions • Reduction in amount of residue 	Commercial	Medium
Soil Washing with Acids and Bases	<ul style="list-style-type: none"> • Improve heavy molecular weight organic recovery through use of chemical additives • Assess practical range of environmental operating temperature conditions 	Commercial	Medium
Aqueous Surfactants	<ul style="list-style-type: none"> • Full-scale demonstration • Assess range of contaminant types and surfactants compatible with process 	Commercial, pilot-scale	High
Chelating Agents	<ul style="list-style-type: none"> • Not a practical technology for treating organic compounds 	Commercial	Low
Steam Stripping	<ul style="list-style-type: none"> • Feasibility of steam stripping versus low temperature air stripping 	Pilot-scale	Medium
Agloflotation TM	<ul style="list-style-type: none"> • Further assessment of range of feed types and extraction efficiency of various organic contaminants required • Develop mobile unit 	Commercial, pilot-scale	High
Mosmans Method TM	<ul style="list-style-type: none"> • Evaluation of pilot-scale and field-scale data on treatment process required before research needs can be identified • Laboratory-scale studies on PCB treatment in progress 	Commercial	Low-medium
<u>CHEMICAL TREATMENT TECHNOLOGIES</u>			
B.E.S.T. TM	<ul style="list-style-type: none"> • Further evaluation of waste feed compositions that affect system performance 	Commercial	Medium
Extraksol TM	<ul style="list-style-type: none"> • Third part critical evaluation of site demonstration • Further evaluation of treatability of waste feed types 	Commercial	Medium
LEEP	<ul style="list-style-type: none"> • Evaluation of pilot-scale and full-scale treatment required 	Commercial	High
BP Oil	<ul style="list-style-type: none"> • Assess treatability for other organic contaminants such as chlorinated phenols and chlorinated solvents 	Commercial	Medium
Accurex	<ul style="list-style-type: none"> • Treatment at pilot-scale and full-scale required • Assess treatability for a range of organic contaminants and waste feed 	Bench-scale	High
Soilex	<ul style="list-style-type: none"> • Treatment at pilot-scale and full-scale 	Pilot-scale	Low-medium

Table 4.1 Summary of Research Needs Cont'd

Process	Research Needs		
EETD	• Still at initial laboratory stages of development	Bench-scale	Medium-High
CF Systems	• Assess systems performance under cold weather conditions • Assess potential of oxidizing organic residue while system still at critical temperature and pressure	Commercial	Medium
APEG	• Investigate inhibitory effects of clay soils and organic materials • Investigate use of solvents to solubilize contaminant and speed up reaction rates • Investigate transformation products and their toxicity	Commercial	Low
Eco Logic	• Test program scheduled for 1990 for Canadian Department of National Defense	Commercial, pilot-scale	High
LANDTREAT	• Assessment of contaminant losses from other processes should be evaluated • Third party evaluation of pilot-scale and field-scale treatment • Further understanding of basic processes and identification of transformation products for a variety of soil and contaminant types	Commercial	Medium
<u>BIOLOGICAL TREATMENT TECHNOLOGIES</u>			
Landfarming	• Improve monitoring for abiotic losses • Identification of intermediate products of biodegradation	Commercial	Low
Enhanced Landfarming	• Optimize conditions for biodegradation of recalcitrant organic compounds • Identify transformation products from biotic and abiotic degradation	Commercial	Medium
Bioreactors	• Optimize biodegradation for recalcitrant organic compounds • Improve transfer of contaminants • Process improvements such as dry reactors • Affects on system performance during scale-up	Commercial	High

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APPENDIX A
LISTING OF KEY CONTACTS, RESEARCHERS,
ORGANIZATIONS AND VENDORS

LISTING OF KEY CONTACTS, RESEARCHERS, ORGANIZATIONS AND VENDORS

Rotary Kiln Incinerators

Weston Services Inc.
Weston Way
West Chester, Pa. 19380
Contact: John W. Noland
Telephone: (215) 430-3103

ENSCO Environmental Services Inc.
First Tennessee Bank Building
Franklin, Tn. 37064
Telephone: (615) 794-1351

IT Corporation
321 Directors Drive
Knoxville, Tn. 37923
Telephone: (615) 690-3211

Vesta Technology Corp.
1670, West McNab Road
Ft. Lauderdale, Fl. 33309
Telephone: (305) 978-1300

Selenco/Sanivan
3027 Harvester Road
Burlington, Ont. L7N 367
Telephone: 1-800-263-6368

Circulating Bed Combusters

Ogden Environmental Services, Inc.
10955 John Jay Hopkins Drive
San Diego, Ca. 92121
Contact: Cynthia M. Hashiguchi
Telephone: (619) 455-3045

Superburn Systems, Ltd.
#201-2034 West 12th Avenue
Vancouver, B.C. V6J 2G2
Contact: Bert Putt
Telephone: (604) 732-7592



Infrared Incineration

O.H. Materials Canada, Ltd.
2180 Speers Road
Oakville, Ontario L6J 6L5
Telephone: (416) 847-1700

ECOVA Corp
12790 Merit Drive
Dallas, Texas 75251
Telephone: (214) 404-7540

Westinghouse/Haztech
5280 Panola Industrial Blvd.
Decatur, Ga 30035
Telephone: (404) 981-9332

Oxygen Enriched

American Combustion Technologies
2985 Gateway Dr., Suite 100
Norcross, Ga 30071
Telephone: (404) 662-8156

Advanced Electric Reactor

J. M. Huber Corp
(Street address unknown)
Borger, Tx.
Telephone (806) 274-5040

Taciuk

Soil Tech Inc.
800 Canonie Dr.
Porter, Indiana
Telephone: (219) 929-4343

Heat Soaking Furnace

PPM Canada Ltd.
1 Yonge Street, Suite 801
Toronto, Ontario M5E 1E5
Telephone: (416) 364-1919



Plasma Arc

Westinghouse
P.O. Box 286
Madison, Pa 15663
Telephone: (412) 722-5714

Retech Inc.
100 Henry Station Road
Ukiah, Ca 95482
Telephone: (707) 462-6522

Pyrolysis Systems
209 Dalton Avenue
Kingston, Ontario
Telephone: (613) 546-1783

Low Temperature Thermal

Canonie Environmental Services Corp
800 Canonie Dr.
Porter, Indiana 46304
Telephone: (219) 926-8651

Weston Services Inc.
Weston Way
West Chester, Pa 19380
Contact: John W. Noland
Telephone: (215) 430-3103

Chemical Waste Management Inc.
3003 Butterfield Road,
Oakbrook, IL 60521
Contact: Robert LaBoube
Telephone: (708) 218-1500

Soil Recycling Company
P.O. Box 295
Gormley, Ontario L0H 1G0
Contact: Jim Phimister
Telephone: (416) 888-9218



Portland Cement Solidification/Stabilization

HAZCON Engineering Inc.,
P.O. Box 1247
Brookshire, Texas 77423
Contact: Ray Funderburk
Telephone: (800) 227-6543

Canadian Waste Management Corp
#205-2003 McKnight Blvd. N.E.
Calgary, Alberta T2E 6L2
Contacts: W. Rama / J. Gardner/ P. Richardson
Telephone: (403) 291-5082

Soliditech Inc.
6901 Corporate Drive, Suite 215
Houston, Texas 77036
Contact: Carl Brassow
Telephone: (713) 778-1800

Lime Solidification/Stabilization

Separation and Recovery Systems Inc.
Irvine, California 92714
Contact: Joseph de Franco
Telephone:

Silicates Solidification/Stabilization

Silicate Technology Corporation
Scottsdale Technology Center
7650 East Redfield Road, Suite B2
Scottsdale, Arizona 85260
Contact: Steve Pegler
Telephone: (602) 941-1400

Chemfix Technologies Inc.
Suite 620, Metairie Center,
2424 Edenborn Avenue
Metairie, Louisiana 70001
Contact: Philip N. Baldwin Jr.
Telephone: (504) 831-3600



Siallon Technologies Inc.
P.O. Box 3324
1659 Industrial Road
Cambridge, Ontario N3H 4T3
Contact: Wendy Moncrieff
Telephone: (519) 653-1442

Miscellaneous Solidification/Stabilization

CECOS International Inc.
2321 Kenmore Avenue
Buffalo, NY 14207
Contact:
Telephone:

Wastech Inc.
P.O. Box 1213
114 Tulsa Road
Oak Ridge, Tennessee 37830
Contact: E. Benjamin Peacock
Telephone: (615) 483-6515

International Waste Technologies
150 North Main Street
Suite 910
Wichita, Kansas 67202
Contact: Jeff P. Newton
Telephone: (316) 269-2660

Glassification

Battelle Pacific Northwest Laboratories
Battelle Boulevard
Richland, Washington 99352
Contact:
Telephone:

Geosafe Corporation
303 Park Place, Suite 126
Kirkland, Washington 98033
Contact: James E. Hansen
Telephone: 206-822-4000



Soil Washing

GKN Keller Canada Ltd.,
21 Conventory Road,
Brampton, Ontario L6T 4V7
Contact: George R. Grisham
Telephone: (416) 791-0505

MTARRI
1511 Washington Avenue
Golden, Colorado 80401
Contact:
Telephone: (303) 279- 4255

Biotrol
11 Peavey Road
Chaska, Minnesota 55318
Contact: Thomas Chresand
Telephone: (612) 448-2515

Harmon Environmental Services Inc.
1530 Alabama Street
Auburn, Alabama 36830
Contact: William C. Webster
Telephone: (205) 821-9253

IT Corporation
312 Directors Drive
Knoxville, Tennessee 37923
Contact: Robert D. Fox
Telephone: (615) 690-3211

Ozoning Recycling Corporation
927 Crandon Boulevard
Key Biscayne, Florida 33149
Contact: Lucas Boeve
Telephone: (305) 361-8936

PEI Associates Inc.
11499 Chester Road
Cincinnati, Ohio 45246
Contact:
Telephone:



Foster Wheeler Enviresponse Inc.
Livingston, New Jersey 07039
Contacts: Carl Gutterman / Ramjee Raghavan
Telephone: (201) 906-6866

Roy F. Weston Inc.
P.O. Box 177
Ohmsett Facility-Waterfront
Highway 36
Leonardo, New Jersey 07737
Contact: James Nash
Telephone: (201) 906-3464

Flotation

Alberta Research Council
P.O. Bag 1310
Devon, Alberta T0C 1E0
Contact: Leszek Ignasiak
Telephone: 403) 987-8111

Mosmans Mineraal techniek BV
Rijnstraat 15
5347 KL OSS
The Netherlands
Contact: Bouwe Bölger
Telephone: 04120-42381

Solvent Extraction

Resources Conservation Company
3006 Northup Way
Bellevue, Washington 98004
Contact: Lisa Robbins
Telephone: (206) 828-2400

Sanexen International
3027 Harvester Road, Unit 204
Burlington, Ontario L7N 3G2
Contact: Mark Cvar
Telephone: (416) 681-3366

ART International Inc.
273 Franklin Road,
Randolph, New Jersey 07869
Contact: Werner Steiner
Telephone: (201) 361-1021



BP Oil Company
200 Public Square
Cleveland, Ohio 44114-2375
Contact: John Laskowski
Telephone: (216) 586-3968

Environment Canada
Environmental Emergencies Technology Division
River Road Environmental Technology Centre
3439 River Road
Ottawa, Ontario K1A 0H3
Contact: Monique Punt
Telephone: (613) 991-1840

CF Systems Corporation
140 Second Avenue
Waltham, Massachusetts 02154-1100
Contact: Thomas J. Cody Jr.
Telephone: (617) 890-1200

U.S. EPA, Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
Cincinnati, Ohio 45628
Contact: Ed Bates
Telephone: (513) 569-7774

Substitution and Reduction-Oxidation

Galson Remediation Corporation
6627 Joy Road
East Syracuse, New York 13057
Contact: Robert L. Peterson
Telephone:

U.S. EPA 15-210
Emergency Response Division
401 M Street, SW
Washington DC 20460
Contact: David Lopez
Telephone: (202) 382-2471

U.S. EPA Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
Cincinnati, Ohio 45628
Contact: Charles Rogers
Telephone: (513) 569-7757



Eco Logic
143 Dennis Street
Rockwood, Ontario N0B 2K0
Contact: Douglas J. Hallett
Telephone: (416) 450-7691
(416) 856-9591

Drexel University
Environmental Studies Institute
Philadelphia, Pennsylvania 19104
Contact: Mirat D. Gurol
Telephone: (215) 895-2268

Ensotech Inc.
11300 Hartland Street
North Hollywood, California 91605
Contact: I.H. Sabherwal
Telephone: (818) 760-8622

Chemisches Laboratorium Dr. E. WeBling
OststraBe 2
4417 Allenberge
Federal Republic of Germany
Contact: Heinrich Ruholl
Telephone: 02505/89-0

Biological - Government Agencies

United States Environmental Protection Agency
J.S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820
Contact: John Mathews
Telephone: (405) 332-8800

Umweltbundesamt
Bismarckplatz 1
1000 Berlin 33
Federal Republic of Germany
Contact: G. Rakette
Telephone (030) 8903-0

Biological Research Institute/Universities

Utah State University
Utah Water Research Laboratory
Logan, Utah 84322 - 8200
Contact: Ronald C. Sims
Telephone: (801) 750-1000 ext. 2926

University of Texas at Austin
Department of Civil Engineering
Austin, Texas 78712 - 1076
Contact: Raymond C. Loehr
Telephone: (512) 471-5602

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831 - 6038
Contact: Barbara T. Walton
Telephone: (615) 574-7839

National Institute of Public Health and Environmental
Protection(RIVM)
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APPENDIX B
CASE STUDY INFORMATION SHEETS



CASE STUDY INFORMATION SHEET

Case Study 1

1. TREATMENT TECHNOLOGY

Type: Rotary Kiln Incinerator (ENSCO MWP-2000)

Organization: Illinois EPA

Stage of Development: Full Scale

2. SITE CHARACTERISTICS

Location: Lenz Oil Site (near Chicago, IL)

Climate: Temperate

Soil Type: Not specified

3. SOIL CONTAMINATION

Contaminants: Solvents, oils, petroleum products, 360 chemical compounds were identified. Sludges, liquids, contaminated soils

Levels of Concentration: BTX (9.2, 890, 2000 ppm max)
PAHs (BAP 40 ppm; fluoranthene 200 ppm; pyrene 83 ppm;
max.)
Acetone (41 ppm max); TCE (22 ppm max)

Extent of Contamination: 7,000 tons of contaminated soil

4. OPERATIONAL INFORMATION

Period of Operation: July, 1987

Process Description: Process consists of:

- 1) Waste feed system - hopper, shredder, conveyor, feed hopper and screw auger, waste reduced to <10 cm
- 2) Rotary kiln incinerator - 1600°F
- 3) Secondary combustion chamber - 2400°F
- 4) Waste heat exchanger
- 5) Air pollution control units - quench system, packed tower, scrubber and neutralization unit



Treatment Rate: up to 6 tons/hour

Treatment Costs: \$607/ton of contaminated soil

System Mobility: Contained on 20 trucks

Installation Time: Approximately 6 weeks

5. TREATMENT EFFECTIVENESS

Efficiency: Test burn using PCE and CCL_4 :

- i) DRE >99.99%
- ii) particulate <0.08 grains/f⁺³
- iii) HCL removed >99%

Process By-Products: Cleaned soil backfilled on site

Research Needs: Improved transportability/mobility

6. CONTACTS FOR INFORMATION

Name: James E. Frank

Address: Division of Land Pollution Control
Illinois Environmental Protection
Springfield, Illinois

7. REFERENCES Frank et al., 1987 Shu, 1989



CASE STUDY INFORMATION SHEET

Case Study 2

1. TREATMENT TECHNOLOGY

Type: Circulating Bed Combustor (CBC)
Organization: Ogden Environmental Services, San Diego, Ca.
Stage of Development: Full scale commercial

2. SITE CHARACTERISTICS

Location: Swanson River, Alaska
Climate: Cool temperate
Soil Type: Silt, clay and gravel

3. SOIL CONTAMINATION

Contaminants: PCB's
Levels of Concentration: Up to 801 ppm; average of six tests was 595 ppm
Extent of Contamination: 75,000 tons of contaminated soil

4. OPERATIONAL INFORMATION

Period of Operation: 3 years (scheduled finish by 1991)
Process Description: Soil is preprocessed (screened, crushed and dried). Contaminated soils circulate through a combustion loop consisting of 36 in. i.d. combustion chamber and cyclone. A flue gas cooler and gas filter conditions exhaust gases prior to exiting through an exhaust stack. No "scrubbers" are required.
Treatment Rate: 100 tons/hour
Treatment Costs: \$100-300/ton
System Mobility: Transportable
Installation Time: Three weeks



5. TREATMENT EFFECTIVENESS

Removal Efficiency: Destruction and Removal Efficiency (DRE) of greater than 99.99993%. Contaminant (PCB) levels in ash averaged 12.6 ppm.

Process By-Products: Dioxin levels in stack gas averaged 0.49 ng/dscm and in ash 177 ppt. HCL and other VOC levels in stack gas were not reported.

Research Needs:

6. CONTACTS FOR INFORMATION

Name: Derrell Young

Address: Ogden Environmental Services
P.O. Box 85178
San Diego, CA

Telephone: (619) 455-3045

7. REFERENCES Anderson B.M. and R.G. Wilbourn, 1989.
 Ogden Environmental Services, undated.
 Shu A.C., 1989.



CASE STUDY INFORMATION SHEET

Case Study 3

1. TREATMENT TECHNOLOGY

Type: Plasma Torch
Organization: Retech Inc.
Stage of Development: Pilot Scale

2. SITE CHARACTERISTICS

Location: Ukiah, Ca (test facility)
Climate: Temperate
Soil Type: sand (31%), gravel (6%), silt (28%), topsoil (20%), clay 15%

3. SOIL CONTAMINATION

Contaminants: Metals, chlorinated organics
Levels of Concentration: PCE (3,277 ppm), anthracene (7,361 ppm)
Bis (2-ethylhexyl) phthalate
Extent of Contamination: 300 lbs. of soil

4. OPERATIONAL INFORMATION

Period of Operation: Days

Process Description: Contaminated soil is fed into the reactor via a spiral feeder. The reactor consists of three chambers: primary containing plasma torch, secondary chamber where PIC's react with supplemented O₂ and a chamber to collect molten glass. The primary chamber is a rotating vessel 1.8 m ID which rotates at 40 rpm. Material is processed in a batch mode and off-gases are treated with a pollution control system consisting of a scrubber, sampler, recirculation and exhaust component at temperatures of 1,000°C.



Treatment Rate: <600 lbs/hr

Treatment Costs: Not specified

System Mobility: Not specified

Installation Time: Not specified

5. TREATMENT EFFECTIVENESS

Efficiency: DRE's of 99.99% to 99.9999%; high levels of organics in slag attributed to feeder malfunction

Process By-Products: Vitrified slag

Research Needs: Higher capacity units; actual field tests

6. CONTACTS FOR INFORMATION

Name: R.C. Eschenbach

Address: Retech Inc.
100 Henry Station Road
Ukiah, California
(707) 462-6522

7. REFERENCES Eschenbach et al., 1989



CASE STUDY INFORMATION SHEET

Case Study 4

1. TREATMENT TECHNOLOGY

Type: Infrared Incineration System

Organization: Shirco Infrared Systems Inc. Dallas, Texas
For Michigan Dept. Natural Resources, USEPA

Stage of Development: Pilot Scale

2. SITE CHARACTERISTICS

Location: Demode Road Superfund Site, Rose Township Mi.

Climate: Temperate

Soil Type: Sandy and silty clay topsoil, moisture content = 9%

3. SOIL CONTAMINATION

Contaminants: Mainly PCB's, trace levels of methylethyl ketone, trichlorethene, bis (2-ethylhexyl) phthalate, lead

Levels of Concentration: 10.2 to 669 ppm PCB; lead 290-3,000 ppm

Extent of Contamination: 1,799 Kg of contaminated soil treated

4. OPERATIONAL INFORMATION

Period of Operation: 17 demonstration burns using various Primary Combustion Chamber Temperatures (900°, 1200°, 1400°, 4600°F), Secondary combustion chamber temperatures (1800, 2200°F), residence times (10, 15, 20 and 25 minutes) in oxidizing and non-oxidizing environments.

Process Description: Consists of a waste feed system, an (electric) infrared primary combustion chamber, a propane fired secondary combustion chamber, an emissions control scrubber, exhaust system and data collection/control system.



Treatment Rate: <150 lbs/hr. (waste feed rate)

Treatment Costs: Not specified

System Mobility: - contained on 45 foot trailer

Installation Time: - less than one week

5. TREATMENT EFFECTIVENESS

Removal Efficiency: Destruction and removal efficiency (DRE) for PCB was greater than 99.99%, although low feed concentration and analytical detection limit prohibited more accurate determination. Highest PCB ash residuals of 21 and 3.4 ppm resulted from low primary combustion temperature (900°F) in pyrolytic environment.

Process By-Products: VOC's (<100 ppb) in stack gas HCL emissions 0.181 to 0.998 gm/hr.
- no dioxins or furans.

Research Needs: The feasibility of higher treatment rates and better characterization of PIC's in exhaust gases and ash especially for higher feed concentrations.

6. CONTACTS FOR INFORMATION

Name: Mr. Howard Wall

Address: EPA SITE Program Manager, Risk Reduction Engineering Lab.
Cincinnati, Ohio 45268

Telephone: (513) 569-7691

7. REFERENCES U.S. Environmental Protection Agency, 1989d.



CASE STUDY INFORMATION SHEET

Case Study 5

1. TREATMENT TECHNOLOGY

Type: Taciuk
Organization: Soil Tech
Stage of Development: Full Scale

2. SITE CHARACTERISTICS

Location: Calgary, Alberta (test facility)
Climate: Continental
Soil Type: Sand, sludge

3. SOIL CONTAMINATION

Contaminants: PCBs
Levels of Concentration: Test #1 0.7% Arochlor 1242
Test #2 1.5% Arochlor 1242
Extent of Contamination: Test #1 16,800 lbs.
Test #2 29,500 lbs

4. OPERATIONAL INFORMATION

Period of Operation: Test #1 2 hours
Test #2 4 hours

Process Description: The Taciuk processor consists of four sections: preheat, retort, combustion and cooling. Preheat section removes water and light oil from soil. Retort vaporizes heavy oil and PCB. The combustion chamber uses supplemental fuel to remove coke residual created on soil and cooling section cools soil for discharge. Air pollution control consisted of a baghouse (particulate) and scrubber (acid gas).



Treatment Rate: 8,400 lbs/hr

Treatment Costs: Not specified

System Mobility: Not specified

Installation Time: Not specified

5. TREATMENT EFFECTIVENESS

Efficiency: PCB levels in clean soil $<14 \text{ ug/m}^3$ ($<0.1 \text{ ppm}$)
Furans ($1,934 \text{ ng/m}^3$) in exhaust gas attributed to waste feed contamination

Process By-Products: PCB contaminated oil, water

Research Needs: Require field demonstration to evaluate mobility/transportability; also air pollution control system requires carbon adsorption system

6. CONTACTS FOR INFORMATION

Name: Lawrence Platter

Address: Soil Tech Inc.
800 Canonie Drive
Porter, Indiana 46304
(219) 929-4343

7. REFERENCES Soil Tech, undated

CASE STUDY INFORMATION SHEET

Case Study 6

1. TREATMENT TECHNOLOGY

Type: Low Temperature Volatilization
Organization: Canonie Environmental Services Corp
Porter, Indiana
Stage of Development: Commercial

2. SITE CHARACTERISTICS

Location: McKin Superfund Site, Gray, Maine
Climate: Temperate
Soil Type: Granular

3. SOIL CONTAMINATION

Contaminants: BTEX, Chlorinated solvents (Dichlorobenzenes, Dichloroethene, 1,1,1 TCA, TCE, Tetrachloroethene), PAHs
Levels of Concentration: Extremely variable, for example: Total BTEX = <1-970 ppm, Chlorinated Solvents = 7.6 - 4100 ppm, TCE = 0.4 - 2500 ppm, Phenanthrene = 0.85-1.2ppm
Extent of Contamination: A minimum of 3500 yd³ of contaminated soil was conservatively estimated.

4. OPERATIONAL INFORMATION

Period of Operation: Pilot Study during February - March 1986.

Process Description: The soils are dumped into feed hoppers and conveyed to the material dryer. In the dryer, the soil flows against a heated air flow causing the volatile and base/neutral organics to volatilize. At the soil exit of the dryer, a burner heats the air to approximately 300°F. This air subsequently heats the soil, effecting the volatilization of the VOCs from the soil to the air stream. The dry hot soils are discharged in a pug mixer where water is reintroduced to lower the dust emissions from the treated material.



The concentration of organics in the treated soil is measured in the on-site laboratory before the ultimate disposition of the soil.

The dryer gases containing VOCs, base/neutral organics, dust and acid vapour, are vented in a cyclone to remove dust particules. The dust is moisturized and mixed with the treated material. The air stream is treated in a venturi scrubber to remove any acid vapour.

Finally, the air is treated into a vapour phase carbon adsorption unit and the cleaned air is vented to the atmosphere. The organics are adsorbed on the carbon, which will be transported at an off-site facility at the end of the project.

Treatment Rate: 120 yd³ soil per day

Treatment Costs: \$248. U.S./yd³ soil including equipment

System Mobility: Approximately 10 system components mounted on trailers.

Installation Time: 4-5 weeks for Pilot Study

5. TREATMENT EFFECTIVENESS

Removal Efficiency: Very Good for BTEX and Chlorinated solvents. All BTEX were reduced below 1 ppm. TCE was reduced to <0.02-0.04 ppm. Other chlorinated solvents were reduced below 0.02 ppm. PAH reduction was less efficient. Ex: phenanthrene was reduced by only 26-58%.

Process By-Products: The process contains granular activated carbon containing volatile and semi-volatile organics at the end of the treatment.

Research Needs: Verify the quality of the air vented to the atmosphere after the process.

6. CONTACTS FOR INFORMATION

Name: Raymond G. Giese

Address: Canonie Environmental Services Corp.
800 Canonie Drive
Porter, IN 46304

Telephone: (219) 926-8651

7. REFERENCES

Gerken S.L. and Bell B.M., 1986.
Canonie Environmental Services Corp., undated.



CASE STUDY INFORMATION SHEET

Case Study 7

1. TREATMENT TECHNOLOGY

Type: Solidification/Stabilization - Portland Cement

Organization: HAZCON

Stage of Development: Pilot Scale

2. SITE CHARACTERISTICS

Location: Douglasville, Pennsylvania. Superfund Site

Climate: Temperate

Soil Type: Topsoil, alluvium, wastes, sludges and backfill from 6 areas:
Moisture = 6-25% Permeability = 6×10^{-1} - 1×10^{-5} cm/s

3. SOIL CONTAMINATION

Contaminants: Lead, Oil and Grease, PCBs, Volatiles Organics (Toluene, TCE, TCA, Ethylbenzene, Xylenes), Base/ Neutral Acid Extractables (Phenols, Naphthalene, Phthalates)

Levels of Concentration: Lead 0.3-2.2%; Volatile Organics 0-150 ppm; PCBs 1.2 - 54 ppm; Oil and Grease 1.0 - 25.3%; BNA Extractables 12.2 - 534 ppm

Extent of Contamination: 6 contaminated areas covering 10-15 acres and containing more than 190,000 m³ of surface and subsurface contaminated soils.

4. OPERATIONAL INFORMATION

Period of Operation: October 5, 1987 - October 20, 1987

Process Description: The HAZCON process consists of a Mobile Field Blending Unit that continuously mixes contaminated soils with Portland Cement, water and a proprietary additive called Chloronan. The contaminated soil was excavated, screened and fed in the HAZCON unit. The soil was mixed with cement, Chloronan and water at ratios which are predetermined in the laboratory. The ratios during this application were 1:1 soil-cement and 10:1 soil-Chloronan. The feed was homogeneously blended in a mixing chamber and extruded into 1 or 12yd³ molds. The molds were allowed to cure during 48-96 hours and were



placed into a lined pit and covered with clean soil.
The blocks were sampled after 28 and 210 days.

Treatment Rate: 300 lb/minute (2,300 lb/minute for commercial unit).

Treatment Costs: \$115 to \$260/metric ton (\$265 for demonstration test conditions)

System Mobility: Mobile - truck mounted

Installation Time: 6 days including site preparation.

5. TREATMENT EFFECTIVENESS

Efficiency: - Permeability = 10^{-8} - 10^{-9} cm/s - Pb leaching concentrations were reduced by a factor of 1000 from TCLP tests.

- Volatile Organics TCLP leaching concentrations were unchanged.
- BNA Extractables TCLP leaching concentrations were unchanged
- PCBs TCLP leaching concentrations were below detection limit.

Process By-Products: The process generates solidified blocks that have to be landfilled on-site or off-site.

Research Needs: Additives to the process should be investigated to reduce the leachability of organic compounds.

6. CONTACTS FOR INFORMATION

Name: Stephen Sawyer
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Levingston, N.J. 07039

Name: Paul R. de Percin
Address: Superfund Technology Demonstration Division
U.S.E.P.A.
Cincinnati, OH 45268

- ## 7. REFERENCES
- Sawyer S., 1989.
 - de Percin P.R. and Sawyer S., 1988.
 - de Percin P.R., 1988.
 - de Percin P.R., 1989.



CASE STUDY INFORMATION SHEET

Case Study 8

1. TREATMENT TECHNOLOGY

Type: Solidification/Stabilization - Portland Cement

Organization: Soliditech Inc.

Stage of Development: Demonstration study completed.

2. SITE CHARACTERISTICS

Location: Morganville, New Jersey

Climate:

Soil Type: Soil, waste pile and storage tank wastes.

3. SOIL CONTAMINATION

Contaminants: PCBs, VOCs, semi-VOCs, oil and grease and lead.

Levels of Concentration: PCBs = 28-43 ppm; VOCs = N.D.-50 ppm; Semi-VOCs = N.D.-79 ppm; oil and grease = 2.5-17%; lead = 650-2500 ppm.

Extent of Contamination: N.A.

4. OPERATIONAL INFORMATION

Period of Operation: A demonstration study was carried out during five days in December, 1988.

Process Description: After excavation, all wastes were screened to remove large objects. Wastes were mixed in a ribbon blender. Water was added to the waste within the blender to provide the proper mixing consistency. Portland Cement (16-51%), a proprietary chemical reagent called Urichem (0.4-0.6%) and proprietary additives (approximately 1%) were added to the contaminated wastes and water mix. The mixture was poured from the mixer to 1 yd³ plywood forms and were allowed to set for 28 days inside a heated warehouse.

Treatment Rate: 14 yd³ of treated wastes in 5 days

Treatment Costs: N/A

System Mobility: The system is trailer mounted.



Installation Time: N/A

5. TREATMENT EFFECTIVENESS

Efficiency: - The process solidified solid and liquid waste mixtures with high organic content (up to 17%) as well as oil and grease. The permeability was reduced to 10^{-7} - 10^{-8} cm/s. Total Analysis of the untreated and treated wastes revealed that the oil and grease content decreased by a factor of two for two types of waste and increased by a factor of two in a third type of waste after the treatment. The reduction can be attributed to the change in volume and bulk density of the material whereas the increase can be due to problems with the sampling protocol. Total Analysis for TOCs, semi-VOCs and PCBs revealed reduced concentrations after the treatment in the order of what is expected after addition of the solidification materials.

- Toxic Contaminants Leach Procedure Tests (TCLP) revealed that the oil and grease increased from 1.4-1.9 mg/L for the untreated waste to 2.4-12 mg/L for treated wastes. TCLP leaching of semi-volatiles increased from 0.12-0.38 mg/L to 0.32-0.97 mg/L. TCLP leaching also increased for oil and grease.

Process By-Products: The process produces blocks of solid material that have a volume 12% higher on average than the initial volume of the waste. The bulk density also increased by approximately 35% after solidification.

Research Needs: This methodology needs the development of new additives that would reduce the leachability of oil and grease and of semi-volatile compounds.

6. CONTACTS FOR INFORMATION

Name: Walter E. Grube, Jr.
Address: USEPA - Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
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Telephone: 513-569-7798

Name: Carl Brassow
Address: Soliditech Inc.
6901 Corporate Drive, Suite 215
Houston, TX 77036
Telephone: 713-778-1800

7. REFERENCES

Grube et al., (1989)
USEPA (1989b)



CASE STUDY INFORMATION SHEET

Case Study 9

1. TREATMENT TECHNOLOGY

Type: Solidification/Stabilization - Silicates

Organization: University of Nevada and Silicate Technology Corporation
sponsored by USEPA

Stage of Development: Treatability study using commercially available reagents

2. SITE CHARACTERISTICS

Location: Tacoma Tar Pits Superfund Site, Tacoma, Washington

Climate:

Soil Type: Pure soil was treated but also mixes of soil with foam fluff (1:1 and 3:1), soil with tar (1:1) and pure tar.

3. SOIL CONTAMINATION

Contaminants: Coal gasification products including tar, PAHs, phenols and BTX. Also lead and PCBs were present.

Levels of Concentration: Total PAHs 13.5 ppm; phenols 377 ppm; benzene .002 ppm; total PCBs 6.2 ppm; lead 2490 ppm.

Extent of Contamination: Approximately 4000 m³ of contaminated soils with coal tar are spread throughout the site.

4. OPERATIONAL INFORMATION

Period of Operation: January 25-26, 1988

Process Description: The materials were processed in 2 kg batches. Field-moist materials were mixed in a rotary mixer and sampled for chemical and leaching analysis. The appropriate reagent mixture was selected based on two trial runs and had a high reagent/material ratio. The general procedure was:

- 1 - Mix 2 kg of raw material for 1 minute
- 2 - Add liquid activator and mix 2 minutes
- 3 - Add measured volume of water and restart mixing
- 4 - Add weighted quantity of dry reagent and mix 10 minutes
- 5 - Pour mix into molds
- 6 - Store in covered trays at 100% humidity.



Treatment Rate: Not specified

Treatment Costs: Not specified

System Mobility: Mobile

Installation Time: Unknown

5. TREATMENT EFFECTIVENESS

Efficiency:

Physical Results: - Volume increase ranged from 62% - 95% for soil mixes.

- Soil and soil-fluff stabilized materials showed weight losses of 3% in average after wet-dry stress test.
- Soil (pure and mixed) showed compressive strength of 200 - 1400 psi after treatment
- The permeability of treated soils (pure and mixed) was 1×10^{-9} - 5×10^{-7} cm/s before wet/dry stressing and 5×10^{-7} - 1×10^{-6} cm/s after stressing.

Chemical Results: - The pre- and post-concentrations results from the total analysis did not reflect closely the dilution factor of 70% caused by adding fixation agents. Reported concentrations for PAHs and PCBs were similar in the raw and treated materials.

Leaching Results: - TCLP leaching tests showed that the process was effective in immobilizing lead reducing its leaching by 99%.

- TCLP leaching of phenols and benzene in soils and soil mixes showed similar concentrations for raw and treated materials.
- PAH and PCBs leaching concentrations were low to below detection for both raw and treated materials.
- In situ long term leaching from solidified material was evaluated. It indicated that low proportions of contaminants would leach from fixed soil or soil-fluff mixes. It was projected that phenols and PAHs might be detectable in groundwater in contact with the fixed material.

Process By-Products: Cylinders of stabilized (solid) material that have to be buried.



Research Needs: The immobilization of organic compounds by this method should be evaluated in greater details to decide if the method is suitable for organic contaminants.

6. CONTACTS FOR INFORMATION

Name: Gretchen Rupp

Address: University of Nevada - Las Vegas
Environmental Research Center
4505 Maryland Parkway
Las Vegas, Nevada 89154

Name: Kenneth W. Brown
USEPA Environmental Monitoring Systems Laboratory

Address: Office of Research and Development
Las Vegas, Nevada 89192-3478

7. REFERENCES

Rupp (1989)
Rupp et al., (1989)

CASE STUDY INFORMATION SHEET

Case Study 10

1. TREATMENT TECHNOLOGY

Type: Soil Washing - Water

Organization: Harbauer, Germany

Stage of Development: Commercial

2. SITE CHARACTERISTICS

Location: Pintsch Oil Refinery, Berlin, Germany

Soil Type: Sandy and clayey soil underlying medium to coarse sand

3. SOIL CONTAMINATION

Contaminants: Mineral oil, chlorinated hydrocarbons, PAHs, PCBs, aromatic hydrocarbons and phenols. Polychlorinated dibenzodioxins and dibenzofurans were also detected.

Levels of Concentration: Oils = 38,000 ppm, chlorinated hydrocarbons = 6,800 ppm, PCBs = 270 ppm, aromatics = 5620 ppm, phenols = 80 ppm.

Extent of Contamination: 12,000 m² of the property are badly contaminated to a depth exceeding 8.5 m.

4. OPERATIONAL INFORMATION

Period of Operation: July, 1987 to after June, 1989

Process Description: The process is divided in four operations:

1. Soil preparation and extraction with water and vibrations
2. Cleanup of process water
3. Treatment/dewatering of remaining sludges
4. Removal and cleaning of gas emissions.

Treatment Rate: 20-40 tonnes/hour

Treatment Costs: \$176/tonne without sludge disposal

System Mobility: Fixed

Installation Time: Not Available



5. TREATMENT EFFECTIVENESS

Efficiency: 85% for mineral oils, 99.7% for phenols. Results for similar sites are in the order of 100% for chlorinated hydrocarbons, 99% for aromatics, 97% for PAHs and 99% for PCBs.

Process By-Products: A residual sludge (<15 um) is generated by the process. Activated carbon containing organics has also to be disposed.

Research Needs: This system is at the commercial stage and Harbauer is doing research to improve removal efficiencies. Harbauer also plans to export their technology in North America.

6. CONTACTS FOR INFORMATION

Name: H.D. Sonnen, M.B. Nels

Address: Harbauer GmbH & Company KG
Bismarckstrasse 10-12
1000 Berlin 12
Federal Republic of Germany

Telephone: 011-49(30) 40417 96

7. REFERENCES

Nunno et al., (1988)
Sonnen et al., (1989)
Sonnen and Klingebiel (1988)



CASE STUDY INFORMATION SHEET

Case Study 11

1. TREATMENT TECHNOLOGY

Type: Soil Washing - Aqueous Surfactants

Organization: University of Cincinnati

Stage of Development: Laboratory Study

2. SITE CHARACTERISTICS

Location: Chem-dyne Hazardous Waste Site, Hamilton, Ohio

Soil Type:

3. SOIL CONTAMINATION

Contaminants: Pesticides, chlorinated hydrocarbons, solvents and waste oils. The study focused on 11 chlorinated hydrocarbons.

Levels of Concentration: Total chlorinated hydrocarbons = 2078 ppm; Select 11 chlorinated hydrocarbons = 216-266 ppm.

Extent of Contamination: Not specified.

4. OPERATIONAL INFORMATION

Period of Operation: Not specified.

Process Description: The effectiveness of 14 surfactant (nonionic, anionic, cationic and mixed) was tested in lab-scale batch and flow through column soil scrubbing experiments. In batch tests, 10 g of soil was shaken for 2-4 hours with 200 mL of 1% or 2% surfactant solution. In column studies, the surfactant solutions were washing 50 g of soil at a rate of 59 mL/hour.

Treatment Rate: Not specified

Treatment Costs: Not specified

System Mobility: Laboratory study

Installation Time: Not applicable



5. TREATMENT EFFECTIVENESS

Efficiency: The effectiveness was measured with the concentration of total organic halogens (TOX). Little difference was obtained between the anionic and the nonionic surfactants. On average the removal of TOX was 30% for a 0.50% surfactant concentration, 62% for 1% concentration and 90% for a 2% concentration.

Process By-Products: All the washing solutions contain chlorinated hydrocarbons and are potentially hazardous

Research Needs: This process has to be coupled to a complete soil washing process with treatment of the washing solution. Bench-scale and pilot-scale studies of soil washing with the use of surfactants are required to make a final statement.

6. REFERENCES Clement et al., (1986)



CASE STUDY INFORMATION SHEET

Case Study 12

1. TREATMENT TECHNOLOGY

Type: Soil Washing - Water, Aqueous Surfactant

Organization: PEI Associates Inc.

Stage of Development: Bench-Scale Study Simulating the USEPA Mobile Soil Washing System

2. SITE CHARACTERISTICS

Location: Not Applicable

Soil Type: Synthetic Analytical Reference Matrix (SARM) composed of 59% sand/gravel, 28% silt and 12% clay and having a 3.2% organic carbon content.

3. SOIL CONTAMINATION

Contaminants: Volatile organics, semi-volatile organics and metals

Levels of Concentration: Volatiles = 770-18666 ppm; Semi-volatiles = 325-7573 ppm; Metals = 1047-60879 ppm.

Extent of Contamination: Not Applicable

4. OPERATIONAL INFORMATION

Period of Operation: Between April and November, 1987

Process Description: The process separates the soil in two fractions (>72 mm and <2 mm) by use of a rotary drum screen. A high-pressure water knife breaks up the soil lumps and strips the contaminants off the soil particles.

Treatment Rate: Not specified

Treatment Costs: Not specified

System Mobility: Mobile

Installation Time: Not specified



5. TREATMENT EFFECTIVENESS

Efficiency: Using water only the removal efficiency for each soil fraction was: >2 mm: >99.9% for volatile and 93.9%-98.9% for semi-volatiles. 250 um - 2um: 99.3%-99.7% for volatiles and 0%-56.2% for semi-volatiles; <250 um:66.2%-99.8% for volatiles and 0%-59.7% for semi-volatiles. Using a 0.5% surfactant solution the efficiency was: >2 mm:>99.8% for volatiles and 93.5%-99.8% for semi-volatiles; 250 um-2 mm:99%-99.8% for volatiles and 29.4%-67.5% for semi-volatiles; <250 mm:88.5%099.4% for volatiles and 0%-43.2% for semi-volatiles.

Process By-Products: The process generates a contaminated sludge (<250 um) and contaminated wash water that has to be treated.

Research Needs: Additional research may be directed to the evaluation of the process on a real contaminated soil. The removal of contaminants from the washing solution may also be investigated.

6. CONTACTS FOR INFORMATION

Name: J. Hessling, B.B. Locke, M. Taylor, M. Szabo

Address: PEI Associates Inc.
11499 Chester Road
Cincinnati, Ohio 45246

7. REFERENCES

Esposito et al., (1989)
Esposito, Locke, Greber and Traver (1989)



CASE STUDY INFORMATION SHEET

Case Study 13

1. TREATMENT TECHNOLOGY

Type: Soil Washing - Aqueous Surfactants, Acids and Chelating Agents

Organization: EEC Inc., Philadelphia

Stage of Development: Bench-scale Demonstration

2. SITE CHARACTERISTICS

Location: New Jersey, USA

Soil Type: From top to bottom: 1-3 m of fill of silt, wood, glass, peat, sand and clay, a peat layer, a silt layer and a clay layer.

3. SOIL CONTAMINATION

Contaminants: PCBs, volatile organics, base neutral organics (PAHs, phthalates, etc), metals

Levels of Concentration: PCBs = ND-212 ppm; Volatiles = 37.4-1878 ppm; Base Neutrals = 27-228 ppm; metals = 2015-3522 ppm.

Extent of Contamination: 88,000 m³ of contaminated fill and peat.

4. OPERATIONAL INFORMATION

Period of Operation: 2 weeks

Process Description: The soil was segregated in 2 fractions. Water plus one of the following chemical combinations a) 5% aqueous surfactants, b) 10% HCL (for metals), c) 5% surfactant and 5% HCL, d) 10% citrate solvent was added to the soil and mixed with soil by mechanical agitation. Three stages of extraction were completed followed by fluid-solid separation.

Treatment Rate: 5 hours per batch

Treatment Costs: Not specified

System Mobility: Not specified

Installation Time: Not specified



5. TREATMENT EFFECTIVENESS

Efficiency: The 5% surfactant solution removed 66-78% of PCBs, 83%-99% of volatile organics and 75-99% of the base neutral organics. The 5% citrate solvent solution removed 91-98% of the volatile and base neutral organics but the removal of PCBs was not conclusive.

Process By-Products: Used wash solutions contained high levels of organic contaminants and metals.

Research Needs: This process needs a used solution treatment system to allow recycling of the washing solution. The process needs additional pilot-scale work to fully demonstrate its applicability to decontaminate soils.

6. REFERENCES Kunze and Gee (1989)



CASE STUDY INFORMATION SHEET

Case Study 14

1. TREATMENT TECHNOLOGY

Type: Chemical - Solvent Extraction B.E.S.T.TM Process

Organization: Resources Conservation Company
3006 Northup Way
Bellevue, Washington 98004

Stage of Development: Full-scale - commercial

2. SITE CHARACTERISTICS

Location: General Refining Superfund Site
Garden City, Georgia

Climate:

Soil Type: Coastal plain physiography characterized by sandy permeable soils and shallow water table

3. SOIL CONTAMINATION

Contaminants: Waste oils, acidic oily sludges, oily filter cake.
Individual contaminants and contaminant groups included PCB's, VOC's, semivolatile organics, and heavy metals.

Level of Contamination: Waste oil: PCB <1 ppm
Oily sludge: PCB 4.4-5.0 ppm, oil and grease 15-20%
Filter cake: PCB 3.5 ppm, oil and grease 30-40%
Lead levels ranged from 170-10,000 ppm and pH ranged from 0.63 to 7.0

Extent of Contamination: Acidic oily sludges were disposed of in four unlined lagoons and oily filter cake was buried or stockpiled on site. A fifth unlined lagoon was used as an oil/water separator and was backfilled with filter cake and sludge. Approximately 9,000 tonnes of contaminated waste on site.

4. OPERATIONAL INFORMATION

Period of Operation: RCC set up its system in mid-1986. Following a period of shakedown and modification the treatment process operated until March 1987.

Process Description: The process is described more fully in section 2.3.1.3.

At this site, sludges were neutralized with sodium hydroxide prior to treatment. Some TEA solvent was lost due to worn seals in the centrifuge and rotating solids dryer. A material balance (see 5) was developed for sludge feed with a composition of 21% oil, 66% water and 7% solids and based on a TEA to feed ratio of 4:1, with the following process rates:

- sludge feed rate - 1542 kg/hour
- oil product stream - 416 kg/hour
- water product stream - 1018 kg/hour
- solids product stream - 108 kg/hour

The process was operated using an automatic control system that monitors process conditions and makes necessary adjustments. Feed and product streams are sampled and analyzed to ensure proper system operation.

Treatment Rate: The process treated 3300 tonnes of waste material over a period of approximately 9 months. This included start up and a period of shakedown. Average feed rate at this site was 1.5 tonnes/hour. At peak efficiency the process is capable of treating 90 tonnes/day.

Treatment Costs: not provided

System Mobility: The system is mobile and can be set up on site.
Set Up Time: Set up time was not given.

5. TREATMENT EFFECTIVENESS

Materials Balance: Based on product stream flow rates (see 4), material balance accounted for the following closure:

- oil product stream - 99%
- solids product stream - 106%
- waste product stream - 99%

Separation Efficiency: Separation efficiencies for product streams often exceeded 98% and the following separation performance was determined:

- solids fraction contained: 0.81% oil, <0.5% water, 0.62% TEA
- oil fraction contained: 0.88% water, <0.5% TEA
- water fraction contained: 0.0033% oil, 0.81% solids, 0.14% TEA

Extraction Efficiencies: Extraction efficiency which measures the efficiency of the process to extract contaminants to the oil or solid phase were calculated on the basis of average concentrations for volatile compounds as follows:

- toluene - 94.8%
- ethylbenzene - 94.4%
- xylene - 97.0%

Results of analyses in product streams for selected semi-volatile organics and PCB's is provided in Table 1.



Sampling was conducted by the vendor (RCC) and analyzed by a U.S. EPA contractor laboratory. Sampling and analytical protocols were developed jointly by the vendor and U.S. EPA, and analyses were evaluated by an independent third party.

Process Byproducts: Some loss of volatile and TEA were detected by air emissions monitoring.

Research Needs: Further evaluation of system efficacy is recommended and should include the following:

- establish the range of contaminant feedstock that the process can effectively treat
- evaluate system performance between laboratory bench-scale tests and field-scale testing and cleanup, to determine if process is affected by scale change
- verify system performance over extended periods of operation
- develop mass and energy balances for process
- verify treatment costs on per tonne basis
- evaluate volatile losses from process

6. CONTACTS FOR INFORMATION

Resources Conservation Company
3006 Northup Way
Bellevue, Washington 98004
Telephone: (206) 828-2400
Name: Lisa Robbins

7. REFERENCES: Sude11 (1988)

Table 1 Semi-Volatile Organics and PCB Analytical Results - B.E.S.T.TM Process

<u>Parameters</u>	<u>Product Fractions</u>		
	<u>Oil (mg/kg)</u>	<u>Solids (mg/kg)</u>	<u>Water (mg/kg)</u>
Anthracene	29-61	N.D.	N.D.
1,2-Dichlorobenzene	N.D.	<17-<20	<.13-<.2
Dibenzofuran	<18-62	N.D.	N.D.
Chrysene	<20-25	<17-<20	<.13-<.2
Fluoranthene	N.D.	<17-<20	<.13-<.2
Fluorene	120-180	<17-<20	<.13-<.2
Napthalene	290-370	2.3-<20	<.13-<.2
2 Methylnapthalene	1200-1700	2.4-<20	<.13-<.2
Acenaphthene	60-92	N.D.	N.D.
Phenanthrene	250-360	2.1-2.5	.13-<.2
Phenol	40-63	<17-<20	.38-1.9
4-Methylphenol	<18-85	3.1-<20	.34-.73
4-Chloro-3methylphenol	N.D.	1.9-<20	<.13-<.2
2,4 Dimethylphenol	N.D.	N.D.	0.05-<.13
Pyrene	23-43	<17-<20	<.13-<.2
PCB's	8.2-11	0.37-<1.7	<.006-<0.01

Source: Sudell (1988)

CASE STUDY INFORMATION SHEET

Case Study 15

1. TREATMENT TECHNOLOGY

Type: Chemical - Solvent Extraction - Extraksol™ Process

Organization: Sanexen International
3027 Harvester Rd., Unit 204
Burlington, Ontario L7N 3G2

Stage of Development: Full-scale - commercial

2. SITE CHARACTERISTICS

Location: Not specified

Climate: Not specified

Soil Type: mixed grain size soil, clayey soil, refinery sludge, Fuller's earth, porous gravels

3. SOIL CONTAMINATION

Contaminants: PCB's, oil and grease, PAH's, PCP

Levels or Concentration:	PCB's	5.3-2055 ppm
	oil and grease	600-447,000 ppm
	PAH's	81-1739 ppm
	PCP	8.2-744 ppm

Extent of Contamination: Not specified

4. OPERATIONAL INFORMATION

Period of Operation: since mid-1987

Process Description: see description section 2.3.1.2

Treatment Rate: 0.9-1.4 tonnes/hour with planned development of mobile unit with treatment rate of 5-7 tonnes/hour

Treatment Costs: \$90-180/tonne

System Mobility: Mobile- trailer mounted

Set Up Time: 3 days - 2 operators



5. TREATMENT EFFECTIVENESS

Removal Efficiency: Table 1 summarizes results of full scale treatment of a variety of soil types and contaminants. Summary of treatment provided by vendor. Third party evaluation of the process was not obtained.

Process Byproducts: Not discussed, but closed system process produces concentrated contaminant residue

Research Needs: The feasibility of higher treatment rates and treatment of coarse materials having matrix porosity.

6. CONTACTS FOR INFORMATION

Name: Mark Cvar
Dave Kerr

Address: Sanexen International
3027 Harvester Rd., Unit 204
Burlington, Ontario L7N 3G2

Telephone: (416) 681-3366

7. REFERENCES
- Hall et al., (1989)
 - Mourato and Paquin, (1989)
 - Paquin and Mourato, (undated)
 - Sanexen International (1989)



TABLE 1. Results of full - scale treatment - ExtraksoTM process

Soil Type	Solvent	Initial Concentration (ppm)			
		Final Concentration (ppm) / Percent Removal			
		<u>PCB's</u>	<u>oil and grease</u>	<u>PAH's</u>	<u>PCP</u>
clay	#2	2,055 48.8 / 97.6%	8,040 590 / 93%		
mixed	#2	5.3 0.70 / 87%	14,400 1,210 / 92%		
clay bearing	#2	150 14 / 91%			
clay bearing	#2	54 4.4 / 92%			
clay bearing	#2		1,801 182 / 90%		
clay bearing	#2		600 80 / 92%		
refinery oil sludge	#2		49,000 4,200 / 91%		
refinery oil sludge	#2		73,000 4,800 / 93%		
refinery oil sludge	#2		70,000 340 / 99%		
Fuller's earth	#2		447,000 5,500 / 99%		
Fuller's earth	#2		313,000 3,700 / 99%		
porous gravels	#2		10,000 3,690 / 63%		
porous gravels	#2		1,040 207 / 80%		
refinery clayey soil	#2			332 55 / 83%	
refinery oil sludge	#2			81 16 / 81%	



TABLE 1. Results of full - scale treatment - Extraksol™ process (cont'd)

Soil Type	Solvent	Initial Concentration (ppm)			
		Final Concentration (ppm) / Percent Removal			
		<u>PCB's</u>	<u>oil and grease</u>	<u>PAH's</u>	<u>PCP</u>
refinery oil sludge	#2			240 10 / 96%	
refinery oil sludge	#2			1,739 130 / 92%	
porous gravel	#2				8.2 <0.82 / >90%
porous gravel	#2				81.4 <0.21/>99.7%
porous stones	#2				38.5 19.5 / 50%
activated carbon	#2				744 83 / 89%

source: Paquin and Mourato (undated)

CASE STUDY INFORMATION SHEET

Case Study 16

1. TREATMENT TECHNOLOGY

Type: Chemical - Solvent Extraction - Critical Fluid Solvents

Organization: CF Systems Corporation
140 Second Avenue
Waltham, Massachusetts 02154
as vendor, with treatability studies conducted by
Roy F. Weston, Inc.
Houston, Texas

Stage of Development: Pilot-scale test. Full-scale commercial unit (45 tonnes/day) available.

2. SITE CHARACTERISTICS

Location: United Creosoting Superfund Site, Conroe, Texas (64 km north of Houston)

Climate:

Soil Type: Soils range from gravelly loam to loam fine sand with woody organic material consisting of bark, sticks and old boards. Surficial soils are underlain by clayey sand and gravel with localized clay beds. The water table exists at a depth of about 4m, and a confined aquifer occurs at a depth of 17m.

3. SOIL CONTAMINATION

Contaminants: PCP, creosote and coal tar wastes including: PAH's, chlorinated dioxins, dibenzofurans, and PCP

Level of Contamination: 1973 - 4169 ppm total PAH
0.26 ppm PCP
0.89 ppm OCDD
0.11 ppm OCDF

Extent of Contamination: About 70,000 m³ of contaminated material (i.e. above background) exists at the 100 acre site. Treatability study evaluated 108 kg (238 lbs) of contaminated material (Test One) from a former waste pond which contained mostly creosote and PCP waste and 127 kg (280 lbs) of contaminated soil (Test Two) from the former operations area.



4. OPERATIONAL INFORMATION

Period of Operation: March 1987

Process Description: TEST ONE: Soil was sieved and the greater than 1.27cm (0.5 in.) fraction was discarded. The <1.27cm fraction was slurried with potable water and mixed for 20 hours. The slurry was passed through a 0.3cm screen (0.125 in.) and the coarser fraction was discarded. Four extraction cycles were carried out using propane as the extraction solvent at an average solvent to feed ratio of 2.2.

TEST TWO: Soil was prepared in a similar manner as in Test One, but settling of coarse sand created problems with slurry handling following mixing and so the feed was diluted. The soil was treated using three extraction cycles with an average solvent to feed ratio of 3.2.

Treatment Rate: Not specified

Treatment Costs: Not specified

System Mobility: Mobile unit

Installation Time: Not specified

5. TREATMENT EFFECTIVENESS

Removal Efficiency: A material balance was undertaken for both tests which were evaluated by an independent third party. Material balances for Test One determined that 31 kg (69 lbs) of water and 37 kg (81 lbs) of soil were lost in the system while for Test Two, 15.4 kg (34 lbs) of water and 48.5 kg (107 lbs) of soil were lost.

Removal efficiencies based on total mass ranged from 81% -99% for PAH's, 91% for PCP, 70 - 83% for dioxins and 66 - 73% for furans.

Removal efficiencies based on concentration expressed in terms of toxicity equivalents or Benzo(a)pyrene equivalents (BAPE) are somewhat lower at 91% and 86% for total BAPE for Test One and Test Two respectively.

Table 1 provides initial and final mass calculations for chemical contaminants. Presumably these calculations are based on a total soil mass of 108 kg (238 lbs) for Test One and 127 kg (280 lbs) for Test Two.



Table 1 Results of Pilot-Scale Testing - CF Systems

COMPOUND	TEST ONE			TEST TWO		
	MASS IN UNTREATED SOIL (MG)	MASS IN TREATED SOIL (MG)	REMOVAL EFFICIENCY (%)	MASS IN UNTREATED SOIL (MG)	MASS IN TREATED SOIL (MG)	REMOVAL EFFICIENCY (%)
ACENAPHTHENE	26,640	143 J	NA	ND	ND	NA
ACENAPHTHYLENE	1,110 J	126	NA	675 J	246 J	NA
ANTHRACENE	24,420	373.8	98%	2,957 J	ND	NA
BENZO(A)ANTHRACENE	7,400	331.8	96%	1,441 J	ND	NA
BENZO(A)PYRENE	3,552	504	86%	24,413	670 J	NA
BENZO(B)FLUORANTHENE	3,774	407.4	89%	20,319	616 J	NA
BENZO(GHI)PERYLENE	1,480 J	504	NA	120,020	5,089	96%
BENZO(K)FLUORANTHENE	3,700	714	81%	136,245	5,357	96%
CHRYSENE	8,140	382.2	95%	44,733	2,679	94%
DIBENZO(A,H)ANTHRACENE	ND	181 J	NA	54,892	3,482	94%
FLUORANTHENE	26,640	462	98%	34,573	4,018	88%
FLUORENE	28,120	160 J	NA	40,714	2,170	95%
INDENO(1,2,3-CD)PYRENE	1,406 J	462	NA	28,508	2,679	91%
NAPHTHALENE	10,360	63 J	NA	12,813	2,009	84%
PHENANTHRENE	43,660	546	99%	2,047 J	964 J	NA
PYRENE	26,640	462	98%	12,207	2,089	83%
TOTAL MASS OF PAH (MG)	213,046	5,149	98%	529,437	29,572	94%

PCP AND CDD/CDF
RESULTS

COMPOUND	TEST ONE			TEST TWO		
	MASS IN UNTREATED * SOIL (UG)	MASS IN TREATED * SOIL (UG)	REMOVAL EFFICIENCY (%)	MASS IN UNTREATED SOIL (MG)	MASS IN TREATED SOIL (MG)	REMOVAL EFFICIENCY (%)
PENTACHLOROPHENOL	28,120 *	2,436 *	91%	3,563 J	455 J	NA
TOTAL TCDD	ND	ND	NA			
TOTAL PeCDD	ND	ND	NA			
TOTAL HxCDD	1,184	202	83%			
TOTAL HpCDD	26,640	7,560	72%			
TOTAL OCDD	96,200	28,980	70%			
TOTAL TCDF	ND	6	NA			
TOTAL PeCDF	74	109	NA			
TOTAL HxCDF	2,220	756	66%			
TOTAL HpCDF	11,840	3,150	73%			
TOTAL OCDF	11,840	3,654	69%			

NA = Not Applicable (because results are below detection limits or not detected)

* = (UG) = micrograms, pentachlorophenol results in milligrams

Note: Dioxin analysis was not performed on soil from drum 2.

source: Kaleri et al (1990)



Process Byproducts: None reported

Research Needs: Treatability test results were favourable since the toxicity of PAH's, dioxins, and PCP were reduced to levels close to the desired concentration. Problems encountered during the pilot-scale test related to waste feed pre-treatment and handling, treatment configuration and general maintenance and mechanical problems. These areas of concern can be eliminated in the full-scale commercial unit through modification to the feed preparation equipment, pumps, dewatering equipment, pipe size, and process flow.

6. CONTACT FOR INFORMATION

Name: Thomas J. Cody Jr., Vice President, Marketing

Address: CF Systems Corporation
140 Second Avenue
Waltham, Massachusetts 02154

Telephone: (617) 890-1200

Name: Calvin Spencer

Address: Roy F. Weston
Houston, Texas

Telephone:

7. REFERENCES: Kaleri et al., (1990) U.S. EPA, (1989(f))

1. TREATMENT TECHNOLOGY

Type: Chemical - Substitution - APEG Process

Organization: Galson Remediation Corporation
6627 Joy Road
East Syracuse, N.Y. 13057

Stage of Development: Pilot-scale research and development completed. Full-scale research and development to start in 1990.

2. SITE CHARACTERISTICS

Location: Wide Beach, Brant, New York
30 miles south of Buffalo

Climate:

Soil Type: 3m of dark grey and brown silty clay till overlying shale bedrock.

3. SOIL CONTAMINATION

Contaminants: PCB (Arochlor 1254)

Levels or Concentration: non-detectable - 1026 mg/kg

Extent of Contamination: 20,000 yds³ (15731m³) of soil in a 55 acre (22ha) subdivision of 60 homes.

Contaminated soil from the application of 30,000-40,000 gallons of PCB contaminated waste oil for dust control, includes driveways, yards, roadways, drainage ditches and surface water sediment.

4. OPERATIONAL INFORMATION

Period of Operation: Pilot-scale studies were undertaken from March-September 1988. Full-scale remediation is to start in early 1990 and be completed by early 1991.

Process Description: The APEG Process is an alkaline dechlorination process in which potassium hydroxide (KOH) is reacted with polyethylene glycolmethyl (PEG) and triethylene glycolmethyl ether (TMH) using dimethyl sulfoxide (DMSO) as a cosolvent and catalyst to form an alkoxide. The alkoxide reacts with a chlorine atom on the biphenyl ring to form a glycol-biphenyl ether and potassium chloride.



The treatment train configuration is an entirely closed system which prevents the release of materials to the environment. Excavated soils are continuously fed into a chemical treatment reactor by backhoe. Reagents, PEG 400, TMH, DM50 and 45% KOH are mixed at a ratio of 1:1:2:2 and added to the reactor at a ratio of 1:1 reagent mixture and soil. The slurry is heated to approximately 150°C using a rotary kiln and reacted for approximately 2 hours. Following the reaction reagents are recovered by filtration and centrifuging and returned to a holding tank for recycling. The soil is worked several times to remove residual reagent and the wash water is recycled to the reagent tank. Cleaned soil is discharged.

Treatment Rate: N/A

Treatment Costs: Projected costs for treating Wide Beach soil will be between \$140-410/tonne (Cleary and Granger 1988)

System Mobility and
Set Up Time: N/A

5. TREATMENT EFFECTIVENESS

Removal Efficiency: Bench-scale testing reported reduction in PCB concentrations from 500-700 ppm to less than 10 ppm which amounts to a reduction of about 98% (Cleary and Granger 1988). Pilot-scale testing of soils showed reduction of PCB concentrations from 30-260 ppm to less than 10 ppm, which suggests a reduction of 66-96% (USEPA 1989).

Process Byproducts: Reaction byproducts include potassium chloride and polyethylene glycol ether. Treated soil was found to be non-mutagenic by the Ames test, and the LD₅₀ of treated soil on guinea pigs is greater than 5000 ppm indicating non toxicity.

Research Needs: Investigate inhibitory effect of clays and organic material in soils. Use of solvents to solubilize contaminants. Identify all transformation products.

6. CONTACTS FOR INFORMATION

Galson Remediation Corporation
6627 Joy Road
East Syracuse, New York 13057

Attn: Mr. Robert L. Peterson, Director of Technology



U.S. EPA, OS-210
Emergency Response Division
401 M Street, S.W.
Washington, D.C. 20460

Attn: Mr. David Lopez (202) 382-2471

7. REFERENCES Cleary, J.G. and T. Granger, 1988.

USEPA, 1989.

USEPA, 1988.

Rogers, C.J., A. Kornel and R.C. Peterson, 1987.

Galson Remediation Corporation.

CASE STUDY INFORMATION SHEET

Case Study 18

1. TREATMENT TECHNOLOGY

Type: Biological - Landfarming

Organization: Biotreatment Ltd.
5 Chiltern Close
Cardiff, CF4 5DL, UK

Stage of Development: Full-scale - commercial

2. SITE CHARACTERISTICS

Location: Greenbank Gas Works
Blackburn, Lancashire, England

Climate:

Soil Type: 0.7-5.5m of fill consisting of soil, gravel, ash, cinders, rubble, slate, wire rope, tar and bitumen, overlying soft to firm grey-brown boulder clay extending from just below topsoil to 14m

3. SOIL CONTAMINATION

Contaminants: Phenols, coal tar, sulphate, cyanide, heavy metals - PAH's

Levels or Concentration: Estimated mean PAH concentration of 22,000 mg/kg

Extent of Contamination: Over half of the 10 ha site was contaminated in distinct areas of the site. Approximately 30,500m³ of soil was contaminated with coal tar and phenols which was treated biologically. Another 13,000m³ consisting of contaminated metals and complex cyanides was encapsulated.

4. OPERATIONAL INFORMATION

Period of Operation: Field scale treatment commenced in August 1986 and was completed by Fall 1987.

Process Description: The process consisted of several bench scale tests in the laboratory designed to isolate those microorganisms which were capable of utilizing PAH compounds as substrate, and to identify surfactants which would enhance the availability of the coal tar compounds to the microorganisms.



Next a series of microcosm studies were undertaken under controlled conditions of nutrient and surfactant additions. Field trials were carried out to establish parameter optimization including the depth of tilling, particle size, water content, oxygen requirements and tillage frequency.

Full scale operations including primary sorting and crushing to reduce particle size and increase surface area for biodegradation. Material discharged from the crusher was moved onto treatment beds using a bulldozer. Selected microorganisms were grown in an on-site bioreactor, mixed with appropriate nutrients and spread onto the treatment beds using a tractor boom sprayer. Optimal moisture content was controlled through regular applications of water, and oxygen movement to the subsurface was enhanced by regular tilling using a rotovator.

Treatment Rate: The process treated 30,500m³ of contaminated soil over a period of roughly 14 months.

Treatment Costs: The total cost was \$840,000 and included encapsulation of 13,000m³ of metals and cyanide contaminated soil. This works out to about \$28.00/m³ or \$14.00/tonne.

System Mobility and

Set Up Time: The process requires very basic agricultural and road construction equipment during actual full scale implementation.

Bench-scale and pilot-scale testing required laboratory and analytical testing. Microbial isolation was conducted in 7 days. Surfactant studies were carried out in 16 days.

Bench scale degradation studies were carried out over 5 weeks.

Pilot scale field trials took place over a period of 8 weeks.

5. TREATMENT EFFECTIVENESS

Removal Efficiency: A target concentration of 10,000 mg/kg total PAH was decided on at the onset of remediation.

Table 1 gives the months for pilot-scale field trials for the degradation of fluoranthene, pyrene, benzo(a)pyrene and total PAH for a variety of treatments. Treatments 1, 2 and 3 consisted of soil inoculation with selected microorganisms grown on-site and nutrient additions. These three treatments showed statistically significant reductions in some or all parameter concentrations.



Treatments 2 and 3 showed 39% and 36% reductions in total PAH concentrations respectively. Treatments 4 and 5 showed increases in total PAH concentration after 8 weeks. This increase was attributed to isolated areas of higher contamination which became spread over the treatment area during tilling.

Process Byproducts: None reported

Research Needs: Controlled microcosm experiments suggested that volatilization losses were not significant, however, microcosm experiments failed to account for volatilization losses at the field scale from wind velocity or regular tilling.

6. CONTACTS FOR INFORMATION

Biotreatment Ltd.
5 Chiltern Close
Cardiff CF4 5DL, UK

Attn: Dr. Richard Bewley Cardiff (0222)

766716/747414

7. REFERENCES Bewley, R.J.F., 1987.

Bewley, R.J.F. and P. Theile, 1988.

Bewley, R.J.F. and P. Theile, 1988.

Bewley, R., B. Ellis, P. Theile, I. Viney and J. Rees, 1989.

Biotreatment Ltd. Technical Information.

TABLE 1. Results of pilot - scale field trials for PAH compounds

Treatment ^(a)	Weeks	Fluoranthene	Pyrene	Benzo(a)pyrene	Total PAH ^(b)
1	0	3271	702	98	9763
	8	1104*	388*	58	7317
2	0	3664	833	159	12476
	8	1019*	366*	70*	7641*
3	0	2271	524	100	7996
	8	647*	209*	45*	5089*
4	0	1049	224	45	3520
	8	637	227	55	5284
5	0	614	170	59	2925
	8	479	161	43	4274

- (a) treatment 1. - selected microorganisms classified as ERB001 plus nutrients
 2. - selected microorganisms classified as ERB002 plus nutrients
 3. - selected microorganisms classified as ERB002 plus nutrients
 4. - no addition of selected microorganisms to soil but nutrients added
 5. - no addition of selected microorganisms or nutrients to soil

(b) total PAH defined by USEPA list of 16 priority pollutants

* statistically significant reduction in concentration

Source: Bewley, 1987.
 Bewley and Theile, 1988.

CASE STUDY INFORMATION SHEET

Case Study 19

1. TREATMENT TECHNOLOGY

Type: Biological - Bioreactor - Slurry Bioreactor

Organization: Delft University of Technology
Department of Biochemical Engineering
Julianalaan 67
2628 BC Delft
The Netherlands

Stage of Development: Lab-scale research

2. SITE CHARACTERISTICS

Location: Delft University

Climate: Laboratory-controlled

Soil Type: Approximately 40% clay and silt, 60% sand

3. SOIL CONTAMINATION

Contaminants: Diesel fuel

Levels of Concentration: 10 g/kg dry matter

Extent of Contamination: Lab-scale experiment/not specified

4. OPERATIONAL INFORMATION

Period of Operation: Ongoing

Process Description: The slurry bioreactor is designed as a three-stage process consisting of 2 single bioreactors set up in series and a dewatering unit. Soil feed is directed to the first bioreactor where after a short residence time the coarse soil fraction is extracted at the base of the reactor while the fine fraction is directed to the second bioreactor. After a residence time of 100 hours the fine natural and coarse material are combined and sent to a dewatering unit. Temperature was maintained at 30°C and pH was 7.0.

Treatment Rate: N/A

Treatment Cost: N/A



System Mobility: Laboratory-scale

Set-Up Time: N/A

5. TREATMENT EFFECTIVENESS

Removal Efficiency: Overall removal of diesel fuel over a period of 60 days was 70% under less than optimal conditions.

Process Byproducts: N/A

Research Needs: Optimize slurry handling and process conditions for maximum degradation activity.

6. CONTACTS FOR INFORMATION

R.H. Kleijntjens
K. Luyben
Delft University of Technology
Department of Biochemical Engineering
Julianalaan 67
2628 BC Delft
The Netherlands

7. REFERENCES: Kleijntjens et al., (1989)



CASE STUDY INFORMATION SHEET

Case Study 20

1. TREATMENT TECHNOLOGY

Type: Biological - Bioreactor - aeration lagoons

Organization: Planning, Design & Research Engineers Inc.
Nashville, Tennessee

Stage of Development: Full-scale commercial

2. SITE CHARACTERISTICS

Location: Eastern Tennessee

Climate:

Soil Type: Contaminated lagoon sludge and underlying soils. Details not provided.

3. SOIL CONTAMINATION

Contaminants: Creosote and phenolic wastes. Phenol, chlorinated phenols, PAH's

Levels of Concentration: In sludges, prior to treatment, phenolic compound ranged from 10 mg/L to 13,000 mg/L while individual PAH's ranged from 1100 mg/L for benzo(a)pyrene to 300,000 mg/L for phenanthrene and anthracene. In soils, phenolic compounds ranged from 45 to 15,400 mg/L and PAH concentrations ranged from 460 mg/L for benzo(a)pyrene to 9,300 mg/L for phenanthrene and anthracene.

Extent of Contamination: An estimated 6,270 yd³ of contaminated sludge was generated from a surface impoundment roughly 1.4 acres in size and varying in depth from 4 to 12 ft. The volume of contaminated soil was estimated to be 7,000 yd³.

4. OPERATIONAL INFORMATION

Period of Operation: N/A

Process Description: A three-stage process is used for the treatment of contaminated sludges. Sludge is placed in a primary treatment cell where emulsifying agents, commercial bactered strains and nutrients are added. Following 1



week of treatment, the primary cell is decanted to a second treatment cell and the primary cell is refilled with waste sludge. The decanted sludge is held in the second treatment cell which acts to polish the waste and break down more recalcitrant organic compounds for 1 week, before being decanted to a third cell settling prior to final discharge or treatment. Treatment for soil is similar except that initially the soil is slurried in a mixing cell before being transferred to the primary treatment cell. The residues from this treatment were solidified and landfilled.

Treatment Rate: The process treated 13,300 yd³ during a period of 6 mos.

Treatment Cost: N/A

System Mobility and

Set Up Time: System was built on site. No details of cell construction or process hardware was provided.

5. TREATMENT EFFECTIVENESS

Removal Efficiency: Table 1 provides concentrations in sludges and soil prior to treatment, with concentrations during 3 periods after treatment for phenolic compounds and PAH's. Following the first treatment period, benzo(a)pyrene showed a 98% reduction in concentration while PCP showed a 99% reduction.

Process Byproducts: none reported

Research Needs: The study failed to account for abiotic losses by volatilization and photolytic degradation. Losses of benzo(a)pyrene are extremely high considering the short contact time of waste in each cell. Further understanding of the conditions which lead to such high removal rate should be investigated.

6. CONTACTS FOR INFORMATION

Planning Design & Research Engineers Inc.
Nashville, Tennessee
Attn: P.A. Shack

7. REFERENCES: Shack et al., (1988)

Table 1 Results of Biotreatment of Wood Preserving Waste

PARAMETER	SLUDGE BEFORE TREATMENT	SOIL BEFORE TREATMENT	PERIOD 1			PERIOD 2			PERIOD 3		
			MIXING	AERATED	POLISHING	MIXING	AERATED	POLISHING	MIXING	AERATED	POLISHING
			CELL	CELL	CELL	CELL	CELL	CELL	CELL	CELL	CELL
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
2-CHLOROPHENOL	10	45	<5	<5	<0.25	<1	<1	<1	0.38	<0.06	0.06
PHENOL	69	1280	<5	<5	<0.25	<1	<1	<1	0.14	<0.06	<0.05
2,4-DIMETHYLPHENOL	120	120	<5	<5	<0.25	<1	<1	<1	0.77	<0.06	<0.05
2,4,6-TRICHLOROPHENOL	37	1870	<5	<5	<0.25	<1	<1	<1	1	0.22	<0.05
p-CHLORO-m-CREOSOL	10	2660	<5	<5	<0.25	<1	<1	<1	<0.6	1.2	<0.05
TETRACHLOROPHENOL	790	NA	370	570	21	<2	<2	<2	19	7.5	8.6
2,4-DINITROPHENOL	20	<50	<10	<10	<0.5	<3	<3	<3	<0.2	<0.2	<0.2
PENTACHLOROPHENOL	13000	15400	5700	14000	44	160	96	32	170	64	41
NAPHTHALENE	51000	3100	2600	76	1	14	0.26	0.11	4	<1	<1
ACENAPHTHENE	38000	3000	25000	12000	110	160	58	14	110	23	<1
PHENANTHRENE + ANTHRACENE	300000	9300	71000	8700	130	960	86	47	700	42	12
FLUORANTHENE	51000	4070	36000	29000	320	210	130	46	160	130	5.1
CHRYSENE + BENZ(A)ANTHRACENE	11000	1500	7600	6200	78	47	28	11	39	33	2.3
BENZO(b,k)FLUORANTHENE	2700	NA	2200	1700	28	14	8.5	4.3	11	12	4.4
BENZO(a)PYRENE	1100	460	890	720	13	6.2	3.6	1.8	4.7	4.6	2
IDENO(1,2,3-cd)PYRENE + DIBENZO(a,h)ANTHRACENE	100	120	380	240	<10	2.3	1.2	<0.2	<3	<3	<3
CARBAZOLE	23000	1530	560	410	8.1	1.7	2	1.5	<1	2.2	<1

Source: Shack et al (1989)



APPENDIX C
LIST OF ACRONYMS



List of Acronyms

- 1) BTEX - Benzene, Toluene, Ethylbenzene, Xylene
- 2) BTX - Benzene, Toluene, Xylene
- 3) DRE - Destruction and Removal Efficiency
- 4) MAH - Monocyclic Aromatic Hydrocarbons
- 5) PAH - Polycyclic Aromatic Hydrocarbons
- 6) PCB - Polychlorinated Biphenyls
- 7) PCE - Perchloroethylene
- 8) PCP - Pentachlorophenol
- 9) TCE - Trichloroethylene
- 10) TCLP - Toxicity Characteristic Leachate Procedure
- 11) VOC - Volatile Organic Compounds

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