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**SCREENING GUIDE FOR  
CONTAMINATED SEDIMENT TREATMENT TECHNOLOGIES**

**Restoration Technologies Division  
Technology Development Branch  
St. Lawrence Centre  
Environment Canada**

**December 1993**

## WORK GROUP

This guide was prepared by Jean-René Michaud under the direction of René Rochon, Chief, Restoration Technologies Division. Lucie Olivier, Jacques Bérubé and Monique Simond contributed feedback and suggestions.

## NOTICE TO READERS

Mention of trade names or commercial products in this report does not constitute recommendation of their use. For more information about this guide and the recommendations it contains, contact the following:

Technology Development Branch  
Environment Canada  
685 Cathcart Street  
8th Floor  
Montréal, Québec  
H3B 1M6  
(514) 283-4670

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## PERSPECTIVE DE GESTION

Le présent **Guide sur l'évaluation et le choix des technologies de traitement des sédiments contaminés** vise à assister les promoteurs et les gestionnaires dans la planification, la conception, l'évaluation et la réalisation de projets de dragage et d'assainissement de sédiments contaminés. En présentant les avantages et les limites des technologies démontrées et en cours de démonstration pour le pré-traitement et le traitement des sédiments et pour le traitement des effluents des opérations de traitement et de mise en dépôt des sédiments, ce guide vise également à encourager le développement de technologies innovatrices pour la dépollution de sédiments contaminés.

Ce guide s'ajoute aux autres documents publiés par la Direction du développement technologique du Centre Saint-Laurent (*Guide méthodologique de caractérisation de sédiments, Critères intérimaires pour l'évaluation de la qualité des sédiments du Saint-Laurent, Guide pour le choix et l'opération des équipements de dragage et pratiques environnementales qui s'y rattachent*).

## MANAGEMENT PERSPECTIVE

The **Screening Guide for Contaminated Sediment Treatment Technologies** was drafted to help project proponents and managers plan, design, assess and conduct contaminated sediment dredging or cleanup projects. The guide is also meant to encourage development of innovative technologies for remediation of contaminated sediment, and to this end, among others, includes descriptions of the strengths and limitations of technologies demonstrated or under demonstration to pretreat or treat sediment and to treat effluent from sediment treatment or disposal operations.

The guide is the latest in a series of publications issued by the Technology Development Branch of the St. Lawrence Centre. Other publications in the series are as follows: *Methods Manual for Sediment Characterization*; *Interim Criteria for Quality Assessment of St. Lawrence River Sediment*; and *Selecting and Operating Dredging Equipment: A Guide to Sound Environmental Practices*.

## RÉSUMÉ

En raison des enjeux environnementaux et économique liés à la présence de sédiments contaminés, à la gestion des matériaux de dragage contaminés, à la dépollution de sites aquatiques contaminés, toute décision de traitement doit faire l'objet d'une analyse au cas par cas afin de bien comprendre l'ensemble de la problématique. La présence de sources actives de pollution, la nature et l'importance de la contamination, les risques de remise en suspension ou en solution des contaminants par des phénomènes naturels ou artificiels et la présence de ressources et usages sensibles sur ou à proximité du site à restaurer, doivent être considérés.

Les différents scénarios de traitement de sédiments contaminés, avec les variantes possibles qui s'offrent aux promoteurs, depuis la décision de ne pas intervenir jusqu'à celle d'éliminer en partie ou en totalité les contaminants présents dans les sédiments, sont précisés en faisant références au degré de décontamination exigé par la réglementation en vigueur. Les avantages et désavantages de chacun des scénarios sont sommairement énumérés et des critères d'évaluation et de choix de scénarios sont également proposés.

Les technologies de pré-traitement qui se traduisent généralement par une réduction significative des volumes de sédiments à manipuler et à traiter sont ensuite décrites en précisant pour chaque type de technologie, le stade de développement ainsi que les avantages et limites.

Les diverses technologies de traitement (thermique, extraction, biologique, chimique et d'immobilisation) qui ont été expérimentées un peu partout à travers le monde pour les sols et les sédiments, ou qui font actuellement l'objet de projets de démonstration de décontamination de sédiments sont présentées. Pour chaque type de technologie, les informations suivantes sont rapportées : principe de base; techniques ou procédés disponibles; domaines d'application; avantages et limites inhérents à chaque technologie; avantages et limites pour le traitement des sédiments; procédés démontrés pour les sédiments; procédés faisant actuellement l'objet de projets de démonstration et ceux retenus pour des projets de dépollution de sédiments contaminés.

Compte tenu des volumes d'eau plus ou moins contaminée résultant de la manipulation et du traitement des sédiments, les technologies démontrées ou en cours de démonstration pour le traitement des effluents ou des lixiviats sont également présentées.



Afin de comparer les diverses technologies, les principes, les avantages, les limites et les coûts de traitement anticipés pour chaque groupe de technologies sont ensuite rappelés. Pour les mêmes raisons, les impacts potentiels de certaines technologies de traitement sur l'environnement et la santé humaine sont sommairement décrits et visualisés dans une matrice d'impact. Une liste de critères d'évaluation et de choix des technologies de traitement visant à prendre en compte l'ensemble de ces considérations, est enfin proposée.

**ABSTRACT**

Environmental impacts as well as costs must be considered when making decisions about contaminated sediment, its management as dredged material and the cleanup of contaminated aquatic sites. In fact, each situation must be studied thoroughly on a case-by-case basis before treatment decisions are made. Factors to consider include presence of active sources of pollution, nature and scope of contamination, risks of contaminant resuspension or return to solution due to natural or anthropogenic phenomena and presence of sensitive resources or uses at or close to the site to be restored.

This guide describes contaminated sediment treatment scenarios (with variants) available to project proponents--everything from no action to partial or total removal of sediment contaminants--depending on decontamination level required by current criteria. Strengths and limitations of each scenario are outlined, and scenario evaluation and selection criteria are proposed.

Pretreatment technologies--generally ways of significantly reducing sediment volume to be handled and treated--are described, and stage of development, strengths and limitations of each pretreatment technology type are indicated.

Soil and sediment treatment technologies (thermal, extraction, biological, chemical and immobilization) tested in different parts of the world or under demonstration for sediment remediation are described. For each type of technology, the following information is given: basic principle, methods or processes available, application, strengths and limitations, processes demonstrated on sediment, processes under demonstration, and processes recommended for contaminated sediment cleanup projects.

Given the amount of contaminated water the handling and treatment of sediment generates, the guide also describes technologies demonstrated or under demonstration for effluent or leachate treatment.

To assist the reader in comparing technologies, the guide closes with a review of the principles, strengths, limitations and anticipated treatment costs of each technology type as well as a brief description and a chart of possible impacts of certain technologies on the environment and human health. A list of criteria that consider all these factors is then proposed for evaluating and selecting treatment technologies.

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## INTRODUCTION

### 1.1 Background

Industrial, agricultural and urban development activities around the Great Lakes and the St. Lawrence River have over the years caused contaminants to accumulate in the water column and in sediment, threatening the river ecosystem, the largest in eastern North America. In many places, untreated water is no longer suitable for consumption, swimming is forbidden and habitats have deteriorated so much that survival of many plant and animal species is threatened, and sport and commercial fishing have been seriously compromised.

Although provincial and federal governments are making efforts to reduce contamination at the source, water quality and aquatic habitats may continue to deteriorate for a number of years because of contaminated sediment already present in certain stretches of the river. In addition, sediment contaminants are liable to be regularly resuspended or redissolved in the water column during periods of high runoff (flood periods or heavy storms) or as a result of violent winds or commercial and recreational navigation and the dredging activities they require.

Aware of these problems, the federal and provincial governments have developed protection, decontamination and cleanup programs for aquatic habitats at greatest risk.

### 1.2 St. Lawrence Action Plan

On 3 June 1988, the governments of Canada and Quebec signed an agreement to cooperate on cleaning up and protecting the St. Lawrence River. On 1 July 1988, the Treasury Board approved federal funds of \$110 million over five years to implement the St. Lawrence Action Plan. One goal of the plan is to assess sediment-related problems in the main federal port areas so cleanup plans can be developed in cooperation with harbour managements.

As part of the St. Lawrence Action Plan's Restoration component, two programs managed by the Technology Development Branch of the St. Lawrence Centre were developed. The purpose of the first program, *Dredging Technologies*, was to develop tools for consultants and dredging project proponents to identify and describe environmental problems associated with

sediment dredging and to improve management of dredging-related activities. One outcome of this program was publication of *Selecting and Operating Dredging Equipment: A Guide to Sound Environmental Practice* (St. Lawrence Centre, 1992).

In preparation for eventual cleanup, contaminated sites along the St. Lawrence River were inventoried and ranked for cleanup urgency, and Environment Canada's Environmental Protection Branch characterized (qualitatively and quantitatively) the sediment of the Montreal, Trois-Rivières and Quebec City harbours. Remediation scenarios were developed for two of the three harbours. To provide guidelines for the scenarios and other projects involving sediment management, the St. Lawrence Centre's Restoration Technologies Division together with Environment Canada's Environmental Protection Branch and the Canadian Wildlife Service, Fisheries and Oceans Canada and the Quebec Department of the Environment undertook to review criteria for evaluating the quality of sediment in the St. Lawrence River.

Probably one of the next steps towards restoring the two top-priority harbours (Montreal and Quebec City), the Lachine canal and eventually other federal sites along the St. Lawrence River will be demonstrations of contaminated sediment treatment technologies to determine limits, effectiveness, costs and general suitability for the specific conditions of the St. Lawrence River.

Hence one of the goals of the second program, *Technologies for the Disposal of Sediment*, is to promote research, development, demonstration and implementation of new technologies for safe disposal of uncontaminated as well as contaminated sediment.

### 1.3 Great Lakes Action Plan

The St. Lawrence Action Plan was introduced in June 1988. In the fall of 1989, the federal government launched the Great Lakes Action Plan with a budget of \$125 million to restore the quality of water in the Great Lakes. The Great Lakes Cleanup Fund provides Environment Canada with \$55 million to develop and demonstrate remedial technologies and programs to meet federal government responsibilities in the seventeen "Areas of Concern" identified on the Canadian side of the Great Lakes by the International Joint Commission; the Commission identified a total of forty-three areas of concern.

The Great Lakes Action Plan is the Canadian counterpart of a similar U.S. plan, *Assessment and Remediation of Contaminated Sediment (ARCS)*, introduced in 1987 under the direction of the *Great Lakes National Program Office* of the U.S. Environmental Protection Agency (USEPA). The ARCS program was developed to study and conduct demonstration projects for control and removal of toxic pollutants in the sediment of the Great Lakes.

As part of the U.S. program, seventeen technologies originally designed for treatment of contaminated soil are currently being demonstrated on a bench (thirteen) or pilot scale (four) in the five following priority Great Lakes areas: the Sheboygan River, Wisconsin; Indiana Harbour and Grand Calumet River, Indiana; the Saginaw River and Saginaw Bay, Michigan; the Ashtabula River, Ohio; and the Buffalo River, New York. Demonstration results are to be published in 1994 together with reports on all related research on sediment characterization, risk assessment methodologies and development of bioassays, dispersion models, mass balances, cleanup scenarios, quality assurance programs and communication programs to publicize results.

On the Canadian side, demonstration of sediment removal techniques and of new and innovative methods for contaminated sediment treatment is under way or planned through 1993-1994 in the following Areas of Concern: the Niagara River, the Welland Canal, Thunder Bay and the Toronto, Hamilton, Port Hope and Collingwood harbours.

In response to a public call for declarations of interest issued in December 1990, more than eighty declarations involving more than 140 technologies were submitted to the Great Lakes Environment Office, Environment Canada. The declarations were analyzed and forty-two prospective bidders were asked to submit offers of service for small-scale work. Twelve innovative contaminated sediment removal processes proposed by these bidders were subsequently selected for demonstration; funding had already been granted in January 1993 for bench-scale or pilot-scale demonstration of seventeen contaminated sediment pretreatment or treatment processes.

#### **1.4 Program for Development and Demonstration of Site Remediation Technology (DESRT)**

While profiting from what is being learned from technology demonstration programs in Canada, the United States and Europe (the Netherlands in particular), the Canadian and Quebec governments want to conduct innovative contaminated sediment demonstration projects in Quebec under the *Development and Demonstration of Site Remediation Technology program* (DESRT), also known by its French name, *Programme de développement ou de démonstration de techniques d'assainissement des lieux contaminés (DÉTALC)*.

Under this five-year federal-provincial agreement ending 31 March 1995, the Quebec Department of the Environment and Environment Canada have a fund of \$12.75 million to develop or demonstrate cleanup technologies for contaminated sediment or soil, mine tailings or groundwater in Quebec. Appendix A lists research priorities and eligibility criteria for the DESRT program and for other technology development funding programs.

#### **1.5 Guide objectives**

Through the *Technologies for the Disposal of Sediment* program, the St. Lawrence Action Plan promotes development, demonstration and implementation of new environmental technologies for treatment of contaminated sediment. With the publication of this guide for screening treatment scenarios and technologies, the St. Lawrence Centre hopes to offer assistance in selecting and developing contaminated sediment treatment technologies based on Canadian, U.S. and European experience.

The St. Lawrence Centre hopes this review of treatment technologies used or under analysis or demonstration for treatment of contaminated sediment will contribute to development of Quebec and Canadian centres of expertise in contaminated sediment treatment technologies.

Specific objectives of this guide are as follows:

- To identify a variety of contaminated sediment treatment scenarios, their strengths and limitations.
- To identify the main components of a treatment scenario.
- To identify options for pretreating and treating contaminated sediment and for treating effluents generated by sediment dredging, pretreatment or treatment.
- To specify stage of development, application, limitations and costs of use of each technology.
- To draft a list of factors and evaluation criteria to be considered when conducting remediation projects and selecting sediment treatment technologies.

## **1.6 Sources of information**

To prepare this guide on contaminated treatment technologies, the Restoration Technologies Division of the St. Lawrence Centre examined and reviewed a great deal of literature published under the technology demonstration programs mentioned earlier and prepared by or for the following agencies:

- The U.S. Environmental Protection Agency (USEPA) (as part of the Superfund Innovative Technology Evaluation (SITE) program).
- The U.S. Army Corps of Engineers (as part of the New Bedford Harbour, Massachusetts, restoration program and the ARCS Great Lakes cleanup program).
- The Netherlands Organization for Applied Scientific Research (TNO).
- The Great Lakes Environment Office, Environment Canada (texts published by the Burlington Wastewater Treatment Centre).

- Environment Canada (as part of the Demonstration and Development of Site Remediation Technology (DESRT) program and the National Groundwater and Soil Remediation Program (GASReP)).
- The St. Lawrence Centre (texts on validating treatment processes for contaminated sediment in the Lachine Canal).

Literature consulted is listed in the bibliography to the guide and cited throughout the guide.

## **1.7 Content of guide**

The guide has seven chapters. Chapter 1 gives background information, lists programs to encourage demonstration projects and outlines guide objectives. Chapter 2 describes available contaminated sediment remediation scenarios.

Chapter 3 is devoted to sediment pretreatment technologies suitable for clean as well as contaminated sediment. Pretreatment technologies are mainly designed to reduce the volume of material to be handled and treated, to condition dredged material for use in building or development work, or to perform conditioning essential for subsequent treatment.

Chapter 4 describes sediment treatment technologies properly speaking. Such technologies destroy contaminants, treat them to make them less dangerous or toxic, remove them from sediment for subsequent treatment or disposal, or immobilize, fix or contain them to prevent their release into the environment.

Since most sediment treatment technologies also require treatment of effluents generated by the treatment itself (because of the high water content of sediment), Chapter 5 is devoted to effluent or leachate treatment technologies.

Chapter 6 describes an approach for selecting technologies. This approach demands all work planned be considered from a technical, economic and environmental point of

view. Environmental considerations include protection of public health and sensitivity to social issues.

Chapter 7 describes conclusions and recommendations stemming from the review of sediment treatment scenarios and technologies. The guide closes with a bibliography of literature cited throughout the text and five appendixes: a list of government funding programs for environmental technologies development and demonstration projects; a list of contaminants in each major contaminant category; addresses of vendors or developers of the technologies described in the guide; addresses of agencies, organizations and government departments where reference literature or more information on the technologies can be obtained; and a glossary of technical terms used in the guide.



## 2 CONTAMINATED SEDIMENT TREATMENT AND CLEANUP SCENARIOS

### 2.1 Objectives

There is sometimes a risk contaminants in undisturbed sediment will turn up in other environmental media--water, aquatic plants and organisms, semi-aquatic wildlife, birds and eventually human beings. The extent of the risk depends on hydrodynamic conditions, the physical and chemical characteristics of the sediment, the abundance and sensitivity of bioresources on or near the site and exposure factors associated with human activity on or near the site.

At sites where contaminated sediment is regularly disturbed by shipping traffic or dredging activities for maintenance of navigable waterways the risk of contaminants becoming resuspended or redissolved in the water column and transferred to other environmental media is higher. When dredged sediment is disposed of at such sites--in the water or upland--there is a risk of contaminating other environments and other environmental media (air, surface water, soil, groundwater, and shoreline or terrestrial plants and animals) if suitable measures are not taken.

Sometimes the risks for the environment or human health are too high and action must be taken. However, sediment treatment and cleanup operations can also contaminate other environments, and there are risks at every stage of the work--dredging, transportation, sediment pretreatment and treatment, effluent treatment, and disposal of treatment residues--depending on scenario, technologies and protective measures selected for each work phase.

As a result, scenarios considered for remediation of contaminated sediment must meet the following criteria:

- a) The work must be justified by degree of contamination and sensitivity of resources and human activities in the vicinity.
- b) The work must remain effective in the medium and the long term.

- c) Risks at all stages of the work must never be greater than the no action option.
- d) Physical and chemical characteristics of the contaminated sediment must be taken into account.
- e) Possibilities of recontamination of the site must be taken into account.

## **2.2 Sediment physical and chemical characteristics affecting contaminant mobility**

Physical and chemical characteristics of sediment exert a strong influence on bioavailability of sediment contaminants. These characteristics, which vary from one site to the next, can have a major impact on remediation scenarios (USEPA, 1991a).

The primary physical characteristic is particle-size distribution, that is, percentages of sand, clay and silt. Sandy sediment generally has little attraction for metals or synthetic organics (pesticides and industrial organics). Fine sediment (silt and clay) has a much stronger affinity for all classes of contaminants. Organic matter content, including humus, is also important, since humic material has a strong affinity for metals and nonpolar contaminants and serves as an energy source for sediment microbial populations. Sediment water content is important in selecting technologies at all stages (dredging, transportation, storage and treatment) of a remediation project.

Chemical properties of sediment also affect contaminant mobility and biodegradability. Important chemical analyses include pH, oxidation-reduction conditions, salinity conditions and sulphide content as well as amount and type of cations and anions, and amount of potentially reactive iron and manganese.

Contaminants may be mobilized or immobilized by physical or chemical modification of sediment during remediation operations. For example, metal carbonates may release their metals if pH is reduced during dredging and treatment. An understanding of sediment chemistry is thus highly important when developing and selecting treatment scenarios (USEPA, 1991a).

### 2.3 Substances to be considered in conducting sediment remediation projects

Table 2.1 lists substances that must routinely be analyzed in any project to assess the quality of St. Lawrence River sediment (St. Lawrence Centre, 1992a). Managers may add substances to the list or delete others depending on specific conditions at the site to be dredged or restored.

Table 2.1 lists only the most common major sediment contaminants (heavy metals and PAHs, for example) as well as significant indicators of sediment type and contamination (total organic carbon and the various Aroclors, for example). The list includes the substances most often mentioned by the principal agencies responsible for setting contaminant priorities.

Table 2.2 lists substances that must be considered when a dredging or restoration project involves ocean dumping of contaminated sediment (under Part VI of the *Canadian Environmental Protection Act*, which governs ocean dumping projects).

**Table 2.1 Substances selected for routine St. Lawrence sediment quality assessment (April 1992)**

INORGANICS	ORGANICS
Extractable arsenic Extractable cadmium Extractable chromium Extractable copper Total mercury Extractable nickel Extractable lead Extractable zinc	Aroclor - 1016 Aroclor - 1248 Aroclor - 1254 Aroclor - 1260 Total organic carbon Mineral oils and greases* Total PAHs Individual PAHs Acenaphthene Acenaphthylene Anthracene Benzo(a)anthracene Benzo(a)pyrene Benzo(b)fluoranthene* Benzo(ghi)perylene Benzo(j)fluoranthene* Benzo(k)fluoranthene* Benzo(e)pyrene* Chrysene Dibenzo(a,e)pyrene* Dibenzo(a,h)anthracene Dibenzo(a,h)pyrene* Dibenzo(a,i)pyrene* Dibenzo(a,j)acridine* Fluoranthene Fluorene Indeno(1,2,3-cd)pyrene Naphthalene Phenanthrene Pyrene Methyl 3-Cholanthrene* Methyl 5-Chrysene* Dibenzo-7H(c,g)carbazole* Dimethyl7,12-benzo(a)anthracene*

\* No quality criterion has been proposed for this substance based on the approaches adopted.

NOTE: The list is recommended but not exclusive. It includes substances that should be routinely analyzed in any project to assess the quality of sediment in the St. Lawrence River. Managers may have to add substances or drop others depending on specific conditions at the site to be dredged or restored. The list may also have to be revised in light of new materials safety data.

**Table 2.2 Substances that must be considered under Part VI of the Canadian Environmental Protection Act (April 1992)**

INORGANICS	ORGANICS
Extractable arsenic Extractable beryllium* Extractable cadmium Extractable chromium Extractable copper Total cyanides* Total mercury Extractable nickel Extractable lead Extractable vanadium* Extractable zinc	Aroclor - 1242* Aroclor - 1254 Aroclor - 1260 Total organic carbon Total carbon Dioxins* Furans* PAH (low molecular weight) PAH (high molecular weight) HCB Total oils and greases* Total phosphorus Pesticides  Aldrin $\alpha$ -BHC $\beta$ -BHC Cis-chlordane* Trans-chlordane* o,p-DDD* o,p-DDT p,p'-DDD p,p'-DDE p,p'-DDT Dieldrin Endrine $\alpha$ -endosulfan* $\beta$ -endosulfan* Heptachlor Heptachlor epoxide Lindane Methoxychlor* Mirex

\* No quality criterion has been proposed for this substance based on the approaches adopted.

## 2.4 Interim criteria for sediment quality assessment

Table 2.3 lists interim criteria adopted for assessing the quality of sediment in the St. Lawrence River. Three levels were defined:

- No effect level (reference concentration, no chronic or acute effects).
- Minimal effect level (concentration with a tolerated effect on most benthic organisms).
- Toxic effect level (concentration with a harmful effect on most benthic organisms).

Detailed information on approaches used to select criteria for each level are given in *Interim Criteria for Quality Assessment of St. Lawrence River Sediment*, published by the St. Lawrence Centre (1992a).

Table 2.4 shows the general decision-making process proposed for managing dredged material and restoring contaminated aquatic sites based on the three levels.

**2.4.1 Application of criteria to dredged material management.** Dredged material is basically sedimented material that has been removed from the bottom of a waterway, usually to improve draft--mainly for commercial shipping but sometimes for recreational navigation.

As Table 2.4 shows, dredged sediment is categorized as Class 1 sediment when concentration (not standardized for organic carbon content) of all priority substances expressed in dry weight is equal to or below no effect level. The dredged material is then deemed uncontaminated and can be used without restriction.

**Table 2.3 Interim criteria adopted for St. Lawrence sediment quality assessment (April 1992)**

PARAMETER ( $\mu\text{g/g}$ or $\mu\text{g/g}$ per 1% TOC <sup>a</sup> )	LEVEL 1 <sup>b</sup> (no effect)	LEVEL 2 (minimal effect)	LEVEL 3 (toxic effect)
Extractable arsenic	3,0	7	17
Extractable cadmium	0,2	0,9	3
Extractable chromium	55	55	100
Extractable copper	28	28	86
Total mercury	0,05	0,2	1
Extractable nickel	35	35	61
Extractable lead	23	42	170
Extractable zinc	100	150	540
PCBs (total)	0,02	0,2	1
Aroclor - 1016	-	0,01	0,4
Aroclor - 1248	-	0,05	0,6
Aroclor - 1254	-	0,06	0,3
Aroclor - 1260	-	0,005	0,2
Aldrin	0,0006	0,002	0,04
BHCs (total)	-	0,005	0,1
$\alpha$ -BHC	0,0003	0,01	0,08
$\beta$ -BHC	0,0002	0,03	0,2
$\gamma$ -BHC	0,0009	0,003	0,009
Chlordane	0,001	0,007	0,03
DDD and p,p'-DDD	0,002	0,01	0,06
p,p'-DDE	0,002	0,007	0,05
DDT	0,006	0,009	0,05
Dieldrin	0,0001- 0,0008	0,002	0,3
Endrine	0,001	0,03	0,1
HCB	0,001	0,03	0,1
Heptachlor	0,0003	0,0003	0,01
Heptachlor epoxide	0,001	0,005	0,03

**Table 2.3 Interim criteria adopted for St. Lawrence sediment quality assessment (April 1992) (continued)**

PARAMETER ( $\mu\text{g/g}$ or $\mu\text{g/g}$ per 1% TOC <sup>a</sup> )	LEVEL 1 <sup>b</sup>	LEVEL 2	LEVEL 3
Mirex	0,0001	0,011	0,8
PAHs (high molecular weight)	1	-	-
Benzo(a)anthracene	0,05 - 0,1	0,4	0,5
Benzo(a)pyrene	0,01 - 0,1	0,5	0,7
Benzo(b)fluoranthene	0,3	-	-
Benzo(ghi)perylene	0,1	-	-
Chrysene	0,1	0,6	0,8
Dibenzo(a,h)anthracene	0,005	-	-
Fluoranthene	0,02 - 0,2	0,6	2
Indeno(1,2,3,cd)pyrene	0,07	-	-
Pyrene	0,02 - 0,1	0,7	1
PAHs (low molecular weight)	0,1	-	-
Acenaphthene	0,01	-	-
Acenaphthylene	0,01	-	-
Anthracene	0,02	-	-
Fluorene	0,01	-	-
2-Methylnaphthalene	0,02	-	-
Naphthalene	0,02	0,4	0,6
Phenanthrene	0,03 - 0,07	0,4	0,8

a) All criteria are expressed in micrograms per gram ( $\mu\text{g/g}$ ) of dry sediment except for toxic effect levels (Level 3) of nonpolar organics which are expressed in micrograms per gram of dry sediment with 1% total organic carbon (TOC). To establish toxic effect level of a specific nonpolar organic (shaded), the value shown in the table must be multiplied by the percentage of TOC in the sample to a maximum of 10% TOC. (For example, toxic effect level of total PCBs in a sample containing 2% TOC is  $1 \mu\text{g/g} \times 2 = 2 \mu\text{g/g}$ .) Values below 10 have been rounded to the nearest significant figure; those over 10 have been rounded to 2 significant digits.

b) When the lower limit of application of an analysis method is greater than Level 1 criterion, then the lower limit should be used until advances in methodology drop the limit to the Level 1 criterion.



**Table 2.4 Dredged material management and site remediation as a function of contamination level and sediment class**

CLASS	LEVEL	APPROACH	EFFECTS	DREDGED MATERIAL MANAGEMENT	SITE REMEDIATION
4			Major damage to aquatic environment	Dredged material must be treated or contained	Sources of contamination must be eliminated and possibility of restoring contaminated environments considered
	Level 3 (toxic effect)	90th percentile, SLC approach (contamination affects 90% of benthic organisms)			
3	Minimum remediation level		Harmful impact on benthic organisms	Environmental impacts of sediment removal and disposal should be studied carefully. Appropriate tests (bioassays, elutriation or others) and chemical analyses should be performed. Disposal must not contribute to deterioration of the quality of the receiving environment.	Target level for remediation, to be determined on a case by case basis through risk analysis or other suitable means. Possibility of eliminating sources of contamination and reducing contaminant migration to areas of better quality should be considered. Restoration probably not a desirable solution.
	Level 2 (minimal effect)	15th percentile, SCL approach (contamination affects 15% of benthic organisms)			
2			Tolerable for benthic organisms Possible impact on use of water		
	Level 1 (no effect)	Background approach, reference level considered pollution free		In general, material may be disposed of in open water or used for other purposes without restriction. Disposal must not however contribute to deterioration of the quality of the receiving environment.	No remediation considered.
1			No chronic or acute impacts on benthic organisms, water quality or water uses		

When concentration of priority substances expressed in dry weight is equal to or above Level 2 (minimal toxic effect), the sediment is categorized as Class 2 sediment. Class 2 dredged material can be disposed of in open water or used for other purposes as long as it does not contribute to deterioration of the receiving environment (presence of sensitive organisms or environments must be considered, for example).

When concentrations exceed minimal effect level but do not exceed toxic effect level, the sediment is categorized as Class 3 sediment. With Class 3 sediment, in-depth environmental assessment of the disposal site as well as additional laboratory tests of sediment toxicity (bioassays, elutriation tests and so forth) are required before any decision is made about open-water disposal. Among other things, the disposal site must be as contaminated or more contaminated than the dredged material for its disposal to be acceptable. Depending on the sensitivity of the disposal site, risk analyses may also be required for more in-depth assessment of the impacts of contaminated sediment dredging and disposal operations.

Sediment is categorized as Class 4 sediment when contaminant concentrations exceed toxic effect level. Class 4 sediment must not be released into open water; it must be treated or contained.

**2.4.2 Application of criteria to aquatic site remediation.** Table 2.4 also lists criteria for restoring contaminated aquatic sites. As the table shows, when contaminant concentrations are below toxic effect level (classes 1 to 3), site remediation is not a desirable solution because the cleanup operations would probably have more negative than positive environmental impacts.

With Class 4 sediment, however, where contaminant concentrations exceed toxic effect level, sources of contamination must be identified and monitored, and the possibility of site remediation considered following environmental assessment and risk analysis.

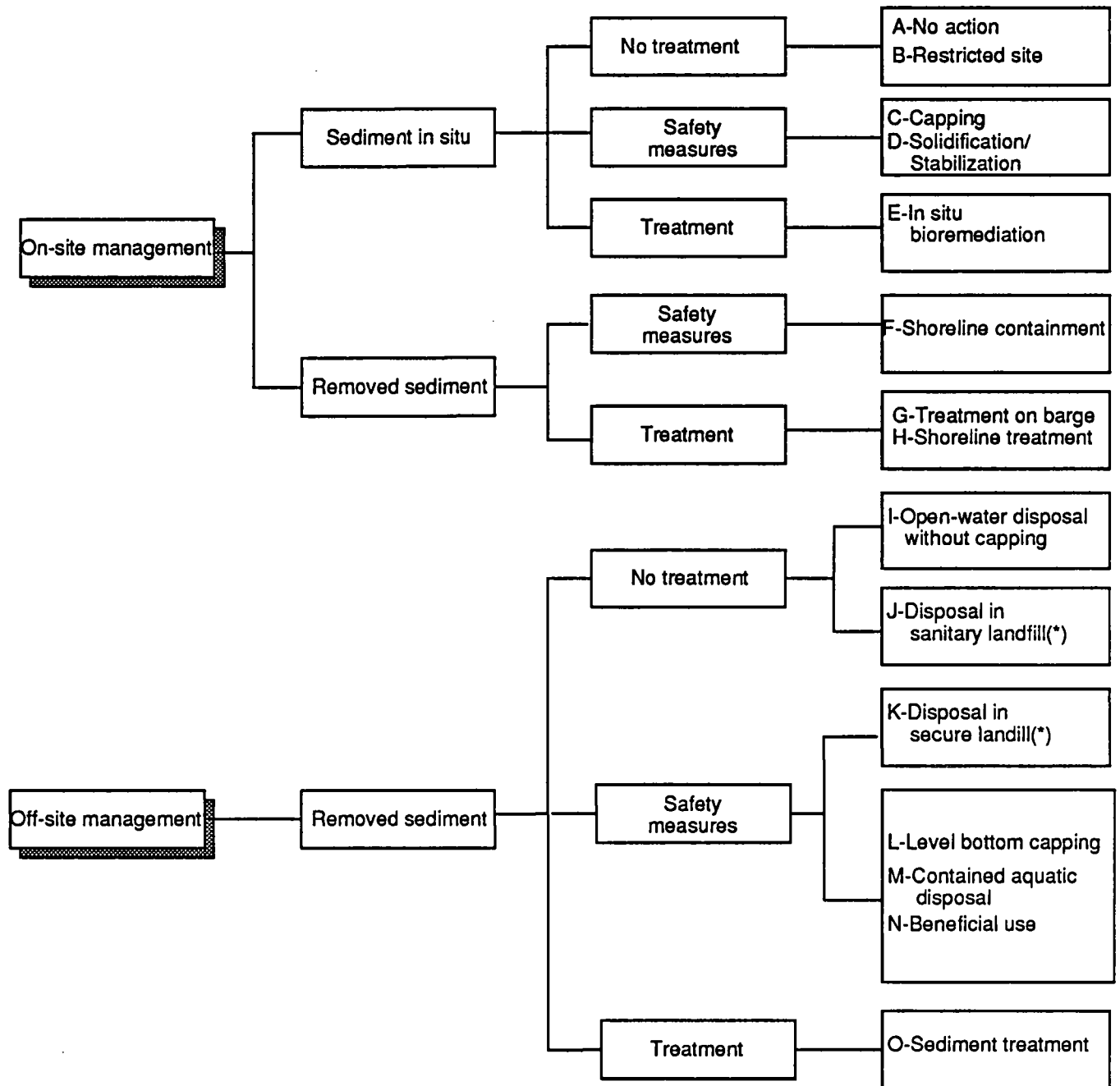
Each case must be studied individually to identify target decontamination level, which depends on conditions at the site to be restored and in the immediate surroundings. The following factors determine this minimum remediation level: local background contaminant concentrations, quality of sediment in adjacent areas, real environmental impacts, human health

or safety risks, hydrodynamic conditions, technical feasibility of the project and socioeconomic impacts of remediation.

## **2.5 Contaminated sediment treatment scenarios**

**2.5.1 Classification of treatment scenarios.** Figure 2.1 shows fifteen possible contaminated sediment treatment scenarios--from no action to total elimination of sediment contaminants directly on-site or through off-site management. Site-specific considerations apart, on-site scenarios are generally easier to implement, and off-site scenarios generally involve greater technical and economic constraints. The more technically difficult scenarios are also usually more costly; that is, on-site scenarios are as a rule less costly to implement than off-site scenarios. These are general rules only however; site-specific conditions and stage of development of technologies used can have a significant effect.

Table 2.5 lists variants for each of the fifteen scenarios depending on treatment site characteristics and technologies selected for sediment removal, pretreatment and treatment or for treatment of effluent and disposal of treatment residues.



(\*) With prior dewatering of dredged material

**Figure 2.1 Remediation scenarios for contaminated sediments**

**Table 2.5 Variants of contaminated sediment treatment/remediation scenarios**

SCENARIO	VARIANTS
A- No action	<ul style="list-style-type: none"> <li>Without environmental monitoring</li> <li>With environmental monitoring</li> </ul>
B- Restricted site	<ul style="list-style-type: none"> <li>Without environmental monitoring</li> <li>With environmental monitoring</li> </ul>
C- Capping	<ul style="list-style-type: none"> <li>Type of capping material</li> <li>Capping method</li> </ul>
D- On site solidification/stabilization	<ul style="list-style-type: none"> <li>Stabilization/solidification technologies</li> </ul>
E- In situ bioremediation	<ul style="list-style-type: none"> <li>Bioremediation technologies</li> </ul>
F- Shoreline containment	<ul style="list-style-type: none"> <li>Site selection</li> <li>Method of containment</li> <li>With or without sediment pretreatment</li> <li>Effluent treatment and pretreatment technologies</li> </ul>
G- Treatment on barge	<ul style="list-style-type: none"> <li>Site selection</li> <li>Treatment technologies</li> <li>Effluent treatment and pretreatment technologies</li> </ul>
H- Shoreline treatment	<ul style="list-style-type: none"> <li>Site selection</li> <li>Treatment technologies</li> <li>Effluent treatment and pretreatment technologies</li> </ul>
I- Open-water disposal without capping	<ul style="list-style-type: none"> <li>With or without sediment treatment</li> <li>Site selection</li> </ul>
J- Disposal in sanitary landfill	<ul style="list-style-type: none"> <li>With or without sediment treatment</li> <li>Site selection</li> </ul>
K- Disposal in hazardous landfill	<ul style="list-style-type: none"> <li>Site selection</li> <li>With or without pretreatment</li> <li>With or without sediment treatment</li> </ul>
L- Level bottom capping	<ul style="list-style-type: none"> <li>Site selection</li> <li>Method of capping</li> <li>Nature and thickness of capping material</li> </ul>
M- Contained aquatic disposal	<ul style="list-style-type: none"> <li>Site selection</li> <li>Method of capping</li> <li>Nature and thickness of capping material</li> </ul>
N- Beneficial use	<ul style="list-style-type: none"> <li>Site selection</li> <li>With or without pretreatment</li> <li>With or without sediment treatment</li> <li>Type and method of development</li> </ul>
O- Sediment treatment	<ul style="list-style-type: none"> <li>Pretreatment technologies</li> <li>Treatment technologies</li> <li>Site selection</li> <li>Residue treatment/disposal technologies</li> </ul>

As Figure 2.1 shows, if the first two scenarios (scenarios A and B, no treatment scenarios listed for reference or comparison only) are excluded, six scenarios (C to H) are suggested for handling sediment directly on site. These six are grouped first according to whether the sediment is handled in situ or removed and second according to whether the sediment is treated or contained (covered with clean material, for example).

Figure 2.1 also suggests seven scenarios for off-site treatment of removed sediment. These scenarios fall into three categories: no treatment (I and J), containment (K to N) and treatment (O).

**2.5.2 Treatment scenario strengths and limitations.** Table 2.6 summarizes the main technical, economic and environmental strengths and limitations of each treatment scenario listed in the preceding section. Although in principle scenarios calling for treatment of contaminated sediment are to be preferred, the risks of contaminant transfer to other environments or other environmental media (water, air or soil) during contaminant removal, transportation or storage are not negligible.

Every scenario must therefore be evaluated on a case-by-case basis taking into account economic constraints as well as site-specific environmental conditions, protection of public health, the nature of the contamination and the treatment technologies available when planning the treatment scenario.

Note that all scenarios suggested for off-site sediment treatment apply as well for management of contaminated dredged material from regular maintenance dredging.

**2.5.3 Treatment scenario evaluation and selection criteria.** Table 2.7 suggests technical, economic and environmental performance criteria for scenarios for treating contaminated sediment. The primary purpose of these criteria is to ensure environmental as well as technical, economic and social feasibility of all treatment plan components (dredging, transportation, storage, treatment, pretreatment, and treatment of effluents and residues) are considered when selecting a scenario. A second purpose is to ensure optimum scenarios are selected given environmental and social concerns at the site.

**Table 2.6 Strengths and limitations of contaminated sediment treatment/cleanup scenarios**

SCENARIOS	STRENGTHS	LIMITATIONS
A- No action	<ul style="list-style-type: none"> <li>• No investment required</li> <li>• To be considered under the following conditions: if impacts of dredging, treatment/disposal are greater than if the sediment is left in situ; if the contaminants will degrade naturally; or if sedimentation is isolating the contaminated sediment</li> </ul>	<ul style="list-style-type: none"> <li>• Health risks and risks of deterioration of water quality, bioresources and site uses remain</li> <li>• Constant monitoring required</li> <li>• Community acceptance difficult</li> </ul>
B- Restricted site	<ul style="list-style-type: none"> <li>• Reduces risk of contact with contaminated sediment</li> <li>• Reduces risk of contaminants becoming resuspended or redissolved</li> <li>• Inexpensive solution</li> </ul>	<ul style="list-style-type: none"> <li>• No protection for aquatic organisms that might come in contact with contaminated sediment</li> <li>• At some sites, seasonal restrictions or relocation of navigation are impossible</li> <li>• Community acceptance difficult</li> </ul>
C- In situ capping	<ul style="list-style-type: none"> <li>• Easy to implement</li> <li>• Relatively inexpensive solution</li> <li>• No transportation required</li> <li>• Demonstrated environmental efficiency</li> <li>• Prevents contaminant diffusion and convection in the water column and direct contact of contaminants and benthic organisms</li> <li>• Sediment need not be transported through urban areas</li> </ul>	<ul style="list-style-type: none"> <li>• Risks of contaminant migration</li> <li>• Long-term maintenance and monitoring required</li> <li>• Need for a sufficient draft can exclude or limit implementability</li> <li>• Community acceptance difficult</li> </ul>
D- In situ solidification/stabilization	<ul style="list-style-type: none"> <li>• Demonstrated environmental efficiency</li> <li>• Sediment need not be transported</li> <li>• Relatively inexpensive solution</li> <li>• Risks for workers and community during work are low</li> </ul>	<ul style="list-style-type: none"> <li>• Contaminants fixed but not destroyed</li> <li>• Organics content can limit implementability</li> <li>• Increase in sediment volume causes decrease in draft, limiting implementability in harbours</li> <li>• Requires long-term monitoring</li> </ul>
E- In situ bioremediation	<ul style="list-style-type: none"> <li>• Relatively inexpensive solution</li> <li>• Risks for workers and community during work are low</li> <li>• Accelerates natural biodegradation process</li> </ul>	<ul style="list-style-type: none"> <li>• Efficiency not yet demonstrated</li> <li>• Nature of contamination can be a limiting factor</li> <li>• Treatment time can be a limiting factor if remediation is urgent because of site resources or uses</li> <li>• Difficult to implement because oxygen, nutrients or microorganisms must be added</li> </ul>
F- Shoreline containment	<ul style="list-style-type: none"> <li>• Inexpensive solution</li> <li>• Remediated site can sometimes be used by industry or for recreation</li> </ul>	<ul style="list-style-type: none"> <li>• Permanent risk of contaminant migration</li> <li>• Community acceptance difficult</li> </ul>
G- Treatment on barge	<ul style="list-style-type: none"> <li>• Sediment need not be transported long distances</li> <li>• Contaminants are destroyed</li> </ul>	<ul style="list-style-type: none"> <li>• No commercial units available</li> <li>• May interfere with commercial or recreational navigation</li> <li>• Very costly solution</li> </ul>

**Table 2.6 Strengths and limitations of contaminated sediment treatment/cleanup scenarios (continued)**

SCENARIOS	STRENGTHS	LIMITATIONS
H- Shoreline treatment	<ul style="list-style-type: none"> <li>• Sediment need not be transported long distances</li> <li>• Contaminants are destroyed</li> </ul>	<ul style="list-style-type: none"> <li>• No commercial units available</li> <li>• Amount of land required not always available</li> <li>• Very costly solution</li> </ul>
I- Open-water disposal without capping	<ul style="list-style-type: none"> <li>• The most inexpensive, the fastest and technically the easiest solution to implement</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable for contaminated sediment unless disposal site is even more contaminated</li> <li>• Risk of contamination of other environments</li> <li>• Possible not negligible impacts during the work</li> <li>• Community acceptance difficult</li> </ul>
J- Disposal in sanitary landfill	<ul style="list-style-type: none"> <li>• Relatively inexpensive solution</li> <li>• Technically easy to implement</li> </ul>	<ul style="list-style-type: none"> <li>• Risk of contamination of other environments</li> <li>• Prior dewatering of sediment required</li> <li>• Feasible only for slightly contaminated or treated sediment</li> <li>• Contaminated sediment must be transported</li> </ul>
K- Disposal in hazardous landfill	<ul style="list-style-type: none"> <li>• Sites available</li> <li>• To be considered when treatment sites are not available</li> </ul>	<ul style="list-style-type: none"> <li>• Risk of contamination of other environments</li> <li>• Prior dewatering of sediment required</li> <li>• Not recommended for highly contaminated sediment</li> <li>• Community acceptance difficult</li> <li>• Relatively costly solution</li> <li>• Contaminated sediment must be transported</li> </ul>
L- Level bottom capping	<ul style="list-style-type: none"> <li>• Inexpensive and technically easy to implement</li> <li>• Guaranteed environmental efficiency</li> <li>• Prevents contaminant diffusion and convection in the water column and direct contact of contaminants and benthic organisms</li> <li>• Sediment need not be transported through urban areas</li> </ul>	<ul style="list-style-type: none"> <li>• Long-term stability and efficiency cannot be guaranteed</li> <li>• Permanent risk of contaminant migration</li> <li>• Requires long-term maintenance</li> <li>• Need for sufficient draft can limit implementability</li> <li>• Community acceptance difficult</li> </ul>
M- Contained aquatic disposal	<ul style="list-style-type: none"> <li>• Minimizes salting-out of contaminants in surface waters and prevents atmospheric and groundwater pollution</li> </ul>	<ul style="list-style-type: none"> <li>• Not recommended for highly contaminated sediment</li> <li>• Requires long-term monitoring</li> <li>• Community acceptance difficult</li> </ul>
N- Beneficial use	<ul style="list-style-type: none"> <li>• Creates wildlife habitats</li> <li>• Prevents shoreline erosion</li> <li>• Improves farmland</li> <li>• Source of construction material</li> </ul>	<ul style="list-style-type: none"> <li>• Can only be used for slightly contaminated sediment or sediment that has been treated or contained to prevent contaminant migration</li> <li>• Requires long-term monitoring</li> </ul>
O- Sediment treatment	<ul style="list-style-type: none"> <li>• Contaminants destroyed and no longer threaten the environment</li> <li>• Most socially acceptable solution</li> </ul>	<ul style="list-style-type: none"> <li>• Very costly</li> <li>• Efficiency of most technologies still to be demonstrated on field scale</li> </ul>



Table 2.7

**Evaluation criteria for contaminated sediment treatment scenarios**

Feasibility	EVALUATION CRITERIA
Technical	<ul style="list-style-type: none"> <li>• Physical and chemical characteristics of the sediment</li> <li>• Nature of contamination (organics, inorganics or both)</li> <li>• Volume of contaminated sediment</li> <li>• Available pretreatment technologies</li> <li>• Available treatment technologies (sediment and wastewater)</li> <li>• Site configuration and size</li> <li>• Technical feasibility</li> <li>• Relative permanence of the solution</li> <li>• Total duration of work (engineering, environmental studies, demonstration and implementation)</li> <li>• Technological risks</li> <li>• Compatibility of technologies (dredging, transport, storage, pretreatment and effluent treatment)</li> <li>• Flexibility</li> <li>• Efficiency</li> <li>• Long-term maintenance and monitoring needs</li> </ul>
Economic	<ul style="list-style-type: none"> <li>• Cost of project implementation (engineering, construction, operation, maintenance)</li> <li>• Cost of environmental studies</li> <li>• Cost of sediment treatment (dredging, transport, storage, pretreatment, treatment and effluent treatment)</li> <li>• Cost of treatment residue disposal</li> <li>• Cost of environmental monitoring during and after work</li> <li>• Funds available for remediation</li> <li>• Cost of technology demonstration (pilot and full scale)</li> </ul>
Environmental	<ul style="list-style-type: none"> <li>• Impact of contaminated sediment on the environment and human health</li> <li>• Impact on the environment of handling the contaminated sediment (dredging, transport, storage, pretreatment and treatment)</li> <li>• Risks to workers and community of handling the contaminated sediment (dredging, transport, storage, pretreatment and treatment)</li> <li>• Level of impact on the environment and human health (with or without remediation): short or long term, local or regional, reversible or irreversible</li> <li>• Environmental efficiency (short, medium and long term)</li> <li>• Community acceptance</li> <li>• Compliance with regulations and government policies</li> <li>• Environmental control and monitoring programs</li> <li>• Reduction of mobility, toxicity and volume of contaminated sediment</li> <li>• Sensitive resources and uses on or near the site</li> </ul>

## **SEDIMENT PRETREATMENT TECHNOLOGIES**

### **3.1 Objectives**

Sediment pretreatment technologies are by definition methods of preparing dredged material for transportation, additional treatment or disposal. They are not effective for removing or treating sediment contaminants.

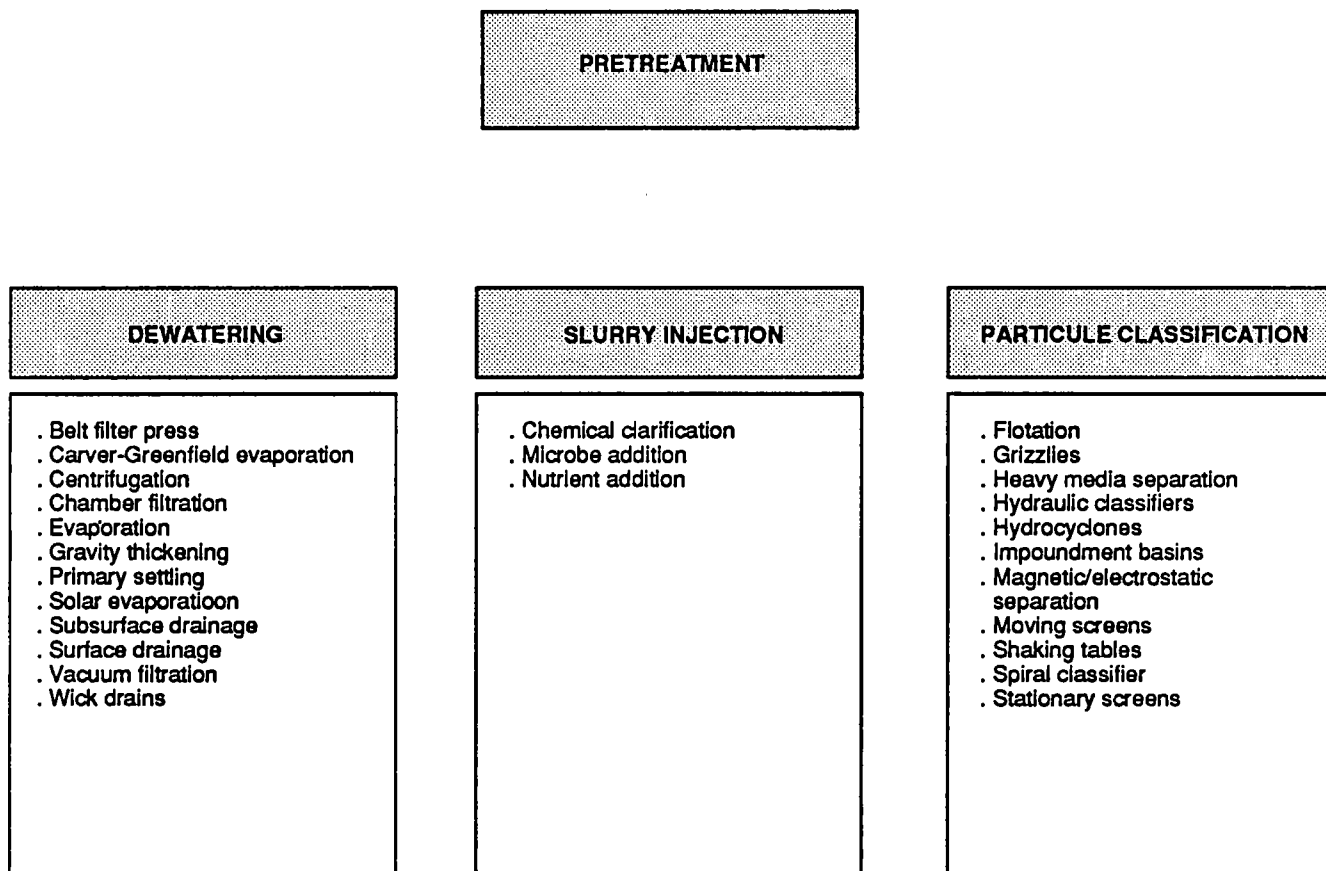
Pretreatment is generally considered to meet one or more of the following objectives (Averett et al., 1990; USEPA, 1991b):

- a) To condition dredged material for further treatment and/or disposal
- b) To enhance or accelerate settling of solids
- c) To reduce water content and hence facilitate transportation, treatment and/or disposal
- d) To separate coarser, potentially uncontaminated, solids from fines, which are generally more contaminated
- e) To reduce overall cost of remediation

### **3.2 Pretreatment processes**

As Figure 3.1 shows, pretreatment technologies fall into three categories: dewatering, slurry injection and particle classification.

**3.2.1 Dewatering.** In fine sediment, water content of mechanically dredged material is generally 50 percent and that of hydraulically dredged material can be 90 to 100 percent or more. Some treatment technologies are appreciably less effective when water content of the material to be treated is high.



Source : Averett *et al.* 1990.

**Figure 3.1** Pretreatment processes considered for cleanup of Great Lakes sediment

Accordingly, the objectives of dewatering are basically to reduce sediment water content for one or more of the following reasons:

- To facilitate sediment handling
- To cut energy requirements when incineration is required
- To reduce costs of many treatment processes, thermal processes in particular
- To facilitate upland disposal
- To reduce transportation costs by reducing sediment volume and weight
- To reduce volume of material to be treated or disposed of (USEPA, 1991b)

Dewatering can be accomplished by air drying processes (that is, passive systems) or by mechanical or thermal processes. With air drying processes, the material is simply dried in settling ponds by gravity and natural evaporation or by induced drainage. Mechanical processes mechanically force water out of the sediment using filtration (belt filter presses, chamber filtration, vacuum filtration), centrifugation (solid bowl and basket centrifuges) or gravity thickening (continuous flow tank). Thermal processes work by evaporation (the Carver-Greenfield evaporation process or thin-film, tubular, kettle or solar evaporation).

Mechanical dewatering systems have been used for many years to condition municipal and industrial sludge. Most mechanical dewatering processes reduce water content to about 50 percent. Process performance can however be affected by clay and organics content of the sediment and is best with a homogenous waste stream (Averett et al., 1990; USEPA, 1991b).

**3.2.2 Slurry injection.** When hydraulic dredges are used, slurry injection can take advantage of the mixing process available in the pipeline that transports the dredged material. Options include injection of chemicals (polymers or flocculants) that condition the sediment for further treatment and/or accelerate settling of suspended solids at the disposal site or injection

of microbes or nutrients that can enhance biodegradation of organics at the disposal site. Another option is to inject chemicals right into the settling ponds--between two ponds, for example.

**3.2.3 Particle classification.** Particle classification separates slurries by grain size and removes oversize material incompatible with subsequent treatment processes. Classification by grain size is important in the management of contaminated sediment since contaminants primarily accumulate in fine organic matter in the sediment. The fine material can be treated while the relatively uncontaminated, coarser material can be disposed of with minimal or no additional treatment (USEPA, 1991b).

Separation technology for a given site depends on the following:

- Volume of contaminated sediment
- Sediment composition (grading, percent clay and percent solids)
- Nature of contamination
- Type of dredge used
- Site environment, including land area available

Particle classification options include screening processes that depend on particle size, processes that depend on particle size and density or density alone and processes that depend on conductive or magnetic properties of the particles.

As Figure 3.1 shows, particle classification or separation technologies include settling ponds, hydraulic and spiral classifiers, flotation, moving or stationary screens, grizzlies, hydrocyclones, magnetic and electrostatic separation, heavy media separation and shaking tables.

### 3.3 Applications and limitations of pretreatment processes

Tables 3.1 and 3.2 summarize applications, limitations, secondary impacts and costs of dewatering and particle classification processes respectively.

Of the *processes that dewater by evaporation*, as Table 3.1 indicates, air drying in settling ponds--with or without induced drainage or consolidation, subsurface drains, pumping or trenching--can be used for a variety of sediment. Such ponds require larger land areas, more labour and longer treatment time than mechanical processes, and there are risks of contaminant releases into air, soil, surface water or groundwater (and uptake by plants and animals) via leaching, seepage, drainage or volatilization.

Performance is better with mechanical dewatering processes (filter press, vacuum filtration and chamber filtration) and risks of contaminant releases into the environment can be better controlled. Mechanical processes generally require a lot of maintenance and most are costly and energy-intensive.

As Table 3.2 indicates, *of the factors listed in section 3.2.3 above*, sediment grading, percent solids and type of contaminants to be treated are determinant when selecting *particle classification processes* for a given site. In addition, some equipment requires considerable maintenance because of moving parts. A variety of equipment is available in different sizes offering a number of application options for sediment treatment.

**Table 3.1 Applications and limitations of sediment dewatering processes**

PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	RELATIVE COST
Settling pond	<p>Dewatering sediment of any grain size to a solids content of up to 60 percent with up to 99 percent solids removal.</p> <p>Generally used for large-scale dredging operations where land space is available.</p>	<p>Requires large land areas.</p> <p>Requires long setup time.</p> <p>Labour costs for removing or dewatering sediment are high.</p> <p>Systems using gravity drainage are prone to clogging.</p> <p>Systems using vacuums require considerable maintenance and supervision.</p> <p>Systems based on electroosmosis are costly.</p>	<p>Potential for groundwater contamination.</p> <p>Potential for localized odour and air pollution problems.</p>	Low to high
Belt filter press	<p>Dewatering fine-grained sediment. Can produce filter cake of up to 45%-70% solids.* Solids capture of up to 85% to 95%.</p> <p>Filtration methods best suited for mobile treatment systems.</p>	<p>Performance is very sensitive to physical and chemical characteristics of incoming feed.</p> <p>Belts deteriorate rapidly in presence of abrasive material.</p>	Generates substantial amount of wastewater that must be treated.	Medium
Chamber filtration	<p>Dewatering fine-grained sediment. Can produce filter cake of up to 50% to 80% solids.* Solids capture of up to 98%.</p>	<p>Costly and energy intensive.</p> <p>Replacement of filter medium is time consuming.</p>	Generates wash water that must subsequently be treated.	High
Vacuum filtration	<p>Dewatering fine-grained sediment. Can produce a filter cake of up to 35% to 40% solids. Solids capture of up to 88% to 95%.</p>	<p>Least effective of the filtration methods for dewatering.</p> <p>Energy intensive.</p>	Generates wash water that must be treated.	High
Solid bowl Centrifuge	<p>Thickening or dewatering sediment. Can produce a dewatered sludge with 15% to 35% solids. Solids capture typically ranges from 90% to 98%.</p> <p>Suitable for areas with space limitations.</p>	<p>Not as effective in dewatering as filtration or lagoons.</p> <p>May result in buildup of fines in centrifuge effluent.</p> <p>Scroll is subject to abrasion.</p>	No significant secondary impacts.	Medium to high

**Table 3.1 Applications and limitations of sediment dewatering processes (continued)**

PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	RELATIVE COST
Basket centrifuge	Thickening or dewatering sediment. Can produce a dewatered sludge with 15% to 35% solids. Solids capture ranges from 90% to 98%.  Suitable for areas with space limitations.	Not as effective in dewatering as solid bowl centrifuge, filtration or dewatering lagoons.  May result in buildup of fines in centrifuge effluent.  Units cannot be operated continuously without complex controls.	No significant secondary impacts.	Medium to high
Gravity thickening	Thickening of sediment slurries to produce a concentrate that can then be dewatered by filtration or dewatering lagoons. Can produce a thickened product with 15% to 20% solids.	Least effective method for dewatering sediment slurries.  Requires substantial amount of land.	Potential for localized odour and air pollution problems.	Low to medium
Evaporation*	Dewatering using heat to vaporize liquids or volatile components from viscous liquid solutions, slurries, suspended solids mixtures or sludge contaminated with oil, grease, paint solids or resins.	Difficult to use with large amounts of sediment.	Potential for localized odour and air pollution problems.	Medium to high

\* Percent solids may represent values achievable under optimal conditions not necessarily results that can normally be expected. Dredged sediment is often fine-grained and difficult to dewater to maximum values indicated.

Adapted from USEPA, 1991b and Averett et al., 1990



**Table 3.2 Applications and limitations of particle classification processes**

PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	RELATIVE COST
Settling pond	<p>Removing particles down to a grain size of 20 to 30 microns without flocculants and down to 10 microns with flocculants.</p> <p>Temporary storage of dredged material.</p> <p>Classifying sediment by grain size.</p>	<p>Requires large land area.</p> <p>Requires long set-up time.</p>	Potential for groundwater contamination.	High
Hydraulic classifier	Removing particles from slurries in size range of 74 to 149 microns (fine to coarse sand).	<p>Hydraulic throughput limited to about 250 to 300 tons per hour regardless of unit size.</p> <p>Cannot produce a sharp size distinction.</p> <p>Requires large land area in cases of large-scale dredging or high solids concentrations.</p>	No significant impacts.	Medium
Hydrocyclones	Separating and classifying solids in size range of 2000 microns or more down to 10 microns or less.	<p>Not recommended for dredged slurries with solids concentration greater than 10 to 20 percent.</p> <p>Not effective in separating highly viscous slurries, slurries with solids concentration greater than 30%, or particles with specific gravity of approximately 2.5 to 3.2.</p> <p>Not very effective in separating slurries with high clay content unless dispersants are injected or the slurry is diluted.</p>	No significant impacts.	Medium

Table 3.2 Applications and limitations of particle classification processes (continued)

PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	RELATIVE COST
Spiral classifiers	<p>Washing, dewatering and separating sand and gravel up to 3/8 in. in diameter.</p> <p>May be used in conjunction with hydraulic classifiers to separate fine materials such as clay and silt.</p>		No significant impacts.	Low
Flotation	Used in the mining industry to separate particles in the size range of 0.1 to 0.01 mm.	<p>Particle sizes must be reduced so fine particles and contaminants will be able to be floated by the air bubbles.</p> <p>Conditioners are sometimes necessary.</p>	No significant impacts.	Medium
Stationary and moving screens and grizzlies	<p>Separating particles of a range of sizes.</p> <p>Moving screens are very effective.</p>	<p>Oversize materials separated by stationary screens may contain a lot of fines.</p> <p>Moving screens are sensitive to abrasive particles in the feed material.</p> <p>Moving screens can be obstructed by material with low water content.</p>	No significant impacts.	Medium
Magnetic and electrostatic separation	Used in the ore and mineral industry to remove mineral impurities.	<p>Not very effective when contaminants are dispersed throughout the soil.</p> <p>Application to sediment limited because liquid stream must have a grain size of 100 <math>\mu</math> or less.</p>	No significant impacts.	Medium

**Table 3.2 Applications and limitations of particle classification processes (continued)**

PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	RELATIVE COST
Heavy media separation	<p>Used in the mining industry to separate oils from tailings and to separate solid materials with different absolute densities.</p> <p>Solids are placed in a fluid (heavy media) of specific gravity that will cause lighter solids to float and heavier ones to sink.</p>	<p>Possible dissolving of solids.</p> <p>Presence of solids with similar densities.</p>	No significant impacts.	Medium

Adapted from USEPA, 1991b and Averett et al., 1990

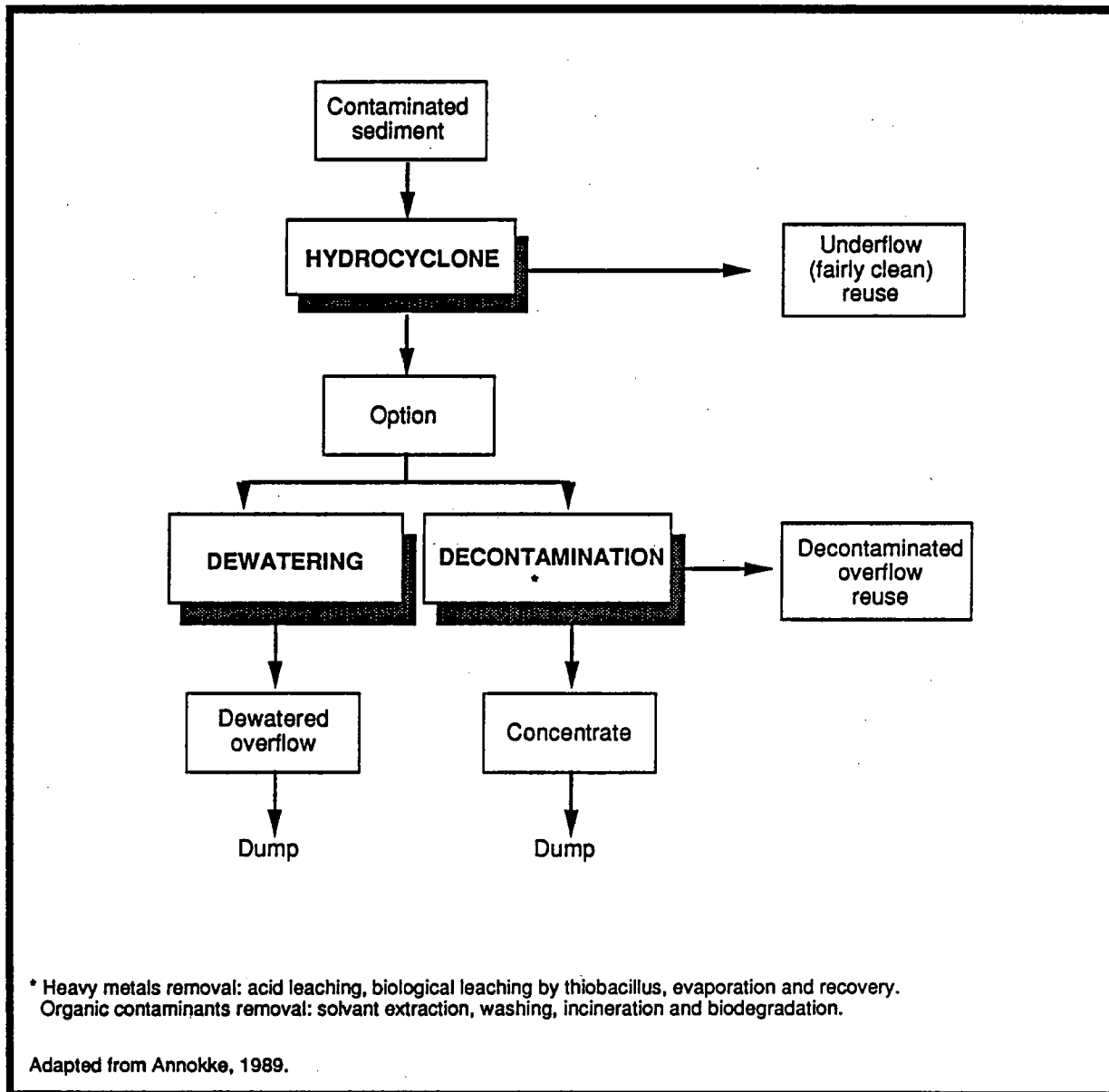
*Slurry injection technologies* are applicable only to hydraulic dredging projects because of the mixing advantage with this type of dredging. Chemical injections to promote settling generally require fairly large settling ponds to ensure adequate mixing. Microbe injections to enhance biodegradation have not yet been demonstrated for large quantities of dredged material (USEPA, 1991b).

### 3.4 Examples of demonstrated sediment pretreatment processes

3.4.1 **Dutch processes.** Contaminated sediment treatment experiments conducted for close to ten years by the *Netherlands Organization for Applied Scientific Research, TNO*, have demonstrated that hydrocyclones can separate sediment into two fractions, one relatively clean and another in which contaminants are concentrated (Van Veen, 1988).

The research has also demonstrated that although hydrocyclone processes can be used for sediment contaminated by heavy metals as well as by organics (oils, PAHs and so forth), contaminants can sometimes be found in the coarse as well as the fine fraction depending on the nature of the soil or sediment treated (Annokke, 1989).

Figure 3.2 shows a contaminated sediment treatment scenario being developed by the Dutch government in which pretreatment technologies are essential components.



**Figure 3.2 Dutch scenario for treating contaminated sediment**

This scenario offers two major routes: 1) hydrocyclone separation and dewatering; 2) hydrocyclone separation and decontamination using treatment technologies--biological and thermal processes, physical and chemical extraction, and washing. These treatment technologies are described in Chapter 4.

As Figure 3.2 shows, both routes start with hydrocyclone separation, which divides the sediment into two fractions: a fraction with a low contaminant content, the underflow, composed mainly of sand; and a second fraction in which contaminants are concentrated, the overflow or slime fraction, generally composed of fine-grain and organic material. The second step in these routes is dewatering (volume reduction) or decontamination (reduction of contaminant content of the overflow) (Van Veen, 1988; Van Dillen, 1989).

Research indicates that particle classification processes are not always successful with contaminated sediment dredging and cleanup projects because they rely heavily on silt/sand ratio. When this ratio is high, hydrocyclone separation is not appropriate and all the sediment must be dewatered or decontaminated (Van Veen, 1988).

When hydrocyclone separation is used in conjunction with dewatering (belt filter presses, centrifuges), a 70 percent to 95 percent volume reduction can be achieved (Van Veen, 1988, Annokke, 1989). Most real-scale applications show a 70 percent volume reduction can be achieved. Capital and operating costs for a belt filtration system are about C\$7 per cubic metre for a facility with a throughput of 100 cubic metres per hour and about C\$5 per cubic metre for a facility with a throughput of 1000 cubic metres per hour. These figures do not include costs of civil engineering, floating platforms, buildings, automatic controls and electric installations (Van Veen, 1988).

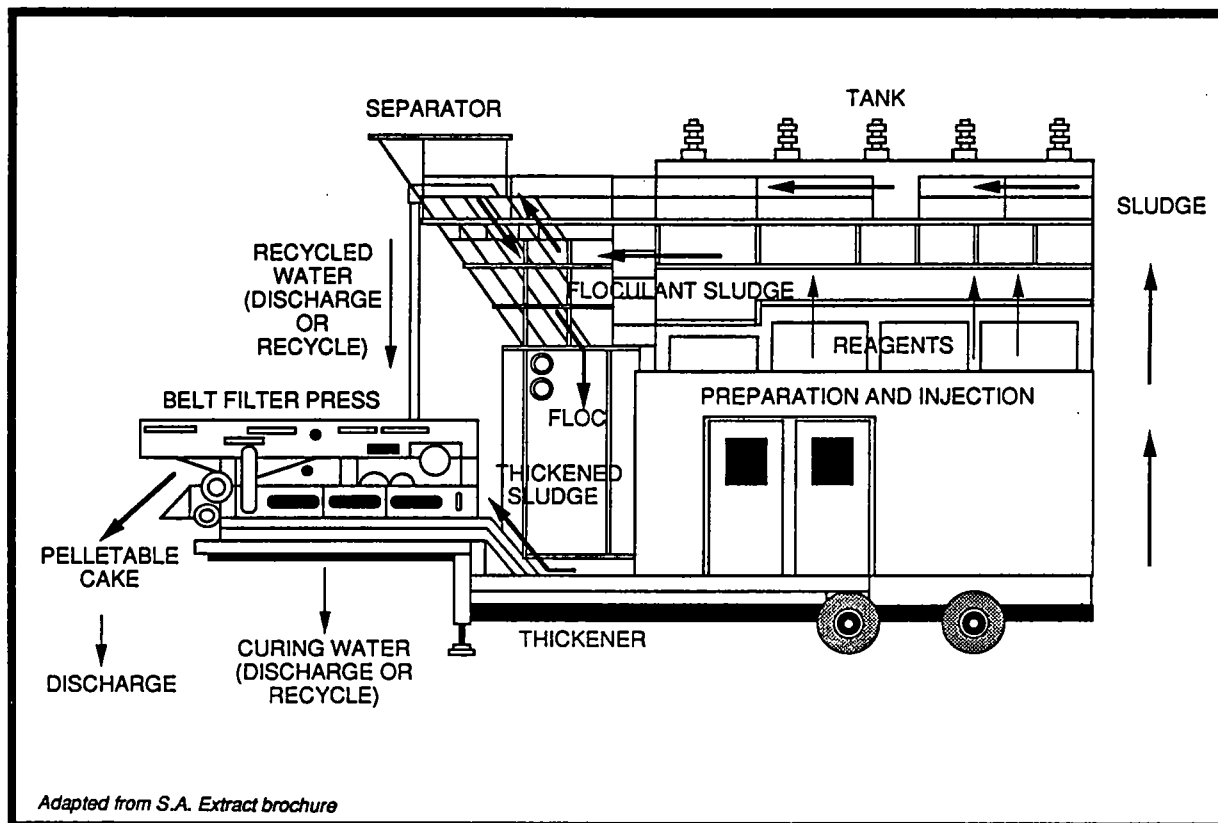
However, maximum capacity of mechanical dewatering equipment on the market is about 50 cubic metres per hour. Such equipment may not prove feasible for standard dredging projects, which produce between 100 to 15 000 cubic metres of dredged material every hour. And multiple dewatering units may not be feasible either given cost and space requirements of the units (Van Veen, 1988). Hydrocyclones, however, are not costly, and extra hydrocyclones can always be added to match dredge capacity.

**3.4.2 French process.** Since 1986, the french firm S.A. Extract has been experimenting with and perfecting a complete continuous in situ extraction and treatment service for sediment and dredged industrial sludge. Hundreds of thousands of cubic metres of sediment have been treated in France, the Netherlands and England.

The semitrailer-mounted treatment/dewatering unit and its skid for screening/hydrocyclone separation operate as follows:

- a) Dredged material is screened to remove all large material (gravel, branches, leaves).
- b) The dredged material is then run through a series of hydrocyclones for separation of sand down to 60 microns (finest possible cut).
- c) Sand and detritus removed, the sludge is homogenized in a tank that holds 30 cubic metres.
- d) The sludge is destabilized by in-line injection of flocculants before it is sent into a thickener where it is stirred slowly to promote liquid/solid separation.
- e) Water discharged from the thickener is run into a lamellar clarifier for final treatment.
- f) The thickened sludge is pumped from the bottom of the thickener and sent to a belt filter press; it leaves the press as a dewatered, pelletable cake 30 percent to 50 percent solids.

Figure 3.3 shows a cross section of the S.A. Extract treatment unit.



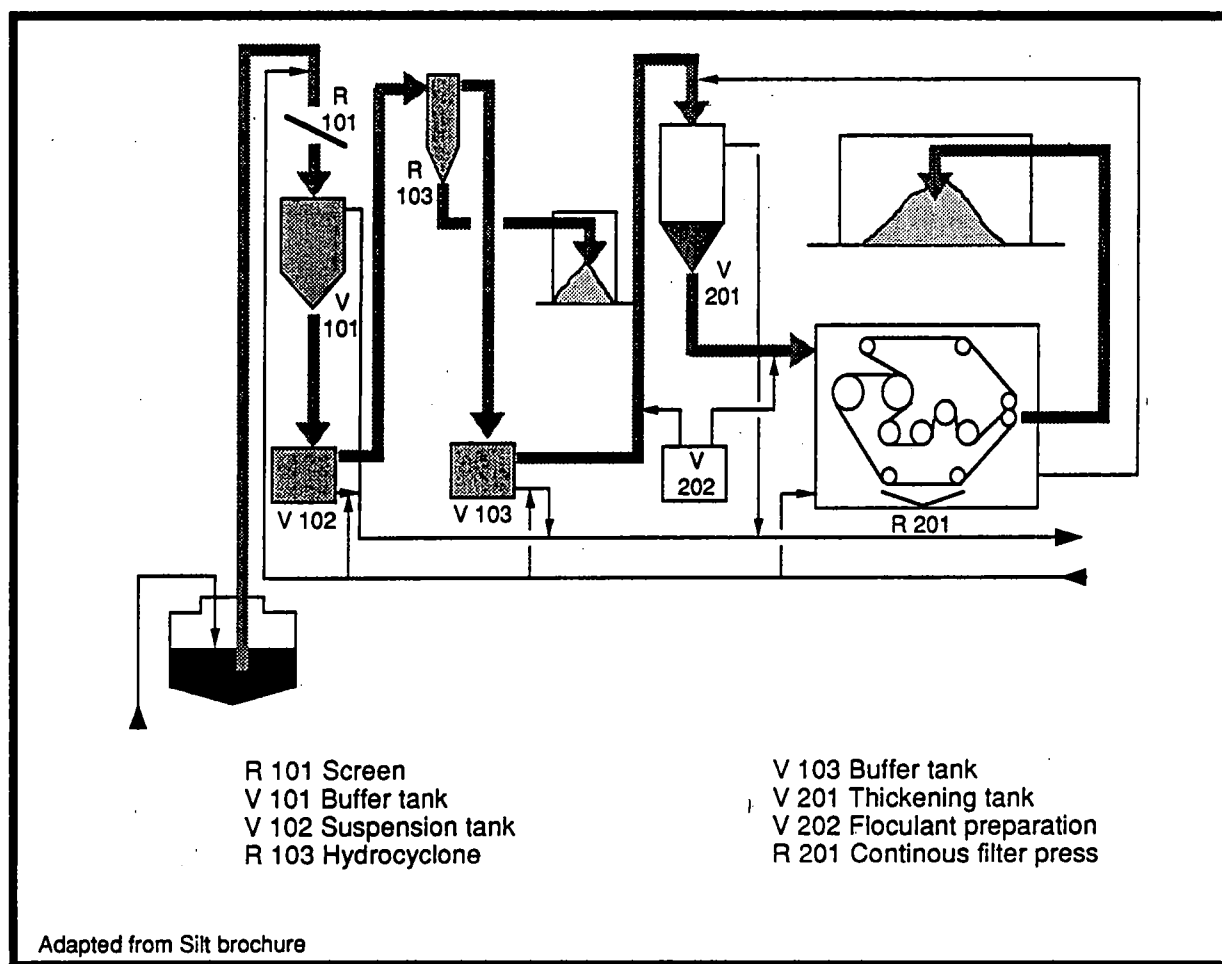
**Figure 3.3** Cross section of S.A. Extract mobile sediment pretreatment unit

S.A. Extract has two units available; a single unit is used when less than 30 000 cubic metres of material are to be treated, otherwise both units are used. Technicians operating the treatment unit or units and the dredging equipment are in constant radio communication throughout the operations.

**3.4.3 Belgian process.** The Belgian firm Silt N.V. also has two moveable facilities (one for small flows and one for large flows) equipped with hydrocyclones and filter presses in series for treatment of small quantities of dredged sediment. The units are designed to reduce sludge volume for storage and to separate and recover the sand fraction of sediment. Sand recovered with these units has been demonstrated to meet standards and can be returned to the environment; the sludge, where contaminants are concentrated, must be treated or contained.

Figure 3.4 shows a process scheme for the Silt N.V. pretreatment facility.

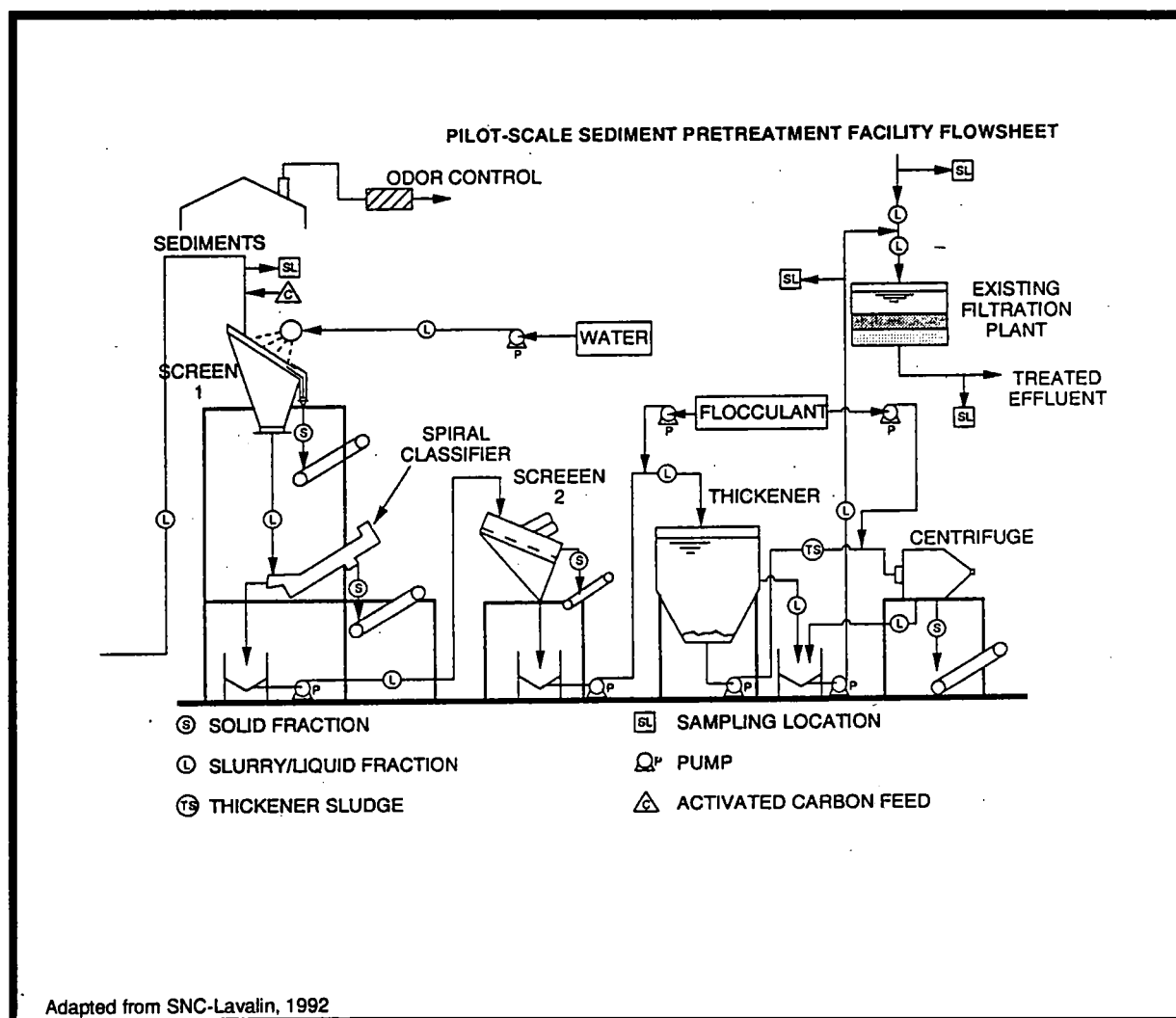




**Figure 3.4 Silt N.V. sediment pretreatment facility process scheme**

**3.4.4 Canadian process.** As part of a demonstration project conducted by the Wastewater Treatment Centre in Burlington, Ontario, and funded by the Great Lakes Cleanup Fund, the Company Acres-Derrick developed a technology for dewatering contaminated sediment. The process involves liquid/solid separation, water treatment and removal of suspended or dissolved contaminants, sediment drying by fine and coarse screening, and separation by continuous cycloning and centrifugation.

Figure 3.5 shows a process scheme of this pretreatment technology.



**Figure 3.5 Acres-Derrick sediment pretreatment facility process scheme**

### 3.5 Processes recommended to clean up the Great Lakes

Under the *Clean Water Act* as amended in 1987, the United States government authorized the *U.S. Environmental Protection Agency (USEPA)* and the *Great Lakes National Program Office (GLNPO)* to coordinate and carry out a program of research and demonstration projects for cleanup of the Great Lakes. Five priority areas around the Great Lakes were selected

for demonstration projects: Saginaw Bay, Michigan; Sheboygan Harbour, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River, New York.

The GLNPO asked the U.S. Army Corps of Engineers (USACE) for help in managing the contaminated sediment treatment technologies demonstration projects, because of the USACE's expertise in managing contaminated as well as uncontaminated sediment. The first step was a review of literature on contaminated sediment treatment technologies--technologies for dredging, transporting, storing, containing, pretreating and treating contaminated sediment as well as technologies for pretreating and treating effluents. The purpose of the review was to identify the most promising technologies for demonstration projects in the five priority areas (Averett et al., 1990).

For each technology, the five following factors were evaluated:

- State of development of the technology.
- Availability of the technology.
- Effectiveness in meeting remediation goals and environment protection and public health objectives during work.
- Application of the technology to clean up of contaminated sediment.
- Treatment costs.

Each process option within each technology type was evaluated for expected performance with contaminated sediment. The goal was to identify the most promising technologies for large-scale demonstration projects.

Pretreatment technologies considered and recommended based on the evaluation and selection criteria adopted are described in the following sections.

**3.5.1 Process evaluation and selection criteria.** Based on their own experience in managing contaminated sediment and that of the USEPA in cleaning up contaminated sediment and soil for the Superfund program, the USACE adopted the criteria summarized in Table 3.3 to evaluate pretreatment and treatment technologies.

In addition to general process information (state of development, sediment application experience and availability of equipment in the United States), the USACE and USEPA review gives each process a performance rating of 1 to 4 for each of the following three factors: effectiveness in removing contaminants and meeting remediation goals; demonstrated application for contaminated sediment; and anticipated unit cost of treatment.

Table 3.4 shows technology selection criteria based on the performance ratings obtained using the evaluation criteria shown in Table 3.3. Processes or technologies with the highest composite score with this rating system were recommended as candidates for demonstration projects. The selection process provides for exceptions to the rule, however (see Table 3.4), because of type of contamination, special site conditions or specific characteristics of a process or technology (it is the only technology that can do the job, for example).

Table 3.5 shows state of development, North American availability and performance ratings of twenty-six processes considered for dewatering, particle classification or direct slurry injection--the three types of technologies outlined in section 3.2 above.

As Table 3.5 shows, most of the dewatering processes have already been used for industry, mining and industrial waste treatment. Natural drying processes apart, most of the mechanical dewatering processes (filters, centrifugation, thickening) have not yet been used on a regular basis for pretreatment of contaminated sediment.

Of the particle classification processes, only hydraulic classifiers, hydrocyclones and settling ponds have been used so far for dredged material. Of the slurry injection options, only chemical clarification has been used to date.

**Table 3.3 Treatment technology evaluation criteria adopted by the USEPA and the USACE for remediation projects in Great Lakes priority areas**

FACTOR	TECHNOLOGY PERFORMANCE RATING			
	4	3	2	1
<b>Effectiveness</b> • Potential for meeting remediation goals  • Reliability with respect to contaminants and site conditions  <b>Implementability</b> • Commercially available  • Demonstrated applicability to contaminated soil or sediment  • Scale of demonstration  <b>Cost</b> • US\$ per cubic yard	>99%  Highly reliable  Yes  Yes  Full scale  <20	70-99%  Moderately reliable  Yes  Yes  Pilot scale  20-100	40-70%  Minimal reliability  No, but the technology is ready for pilot-scale demonstration  Yes  Bench scale  100-200	<40%  Unreliable  No  To be demonstrated  Conceptual or emerging  >200
ADDITIONAL INFORMATION				
• Technology  • Availability in the United States	Name of option or technology identified in the literature review.  Indication whether the technology is available in the United States, if it is proprietary or if it is foreign.			

Adapted from Averett et al., 1990

**Table 3.4 USEPA and USACE criteria for recommending technologies for sediment remediation projects in Great Lakes priority areas**

LEVEL	CRITERIA
1	<p>The process option must have the first, second or third highest composite score within its technology type.</p> <p>Where the second or third highest scores are three or more points lower than the top score, only the first or second highest rated process option will be recommended.</p> <p>Exceptions to this rule may occur when treatment objectives require a process of greater removal or destruction efficiency or a more economical solution.</p>
2	<p>Process options that receive a 1 rating for any one of the three evaluation factors (efficiency, implementability, cost) are not recommended.</p> <p>One exception to this rule provides for a second tier of processes for consideration: a process with a high composite score in its technology type may be recommended for the second tier if costs are estimated at more than US\$200 but less than US\$500 per cubic yard.</p>
3	<p>Process options unavailable in the United States are not recommended for consideration for the moment because of logistical and administrative problems in testing foreign technologies.</p>

Adapted from Averett et al., 1990

**Table 3.5 Anticipated performance of pretreatment technologies recommended for Great Lakes remediation**

PROCESS	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABLE	PERFORMANCE RATINGS**		
				Effective-ness	Implement-ability	Cost
Dewatering						
Belt filter press*	Demonstrated	Yes	Yes	4	3	3
Carver-Greenfield evaporation	Demonstrated	No	Yes	3	2	3
Centrifugation	Demonstrated	No	Yes	4	2	3
Chamber filtration	Demonstrated	No	Yes	4	3	3
Evaporation	Demonstrated	No	Yes	3	1	2
Gravity thickening	Demonstrated	No	Yes	3	3	3
Primary settling	Demonstrated	Yes	Yes	3	4	4
Solar evaporation	Demonstrated	Yes	Yes	1	3	4
Subsurface drainage	Demonstrated	Yes	Yes	3	3	3
Surface drainage	Demonstrated	Yes	Yes	2	4	4
Vacuum filtration	Demonstrated	Yes	Yes	3	3	3
Wick drains	Demonstrated	Yes	Yes	3	4	3
Particle classification						
Flotation	Demonstrated	Bench	Yes	3	2	3
Grizzlies	Demonstrated	No	Yes	2	3	4
Heavy media separation	Demonstrated	No	Yes	2	1	3
Hydraulic classifiers	Demonstrated	Yes	Yes	3	2	3
Hydrocyclones	Demonstrated	Yes	Yes	3	3	4
Settling basins	Demonstrated	Yes	Yes	2	3	4
Magnetic/electrostatic	Demonstrated	No	Yes	3	2	3
Moving screens	Demonstrated	No	Yes	3	2	3
Shaking table	Demonstrated	No	Yes	3	2	3
Spiral classifiers	Demonstrated	No	Yes	3	2	3
Stationary screens	Demonstrated	No	Yes	3	2	3
Slurry injection						
Chemical clarification	Demonstrated	Yes	Yes	2	3	4
Microbe addition	Conceptual	No	Emerging	3	3	3
Nutrient addition	Conceptual	No	Emerging	1	3	4

**Notes**

\* Technologies shown in bold have been recommended by the USACE and USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

Adapted from Averett et al., 1990

**3.5.2 Processes recommended.** Based on the selection criteria shown in Table 3.4, most of the pretreatment technologies or processes considered from the start for sediment dewatering or particle classification were recommended as candidates for Great Lakes sediment cleanup projects. In fact, as Figure 3.6 shows, most of the technologies have been demonstrated and costs are relatively acceptable.

Dewatering by evaporation and particle classification by heavy media separation were not recommended for demonstration projects because they are still emerging technologies. Dewatering by solar evaporation and nutrient addition were also eliminated because of their minimal effectiveness for meeting the remediation goals set.



COST (\$US/cy)	IMPLEMENTABILITY RATING			
	1* CONCEPTUAL OR EMERGING	2 BENCH	3 PILOT	4 COMMERCIAL
\$200 OR MORE				
\$100 TO \$200	Evaporation(3) **			
\$20 TO \$100	Heavy media separation(2)	Centrifugation(4) *** Spiral classifier(3) Hydraulic classifier(3) Carver-Greenfield evaporation(3) Flotation(3) Stationary screens(3) Moving screens(3) Magnetic and electrostatic separation(3) Shaking table(3)	Microbe addition(3) Subsurface drainage(2) Gravity thickening(3) Vacuum filtration(3) Belt filter press(4) Chamber filtration(4)	Wick Drains (CDF) (3)
\$20 OR LESS			Solar evaporation(1) Nutrient addition(1) Grizzly screen(2) Settling basin(2) Chemical clarification(2) Hydrocyclone(3)	Primary settling (CDF) (3) Surface drainage CDF (2)

Notes:      \* Performance rating (see Table 3.3)  
              \*\* Effectiveness rating (see Table 3.3)  
              \*\*\* Processes shown in bold have been selected for Great Lakes cleanup demonstration projects.

Adapted from Averett et al., 1990

**Figure 3.6 Classification of 26 pretreatment technologies considered and retained for Great Lakes sediment cleanup demonstration projects**

#### 4.1 Treatment objectives

Technologies for treating contaminated sediment--like those for treating hazardous waste and contaminated soil, sludge and water--are mainly designed to destroy, remove, immobilize, or otherwise detoxify the contaminated material, if possible at reasonable cost. Specific treatment objectives include the following:

- a) Destruction of toxic organic contaminants by conversion to nontoxic products.
- b) Removal of heavy metal or organic contaminants from dredged material, either by concentrating the contaminants in a medium of smaller volume (extraction) or by reducing volume of solids for further treatment or disposal.
- c) Reduction of mobility of contaminants in dredged material to an acceptable risk level.
- d) Compatibility with options selected for removal, transport and final disposal of the contaminated sediment.
- e) Implementability at acceptable capital and operating costs.
- f) Minimum contamination of other environmental media (air, water, soil).
- g) No addition or production of potentially toxic materials during the treatment process (Averett et al., 1990).

In the sections that follow the different types of treatment technologies mentioned in the technical literature are introduced and then technologies considered, recognized or currently under demonstration for contaminated sediment are described. For each treatment type (biological, extraction, chemical, thermal and so forth) the following information is given:

- Treatment principle.

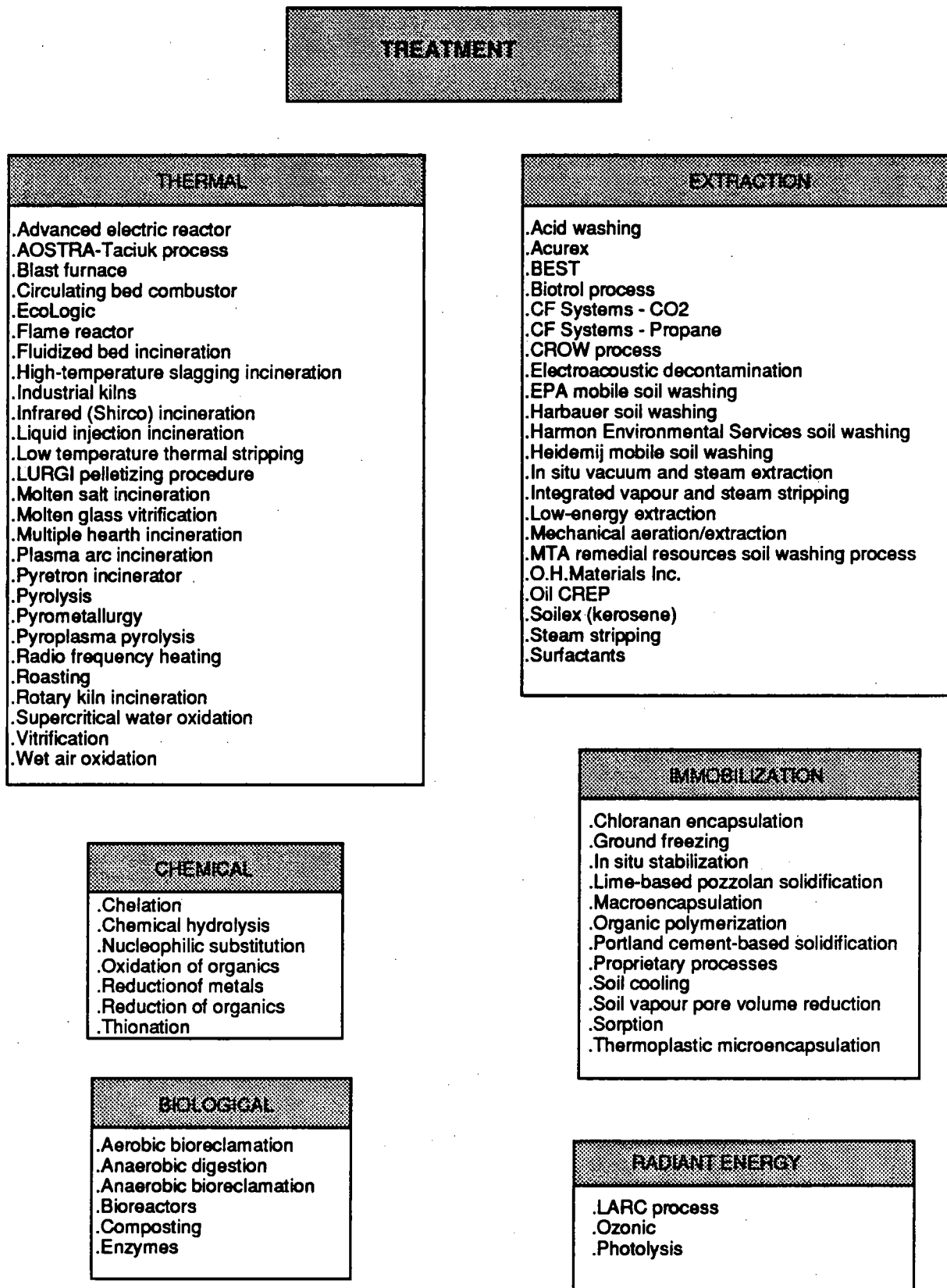
- Process scheme.
- Technologies or processes currently available from vendors or developers.
- Applications (media and contaminants).
- Strengths and limitations of each technology or process.
- Strengths and limitations for treating sediment.
- Technologies demonstrated for treatment of sediment.
- Technologies considered for treating Great Lakes sediment.
- Technologies under demonstration for treatment of Great Lakes sediment.
- Technologies recommended for contaminated sediment remediation projects.

The chapter closes with examples of the treatment train approach, that is, the combination of several technologies to address a contamination problem.

#### **4.2 Soil and sediment treatment processes**

Because of the rapid development of technologies, the literature includes a number of ways of classifying technologies depending on author or dominant treatment type. In their review of treatment technologies for remediation of Great Lakes sediment, the USACE and USEPA divide the 147 treatment techniques they consider into six broad categories (Averett et al., 1990).

**Figure 4.1 Processes considered by the U.S. government for sediment cleanup of the Great Lakes**



As Figure 4.1 shows, the treatment technologies are classified as follows:

- 1) Biological
- 2) Chemical
- 3) Extraction
- 4) Thermal
- 5) Immobilization
- 6) Radiant energy

This method of classification groups processes (for example, incineration, pyrolysis, washing and so forth) with technology developers (EcoLogic, O.H. Materials Inc. and so forth) indiscriminately without reference to the type of process promoted by the developer.

The Wastewater Technology Centre of Burlington classifies in seven main categories (excluding the pre/posttreatment category) the 206 treatment technologies entered in its *Sediment Treatment Technologies Database (SEDTEC)* in response to an open call to firms selling treatment technologies:

- 1) Alternate heat process
- 2) Biological treatment
- 3) Chemical treatment
- 4) Conventional incineration
- 5) Extraction
- 6) Fixation/stabilization
- 7) Other Treatment

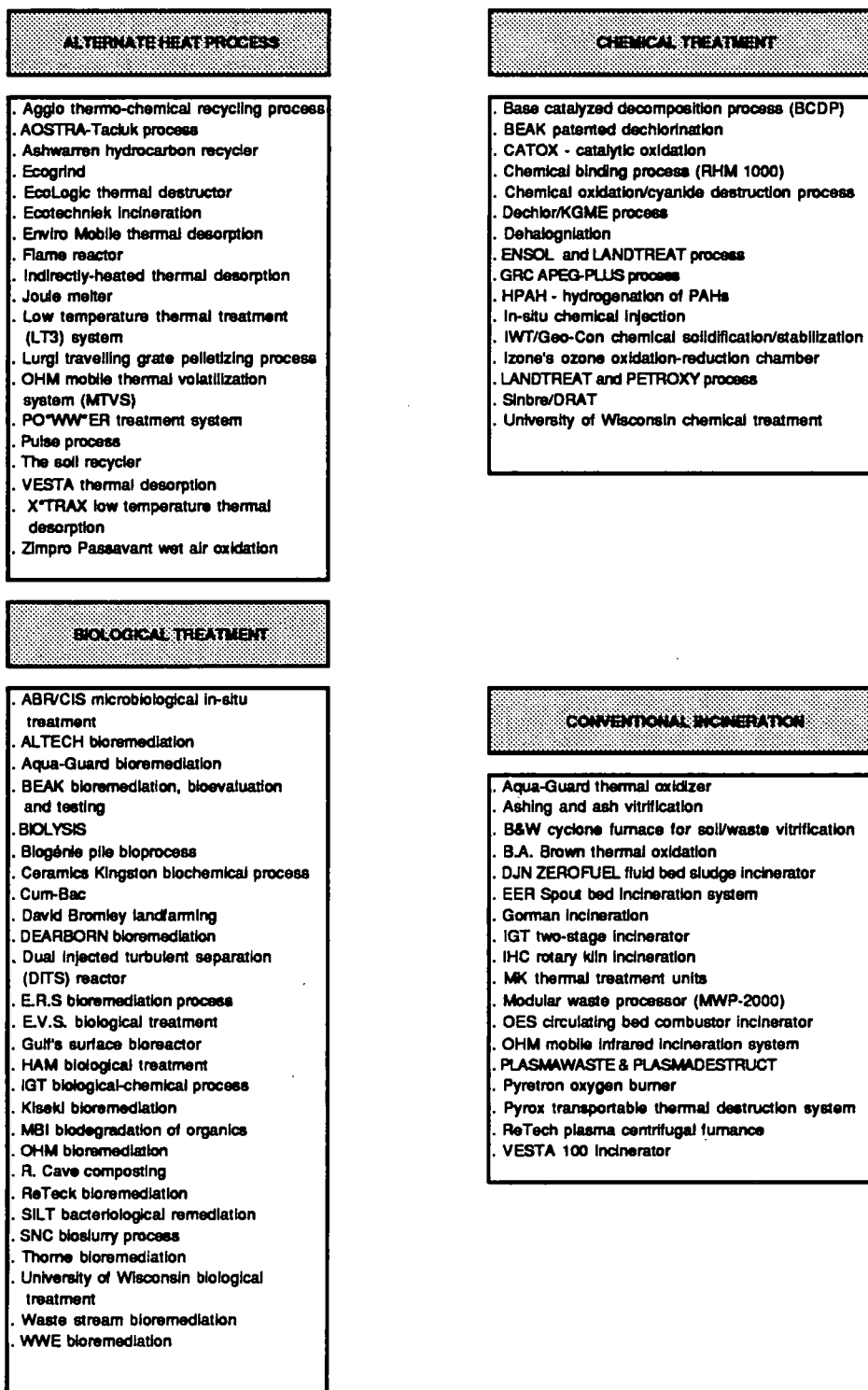


Figure 4.2 Sediment treatment options registered with SEDTEC, the Canadian data bank for the Great Lakes Action Plan

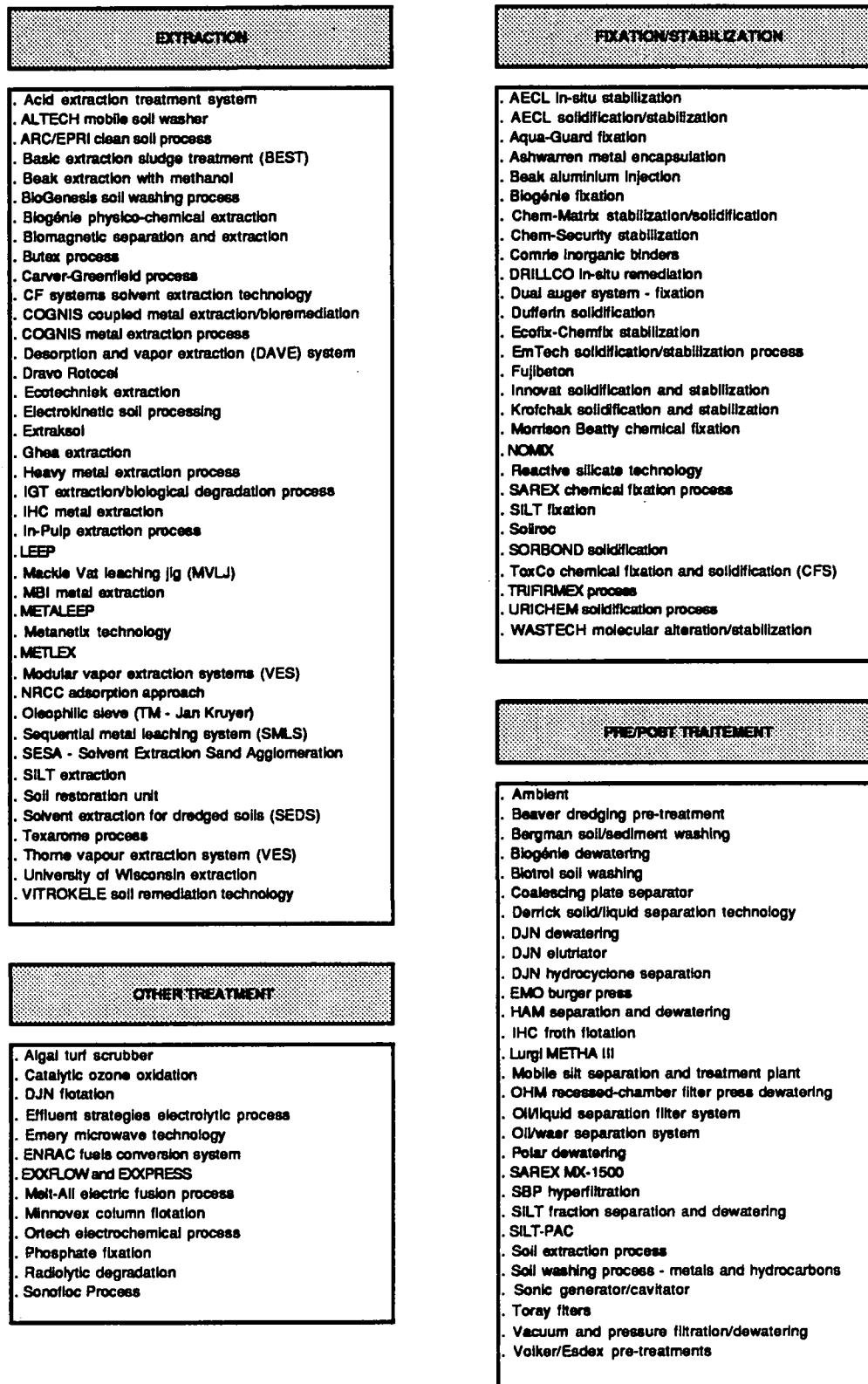


Figure 4.2 Sediment treatment options registered with SEDTEC, the Canadian data bank for the Great Lakes Action Plan (cont'd)

The data bank was developed to help in the selection of technologies for cleanup of Great Lakes sediment on the Canadian side. SEDTEC's classification system (Figure 4.2) is similar to that used by the USACE and the USEPA in that process types and technology developers are categorized indiscriminately.

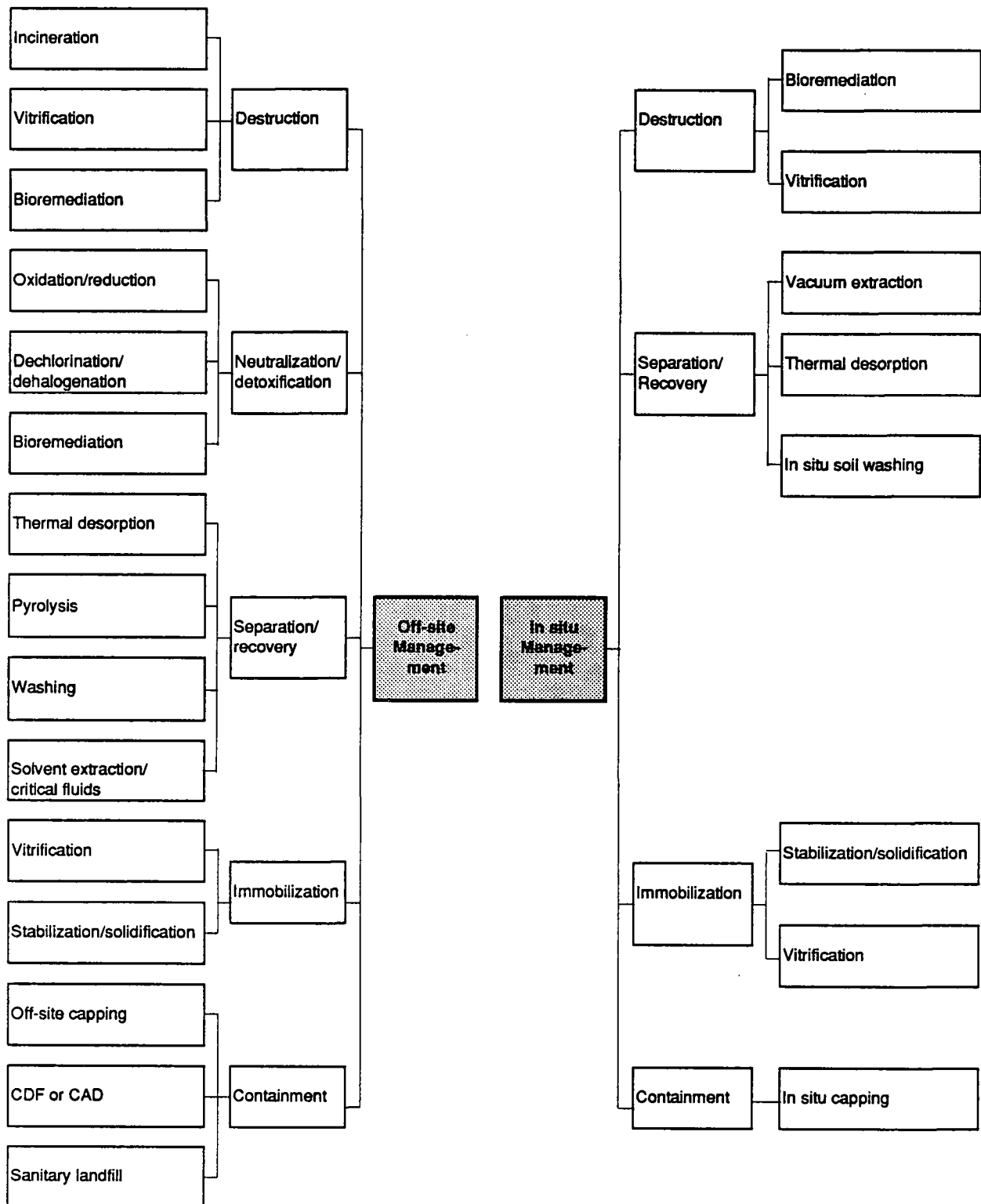
Figure 4.3 shows another classification system found in the literature. Treatment technologies are classified by place of treatment (in situ, on site or off-site) and by level of treatment of contaminants in the matrix to be treated. In other words, technologies are classified as follows: destructive or neutralizing (detoxification) technologies; separation/extraction technologies; technologies that immobilize contaminants in matrices to be treated; or containment technologies (Beck et al., 1991; USEPA, 1991c).

This classification system is of interest because it indicates immediately which technologies can be used to treat contaminants in situ (that is, without excavating the sediment) and which demand the sediment be removed and transported to a treatment site.

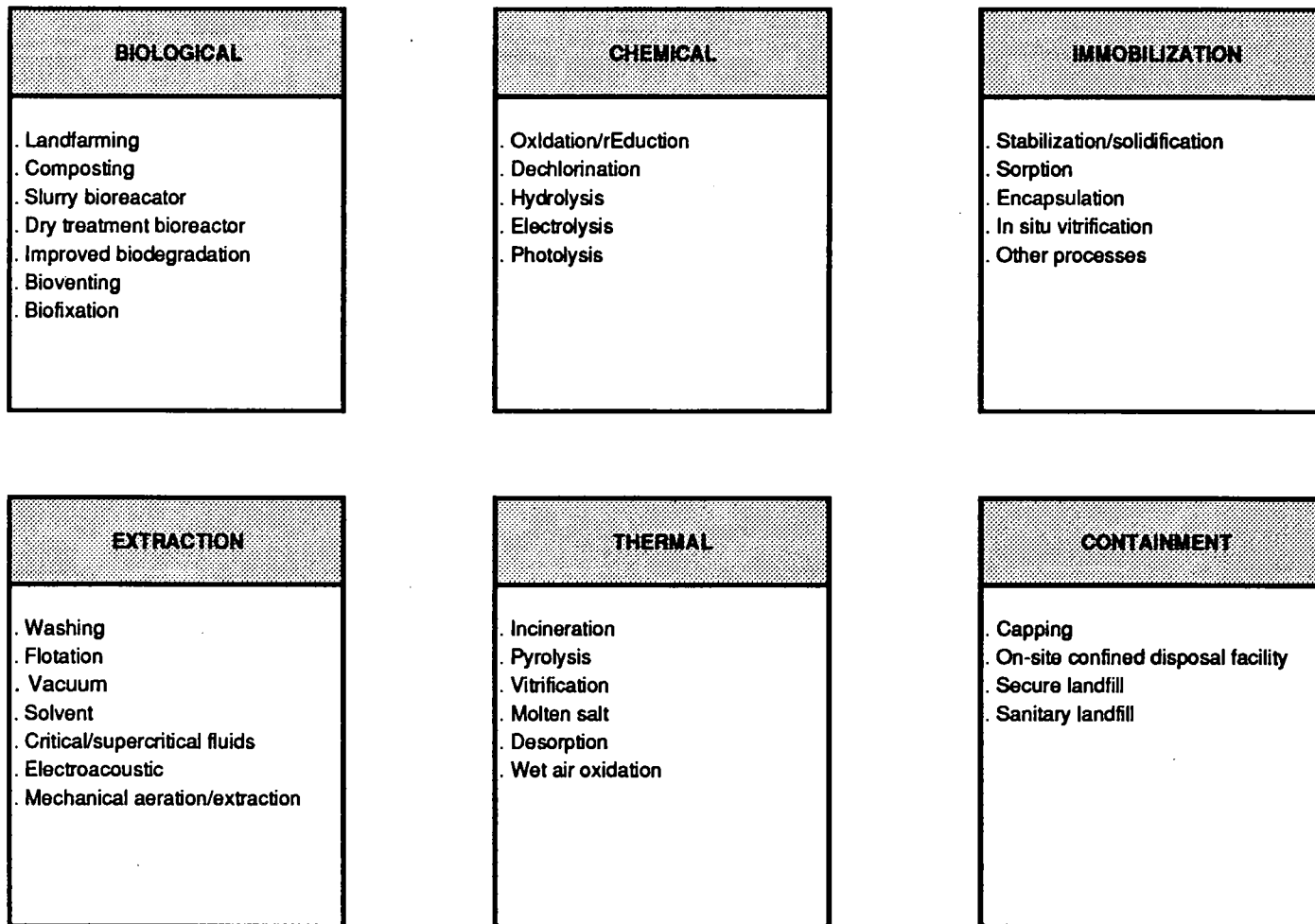
Figure 4.4 shows the classification system used for this guide. Technologies are divided into six categories:

- 1) Biological treatment
- 2) Extraction
- 3) Chemical treatment
- 4) Thermal treatment
- 5) Immobilization
- 6) Containment





**Figure 4.3** Waste treatment technologies classified by place and level of treatment



**Figure 4.4** *Treatment technologies classified by type of process*

Though they do not destroy contaminants, containment technologies are briefly described in this guide because they are often used to dispose of untreatable residues of a treatment process or to isolate contaminants when there is no effective destructive process. They are also sometimes used for technical, economic, administrative or other reasons.

In the sections that follow, processes of each category are described in detail, with special reference to technologies or developers considered and recommended for Great Lakes sediment cleanup projects on the U.S or Canadian side (listed in figures 4.1 and 4.2 respectively).

### 4.3 Biological treatment

#### 4.3.1 Principle of treatment

Biological treatment technologies use bacteria, fungi, or enzymes to break down PCBs, pesticides and other organic contaminants into innocuous or less toxic compounds such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) or inorganic salts.

Biological processes exploit the ability of an organism to use contaminants as a growth substrate. To accelerate natural biodegradation, the environment of the microorganisms is improved by adding nutrients and oxygen and adjusting the temperature. Recent discoveries in microbiology and genetics have led to development of bacterial strains capable of attacking components not considered biodegradable only a few years ago (Samson, 1992).

Contaminant biodegradation can be performed in aerobic or anaerobic environments. The main condition for an *aerobic* environment is aeration or oxygenation of the material or waste to be treated. Microorganisms that can live or thrive in an environment deprived of air--or to be more exact in the absence of elemental oxygen--are called anaerobic. Anaerobic processes are slower than aerobic ones; and though they usually allow biogas recovery, they also often release ill-smelling and sometimes dangerous volatiles such as H<sub>2</sub>S and mercaptans (Petitpas, 1990).

Certain organic contaminants (halogenated compounds, for example), various aromatics and some pesticides can be destroyed by anaerobic biodegradation. Temperature plays an important role, affecting composition of active communities as well as enzyme-catalyzed reactions. Microbial activity generally decreases with decreasing temperature and is near zero at temperatures below 4°C (Averett et al., 1990).

Accelerated, large-scale production of specialized enzymes using recombinant microorganisms offers a new avenue for bioremediation processes. This technology will probably be applicable in the long term, and it does not require that microorganisms be introduced into the environment (Samson, 1992).

The following factors determine rate of contaminant biodegradation:

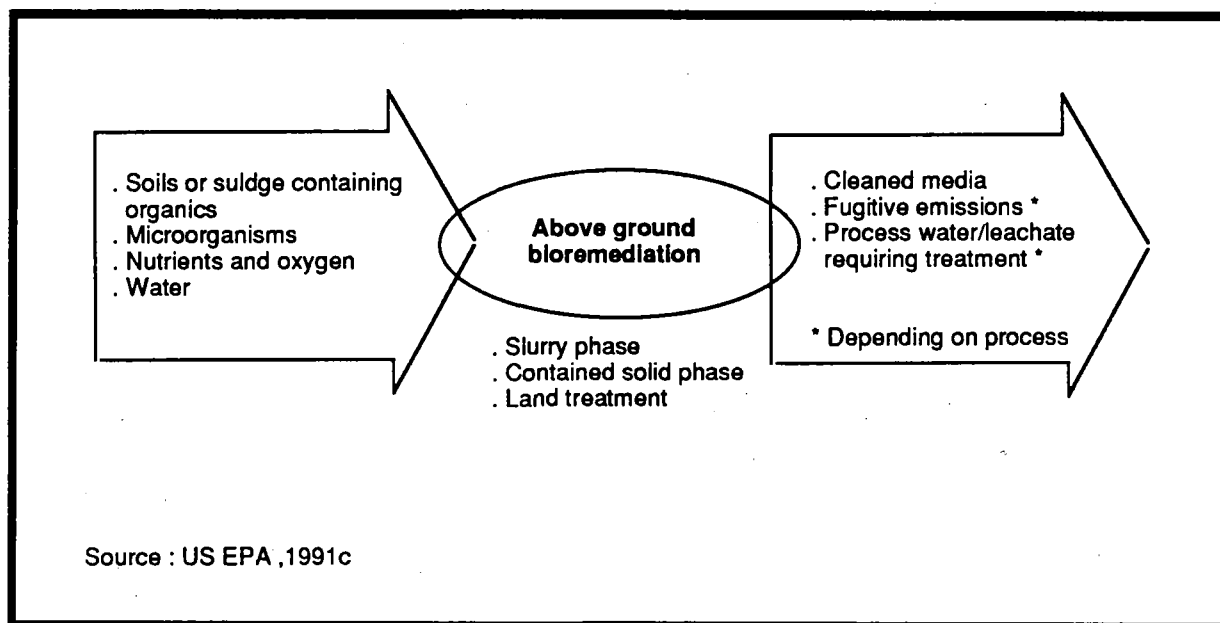
- 1) The presence of appropriate microorganisms.
- 2) Adequate concentrations of essential nutrients.
- 3) Availability and concentration patterns of compounds to be degraded.
- 4) Contaminant effects on microbial population activity (USEPA, 1991b).

Since heavy metals in the slurry can inhibit biodegradation, pretreatment (soil washing, metal extraction, biological treatment using algal cells in a silica gel medium) may be required to eliminate such inhibitors or decrease their concentration.

**4.3.2 Available technologies.** Biotechnologies used to treat contaminated material can be classified in three broad categories:

- On or off-site aboveground technologies (landfarming, composting, slurry or dry-treatment bioreactors).
- In situ treatments.
- Biofixation.

**4.3.2.1 Aboveground technologies.** Aboveground technologies involve removal of soil or sediment prior to treatment properly speaking. Figure 4.5 shows inputs and products of this type of treatment.



**Figure 4.5 Inputs and products of on-site aboveground bioremediation technologies**

Once excavated, the contaminated material can be treated by one of the bioremediation technologies described below.

**a) Landfarming**

This bioremediation technology involves simply spreading excavated soil or sediment, generally in a layer 15 to 30 cm thick, on a prepared treatment bed. Nutrients such as nitrogen and phosphorous are added to accelerate biodegradation and the soil is periodically tilled to introduce oxygen. Exogenous microbes are sometimes added to help degrade certain more recalcitrant organic compounds.

**b) Composting**

Composting can be performed in aerobic or anaerobic environments. It involves storage of highly biodegradable and structurally firm material such as chopped hay and wood chips mixed with a 10 percent or less concentration of biodegradable waste (USEPA, 1991b).

The three basic types of composting are as follows:

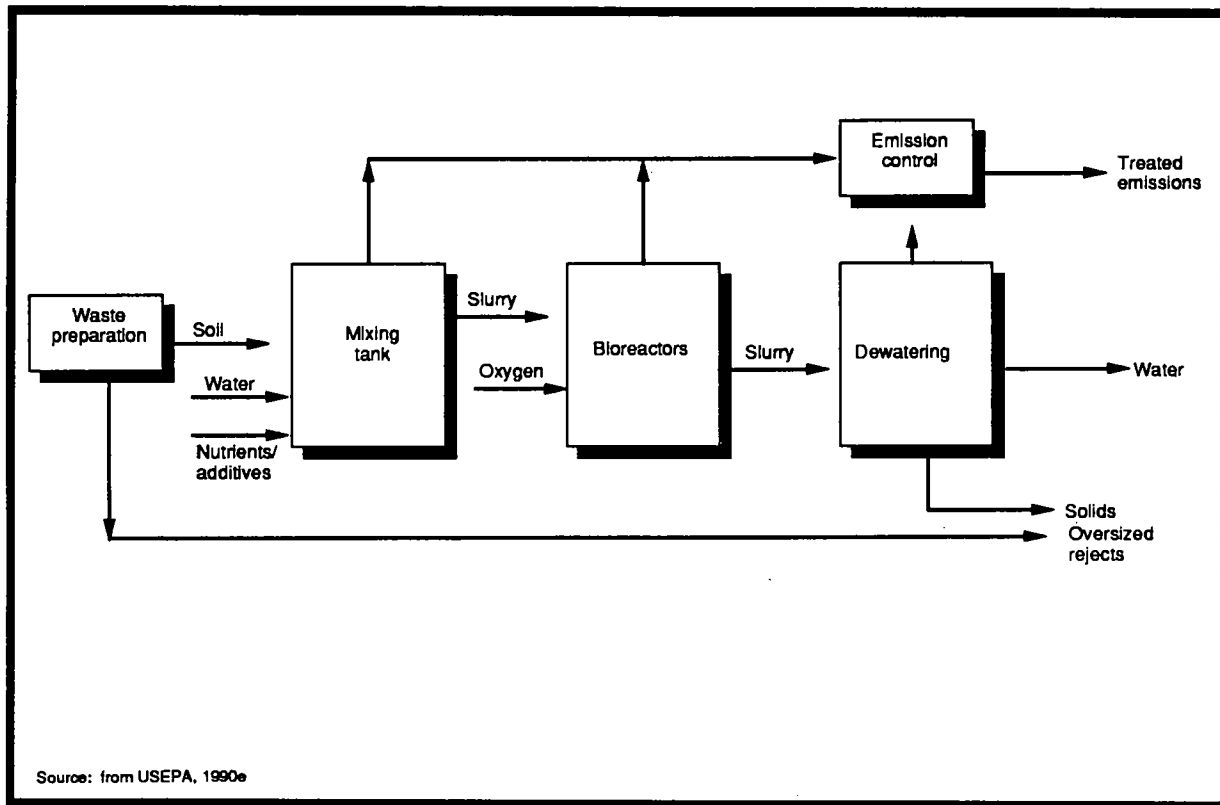
- i) Open windrow systems. The compost bed is stacked into elongated piles, and the compost is aerated by tearing down and rebuilding the piles.
- ii) Static windrow systems. The compost is also piled in elongated rows, but aeration is accomplished by a forced-air system consisting of a grid of perforated pipes underneath the compost.
- iii) In-vessel systems or reactors. The compost is aerated by tumbling, stirring and forced aeration.

In anaerobic composting, the compost is placed in a vessel and flushed with nitrogen regularly to remove oxygen (Averett et al., 1990 & USEPA, 1991b).

**c) Slurry reactors**

Slurry reactors are generally used to treat aqueous industrial or municipal effluents as well as aqueous waste. To treat contaminated waste or soil, water is added to form a slurry which is then mechanically agitated in a bioreactor (generally a tank, a lagoon or an activated sludge system). Nutrient and oxygen content as well as pH and temperature must be carefully controlled for normal microbe growth. The system is designed to maintain intimate mixing and contact of the microorganisms with the compounds to be treated.

Figure 4.6 shows a slurry biodegradation process scheme.



**Figure 4.6 Slurry biodegradation process scheme**

The slurry is mechanically agitated in the reactor vessel to keep solids suspended and maintain appropriate reaction conditions. Besides organic and inorganic nutrients, oxygen, acid or alkali for pH control, or commercial preparations of microorganisms may have to be added.

A typical soil slurry feedstock contains approximately 50 percent solids by weight. Adequate dissolved oxygen levels must be maintained and temperatures should be stabilized to range between 15° and 70°C (60°-160°F) (USEPA, 1991b).

Bioreactors can be operated in batch mode or continuous mode. As Figure 4.6 shows, the sludge is dewatered by filtration or centrifugation when treatment is completed. Solids are then removed to an authorized site. Effluent from the dewatering process can be



redirected back to the mixing tank to slurry the next batch of contaminated soil. Volatile emissions can be treated by a cleaning system (activated charcoal for example) or redirected back into the bioreactor to be biodegraded (Beck et al., 1991).

Another bioslurry method is anaerobic digestion; with this method, microorganisms degrade waste in an oxygen-free environment. Anaerobic digestion is performed in airtight vessels or reactor with provisions for venting or collecting gas, methane and carbon dioxide (USEPA, 1991b). Anaerobic digestion uses less energy and produces less sludge as a byproduct than activated sludge systems. It also generates  $H_2S$ , which precipitates heavy metal ions and produces methane ( $CH_4$ ), which can be used as a source of energy (Manahan, 1990). The method has a number of drawbacks, however--notably odours and risks of explosion--and the process must therefore be very well controlled.

#### **d) Dry reactors or contained solid phase treatment**

These processes are similar to landfarming but allow greater control of the speed of biodegradation. Common in Europe, these systems have not been used much in North America to date.

Excavated soil or sediment is mixed, soil amendments (water, nutrients, pH modifiers, bulk modifiers and microbes) are added, and the conditioned soil is placed in an enclosure such as a building, tank or modified pad. These technologies can improve process control by eliminating water runoff, allowing greater moisture control and controlling volatile emissions during biodegradation. The soil or sediment under treatment may be several metres deep and require special equipment for reconditioning or aeration (USEPA, 1991c).

Optimization of dry reactor design should continue. These reactors offer significant advantages in northern climates and unlike slurry bioreactors do not generate effluents which must later be treated (Samson, 1992).

**4.3.2.2 In situ biodegradation.** In situ biological treatment processes promote and accelerate natural biodegradation processes. Figure 4.7 shows inputs and products of such processes.

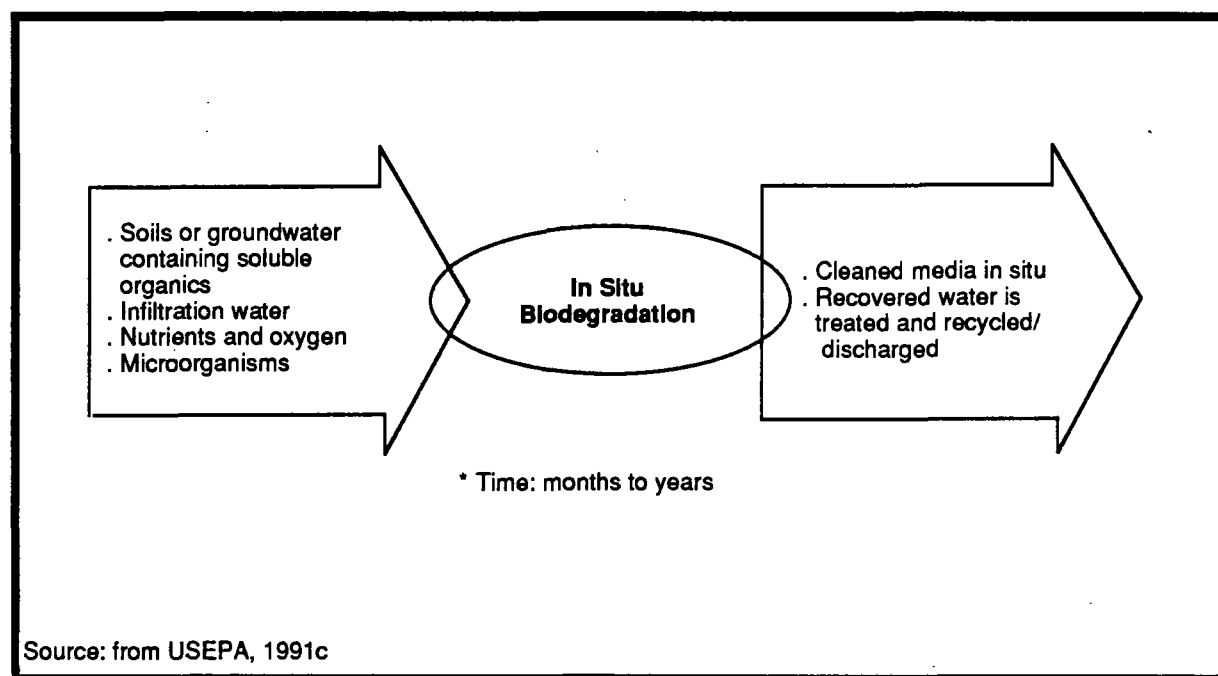


Figure 4.7 Inputs and products of in situ biodegradation technologies

In situ biodegradation relies on indigenous or introduced aerobic or anaerobic bacteria to degrade organic compounds in the material to be treated.

In situ biodegradation processes generally involve pumping and surface treatment of groundwater. The treated water is then conditioned with nutrients and an oxygen source before being reinjected into the groundwater and the contaminated soil (USEPA, 1991c). Target environments for this technology are generally surface soil and the vadose zone above the groundwater.

Presence of dissolved oxygen is usually the limiting factor for in situ biodegradation. The usual sources of oxygen are air, pure oxygen, and hydrogen peroxide

(USEPA, 1991c). The advantage of peroxide is that it releases oxygen into the environment gradually, so biodegradation is continuous. Iron fouling can however counteract or even eliminate this effect, though phosphate compounds can be added to complex the iron and increase the stability of the peroxide in situ (Petitpas, 1990). Although hydrogen peroxide is commonly used as a source of oxygen, it is relatively expensive and a variety of technical problems are associated with its use (USEPA, 1991c).

It is also possible to combine vapour extraction with bioremediation. This is called bioventing and requires a vapour well injection system that uses injection or a vacuum to force air into the surface soil. Adding air increases the amount of oxygen available for biodegradation. A solution of nutrients can also be injected or allowed to percolate through the material to enhance biodegradation.

**4.3.2.3 Biofixation.** With this technology, microbes with the ability to adsorb heavy metals are immobilized on a solid medium which is then introduced into the material to be treated. Once the metals are adsorbed, the solid medium is removed and the microbes generally destroyed by thermal treatment. The solid matrix, or support, is regenerated with an acid solution and the heavy metals recovered.

**4.3.3 Applications.** Biological technologies are suitable for treating the organic fraction of soil, sludge, sediment, surface water and groundwater. They are not, however, applicable when contaminated material contains high concentrations of heavy metals, highly chlorinated organics, pesticides, herbicides or inorganic salts (USEPA, 1991c).

Table 4.1 indicates the effectiveness of biological technologies for various matrices (soil, sediment, sludge and waste) and for the main contaminant groups--organic, inorganic and reactive contaminants. Appendix B lists constituents within the groups (volatile halogen compounds, for example).

Table 4.1 Effectiveness of biotechnologies on contaminant groups for different matrices

CONTAMINANT GROUP	EFFECTIVENESS RATINGS*	
	On-Off site	Slurry phase processes
	SOIL/DEBRIS	SOIL/SEDIMENT/SLUDGE
<b>ORGANICS</b>		
Halogenated volatiles	2	1
Halogenated semivolatiles	1	2
Nonhalogenated volatiles	2	1
Nonhalogenated semivolatiles	2	2
PCBs	1	1
Pesticides (halogenated)	1	2
Dioxins/furans	Insufficient data	0
Organic cyanides	x	1
Organic corrosives	x	0
<b>INORGANICS</b>		
Volatile metals	x	0
Nonvolatile metals	x	0
Asbestos	0	0
Radioactive materials	x	0
Inorganic corrosives	x	0
Inorganic cyanides	x	1
<b>REACTIVES</b>		
Oxidizers	x	0
Reducers	x	0

## \*EFFECTIVENESS RATINGS

- 2 Good to excellent. High probability the technology will be effective.
- 1 Marginal to moderate or potential. Exercise care in choosing the technology. Expert opinion is that the technology will be effective.
- 0 Ineffective. Expert opinion is that the technology cannot be used to treat this type of waste or contaminant.
- X May have adverse effects.

Adapted from USEPA, 1989b; 1990e; 1991c

As Table 4.1 shows, biological technologies are suitable for a range of organic contaminants, including pesticides, volatile organic compounds, PCBs and pentachlorophenols. Inorganic compounds (volatile and nonvolatile metals, radioactive materials, inorganic corrosives and cyanides) and reactives are not degraded and can even inhibit biodegradation.

Note that effectiveness levels listed were achieved in demonstration projects of different scales and hence may not necessarily be achieved everywhere. Ratings of potential effectiveness or ineffectiveness for a particular contaminant group are based on expert judgment. These remarks are applicable to all tables of this type that appear in this guide.

Standard biodegradation tests are not very reliable for contaminated sediment; contaminated sediment very often contains a number of contaminants with toxic effects that can significantly influence effectiveness and reliability of biological treatment processes. In addition, field biodegradation rates may be appreciably lower than laboratory rates, where conditions for biodegradation can be optimized (USEPA, 1991b).

Biological processes inevitably require a longer treatment time than thermal or chemical processes and so far have only been applied to contaminated sediment on a bench or pilot scale.

**4.3.4 Strengths, limitations and demonstrated applications of each technology.** Table 4.2 provides a synopsis of the main strengths and limitations of biological technologies for treating contaminated matrices.

In general, the main strengths of biological treatment systems are that they are simple and inexpensive to implement and environmentally sound. There is general agreement that biological processes are five to twenty times less costly than chemical or thermal processes and that they can be used to treat contaminants in situ, which eliminates costs and risks of using and transporting hazardous materials (Samson, 1992).

In addition, biological methods have been demonstrated for remediation of contaminated sites throughout the world and have as a result been selected to restore

contaminated soil at thirty-one *Superfund* sites in the United States and groundwater at another five Superfund sites (USEPA, 1991c).

However, biological processes can only eliminate contaminants completely under optimal conditions, and they inevitably require longer treatment time than thermal or chemical processes.

As Table 4.2 indicates, in situ biodegradation of contaminated media offers undeniable economic and environmental advantages. It does nevertheless raise a number of questions--mainly about on-site control of contaminants and nutrients and their environmental impacts, and about the toxicity of intermediates of biodegradation and their long-term effects.

In situ biological treatment of contaminants is nonetheless probably the only technology that can be used to treat large volumes of contaminated soil and sediment. It is also the only technology that can be used when there is a risk of groundwater contamination. This application is however not yet well developed, and groundwater movement complexity, type of soil, rock fractures and water table depth can all affect biological activity in ways that are hard to predict (Samson, 1992).

Landfarming methods are proven technologies for treatment of soil contaminated by hydrocarbons. They are also relatively inexpensive and do not require highly skilled operators. As Table 4.2 indicates, they do require excavation and management of contaminated materials and generally require large amounts of land.

Bioreactors available on the U.S. market (Ecova Corporation, Detox, Remediation Technology Inc., Encore, Biotrol Inc., Groundwater Technology and ReTec) and in Quebec (SNC-Lavalin, Sanexen Environmental Services Inc.) can provide optimum biodegradation and better process control. These technologies require that control equipment and systems be put in place and that emissions of volatile organic compounds be treated. Highly skilled operators are therefore required, which increases costs of treatment.

**Table 4.2 Strengths, limitations and contaminated-soil applications of biotechnologies**

TECHNOLOGY	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATION
In situ biodegradation	<ul style="list-style-type: none"> <li>Hydrocarbons and certain organics can be treated, particularly those that are water soluble and in low concentrations.</li> <li>Very environmentally sound.</li> <li>Generally inexpensive.</li> <li>Generally minimizes safety, environmental and public health risks associated with excavation and with other treatment technologies.</li> </ul>	<ul style="list-style-type: none"> <li>Difficult to contain contaminants and nutrients unless hydrologic conditions are ideal.</li> <li>Difficult to obtain good mixing when hydrophobic contaminants are present as a separate phase or when heterogeneous strata are present.</li> <li>Nutrients introduced may adversely affect nearby water courses.</li> <li>Toxic byproducts or intermediates of biodegradation may be released into the environment.</li> <li>Bacteria may plug soil and limit circulation of groundwater.</li> <li>Residues may cause taste and odour problems.</li> <li>Long-term effects are unknown.</li> <li>Complete removal of contaminants is not possible.</li> <li>Highly dependent on appropriate site hydrogeologic conditions.</li> </ul>	<ul style="list-style-type: none"> <li>Technologies proven for soil in North America and abroad.</li> </ul>
Landfarming	<ul style="list-style-type: none"> <li>Good mixing of soil during excavation reduces negative effects of clays and silts on treatment efficiency.</li> <li>Faster rate of biodegradation because parameters can be controlled better.</li> <li>Process can be enclosed to capture emissions of hazardous compounds during treatment.</li> <li>Well-proven technology for remediation of soil contaminated with hydrocarbons.</li> <li>Relatively inexpensive.</li> <li>High level of operator skill is not required.</li> </ul>	<ul style="list-style-type: none"> <li>Excavation of contaminated soil can entail emission of hazardous compounds.</li> <li>Additional cost of excavation.</li> <li>Requires land area in addition to the contaminated area.</li> <li>Management of excavated material required.</li> </ul>	<ul style="list-style-type: none"> <li>Technologies demonstrated for treatment of hydrocarbons and wood treating wastes in soil.</li> <li>A great deal of research has been conducted in Germany, the Netherlands and Denmark to enhance biodegradation with these technologies.</li> </ul>
Bioreactors	<ul style="list-style-type: none"> <li>High degree of process control because of the reactor.</li> <li>Nutrient additions, aeration, temperature and pH can be closely monitored and controlled to keep conditions within the reactor optimal for biodegradation.</li> <li>Relatively high contaminant destruction efficiencies.</li> <li>Accelerated biodegradation increases destruction rate by up to 100 times over conventional land treatment.</li> </ul>	<ul style="list-style-type: none"> <li>Some organic compounds may be volatilized by vigorous mixing to keep soil suspended, creating potential for air emissions.</li> <li>Monitoring and emission control equipment must be put in place.</li> <li>Treatment times can run as long as several weeks, despite improvement in overall removal kinetics.</li> <li>Process is more complex and treatments costs are higher.</li> </ul>	<ul style="list-style-type: none"> <li>Technologies demonstrated on a bench or pilot scale for treatment of soil in Europe and North America.</li> <li>Treatment efficiencies range from 43 percent for oils to 99 percent for PAHs.</li> <li>Full-scale demonstration at a site contaminated by creosote (PCP).</li> </ul>

Adapted from CH2M Hill Engineering Ltd., 1991

**4.3.5 Strengths and limitations for treating sediment.** In situ biodegradation technologies seem very promising options for treating contaminated sediment because of the potential impacts of dredging such sediment.

Sediment, like soil, can be biodegraded in two ways: the sediment can be dredged and then treated, or it can be left in place and treated in situ.

Dredging allows four types of biological treatment: composting, bioslurries, solid phase treatment and landfarming. *Composting* and solid phase treatment involve storage and mixing of sediment in ponds or treatment units where moisture and nutrients are regularly controlled (USEPA, 1991a).

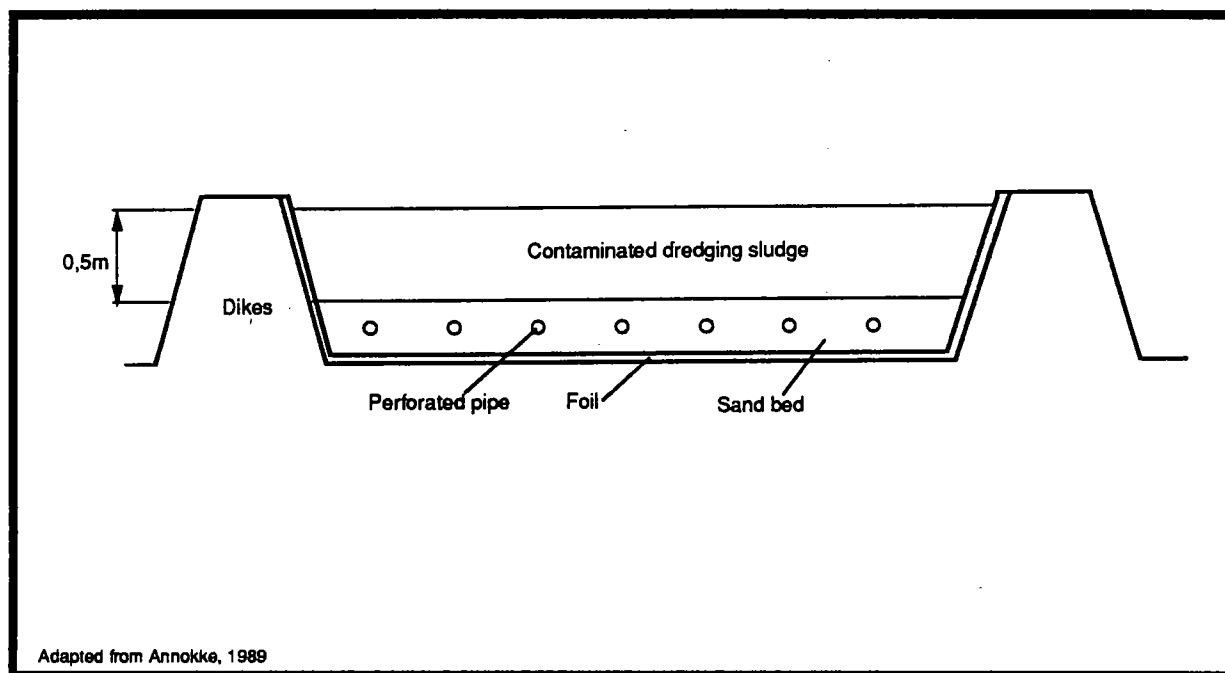
In *landfarming*, dredged sediment is spread on surface soil in lifts 15 to 22.5 centimetres thick. The area may potentially be farmed if contaminant levels are reduced to safe levels.

In situ bioremediation is the enhancement of naturally occurring biodegradative processes by adding nutrients and an electron acceptor. If oxygen is to be added as the electron acceptor, amounts of iron and manganese in the sediment are important considerations (USEPA, 1991a).

One way of achieving aerobic bioreclamation of contaminated sediment is to optimize conditions for development of aerobic organisms in a confined disposal facility (CDF) by adding nutrients and/or oxygen, or by managing the CDF to maintain aerobic conditions.

Figure 4.8 shows a method of aerobic solid phase sediment treatment.

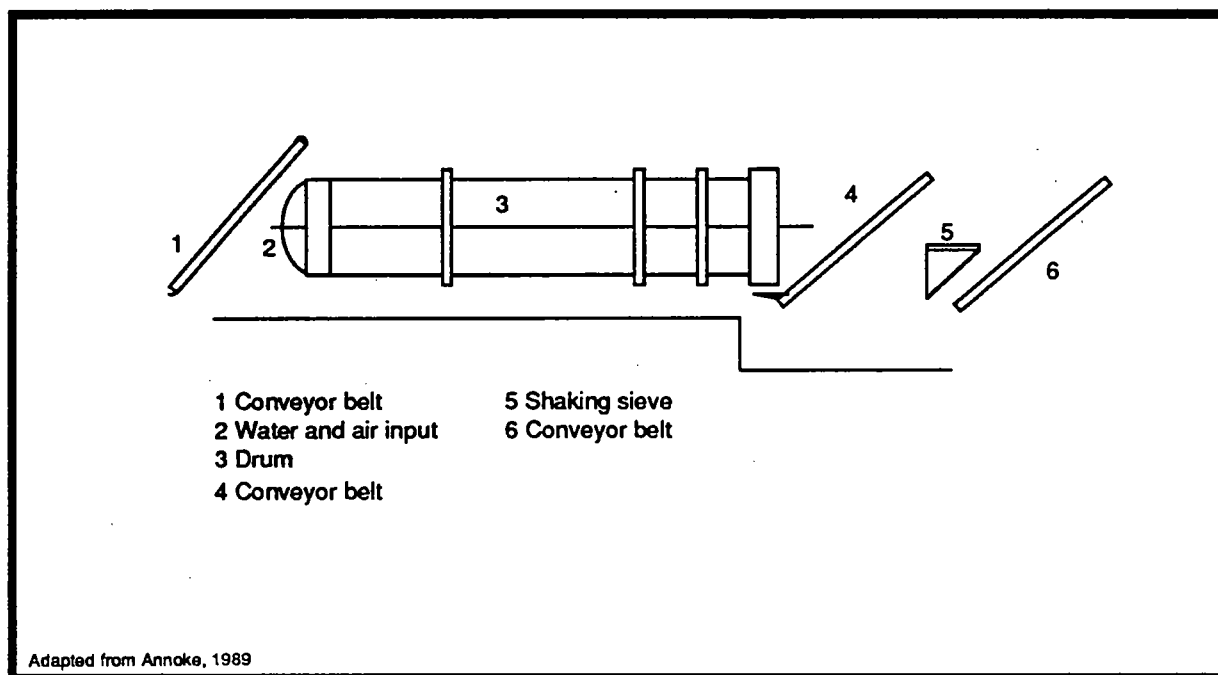




**Figure 4.8 Schematic cross section of solid phase sediment biodegradation**

Bioslurry processes require production of a slurry which is then treated in a bioreactor, where intimate mixing of sediment and microorganisms can be maintained. Figure 4.9 shows how sediment is treated in a rotating bioreactor.

The primary mechanism involved in anaerobic biodegradation of halogenated organics is reductive dehalogenation. A redox potential of -250 mv or less is required, and no oxygen, nitrates, or sulphates can be present. Most sediment is anaerobic in situ with ample opportunity for contaminant biodegradation under ambient conditions. Sediment could be treated by anaerobic bioreclamation in a CDF designed to maintain anaerobic conditions (Averett et al., 1990).



**Figure 4.9** Cross section of rotating drum slurry bioreactor

Anaerobic biodegradation tests were conducted on sediment from two lakes near Athens, Georgia, in the United States to determine the effect of temperature and redox conditions on anaerobic biodegradation of 2,4-dichlorophenol. After 127 days of incubation under conditions favourable for denitrification, no reductive dechlorination was noted (Averett et al., 1990).

The anaerobic biodegradation technology is still conceptual. This technology is slow and degrades far fewer compounds than aerobic bioreclamation.

Anaerobic digestion is a widely used technology for treating low to moderate levels of organic contaminants in wastewater. The anaerobic bacteria used are commonly a mixture of methanogenic bacteria that use methane as their main source of carbon; these bacteria

are found in anaerobic sediment or digester sludge. Anaerobic digesters are usually airtight reactors with provisions for venting or collecting methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ).

The USACE District, Buffalo, tested anaerobic digestion of dredged sediment. Results were not as good as those obtained with wastewater sludge. Reactor volumes required and the low efficiency of the technology limit its use for treating contaminated sediment (Averett et al., 1990).

Biodegradation of contaminants by composting requires a lot of space. In addition, results are uncertain because weather and other conditions cannot be controlled. Also, composting is difficult to apply to dredged sediment because of the high water content of sediment and composting's need for a high organics content. Other difficulties are the requirements to turn or aerate the material and to control leachate and runoff. Costs for a West German composting process range from US\$82 to US\$136 per ton (Averett et al., 1990).

Organic compounds such as aliphatics, aromatics, and heterocyclics can be degraded by enzymes. Enzymes produced by microorganisms can be cultivated in reactors and applied to contaminated soil or sediment. Enzyme activity can remain viable in harsher environments than can microorganisms. Such environments include pH and temperature extremes, high salinity, and high solvent concentrations. Enzymes are also subject to chemical or biological degradation, may be leached out of the treatment zone, or may become inactive or less active if they become bound to clay or humus in the soil (Averett et al., 1990).

Sediment properties which greatly influence biodegradation include type and amount of clay, ion exchange capacity, organic matter content, pH, amount of active iron and manganese, oxidation-reduction conditions and salinity. Site characteristics that can appreciably affect biodegradation are as follows:

- Physical and chemical sediment characteristics and contaminant concentrations, of organics in particular.
- Microorganisms present in the sediment and their ability to degrade, co-metabolize, or adsorb the contaminants.
- Biodegradability of contaminants (half-life, rate constants).

- Biodegradation products.
- Depth, profile, and real distribution of sediment contaminants.
- Sediment properties that can affect biological activity: pH, oxygen content, moisture content, nutrient content, organic matter, temperature and so forth.
- Sediment texture, water-holding capacity, degree of structure, erosion potential.
- Hydrodynamics of the site (USEPA, 1991b).

As part of the project to remediate and improve the Lachine canal, the Restoration Division of the St. Lawrence Centre selected treatment processes applicable for contaminated sediment in the canal and validated them in the laboratory. Seven technology developers--six that use physical or chemical fixation processes and one that uses a biological process--participated in the laboratory validation phase and submitted proposals for a pilot-scale project that could eventually lead to a comprehensive restoration project (St. Lawrence Centre, 1992b).

One of the laboratory-tested treatments was a three-phase process. The first phase consisted of biodegrading organic sediment contaminants with patented microorganism. In the second phase, heavy metals in the sediment were eliminated by chemical extraction or fixation using patented bacteria. Solvent and biomass containing the heavy metals was then recovered.

Laboratory test results demonstrated however that the treated sediment was unsuitable for disposal in the canal or in a sanitary landfill because contaminant concentrations exceeded acceptability criteria for protection of benthic organisms. In addition, leachate contaminant concentrations exceeded standards governing sanitary landfills (St. Lawrence Centre, 1992b).

**4.3.6 Technologies demonstrated for sediment treatment.** Until the end of the 1980s, biotechnologies for treatment of contaminated sediment had been tested only on a bench scale (Table 4.3). Some large-scale sediment remediation projects have been conducted since 1990, however. Table 4.4 lists biotechnologies demonstrated for treatment of contaminated sediment

**Table 4.3      Anticipated performance of biological technologies applied to sediment remediation**

TECHNOLOGY	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABLE	PERFORMANCE RATINGS**		
				Effec- tiveness	Implement- ability	Cost
<b>Bioreactors*</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	3	1	3
<b>Aerobic bioreclamation</b>	<b>Demonstrated</b>	<b>Bench</b>	<b>Available</b>	3	3	3
<b>Anaerobic bioreclamation</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	3	3	3
<b>Anaerobic digestion</b>	<b>Demonstrated</b>	<b>Bench</b>	<b>Available</b>	3	2	2
<b>Composting</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	2	2	2
<b>Enzymes (including fungi)</b>	<b>Conceptual</b>	<b>No</b>	<b>Available</b>	2	1	3

**NOTES**

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

Source: Averett et al., 1990

**Table 4.4 Biotechnologies demonstrated for sediment remediation**

Technology	Developer*	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Biodegradation • Composting	Not specified	U.S.	Louisiana Army Ammunitions plant	Full	Trinitrotoluene (TNT)	USEPA, 1991b
Biodegradation • Bioreactor	Netherlands Organization for Applied Scientific Research (TNO) Encore Environmental	Holland	Rotterdam Harbour	Laboratory	Oil and organics	USEPA, 1991b
		U.S.	Hudson River	Bench	PCBs	Averett et al., 1990
Biodegradation • Aerated lagoon	Development Program Treatment Processes for Polluted Aquatic Sediment (DTPP) and TNO	Holland	De Geul and Zierickzee harbours	Full	PAHs, oils and chlorinated hydrocarbons	Dillen & Bruggeman, 1992
Biodegradation • Landfarming	Netherlands Organization for Applied Scientific Research (TNO) Development Program Treatment Processes for Polluted Aquatic Sediment (DTPP)	Holland	Rotterdam Harbour	Bench	Heavy metals and organics	USEPA, 1991b
		Holland	De Geul and Zierickzee Harbours	Full	PAHs, oils and chlorinated hydrocarbons	Dillen & Bruggeman, 1992
Biodegradation • Aerobic	Radian Corporation (1989)	U.S.	New Bedford Harbour, MA	Bench	PCBs	USEPA, 1991b Averett et al., 1990
Biodegradation • In situ	Haecon N.V.	Belgium	Edegemand Zebrugge	Full	Specific organic hydrocarbons	Environment Canada, 1993
		Holland	Bakhuisterwant, Zoeterwoude			
Biodegradation • Composting	Dearborn	Canada	Thunder Bay St. Marys River Hamilton Harbour	Bench	PAHs, chlorophenols	Environment Canada, 1993

\* See Appendix C for telephone numbers and addresses of developers.

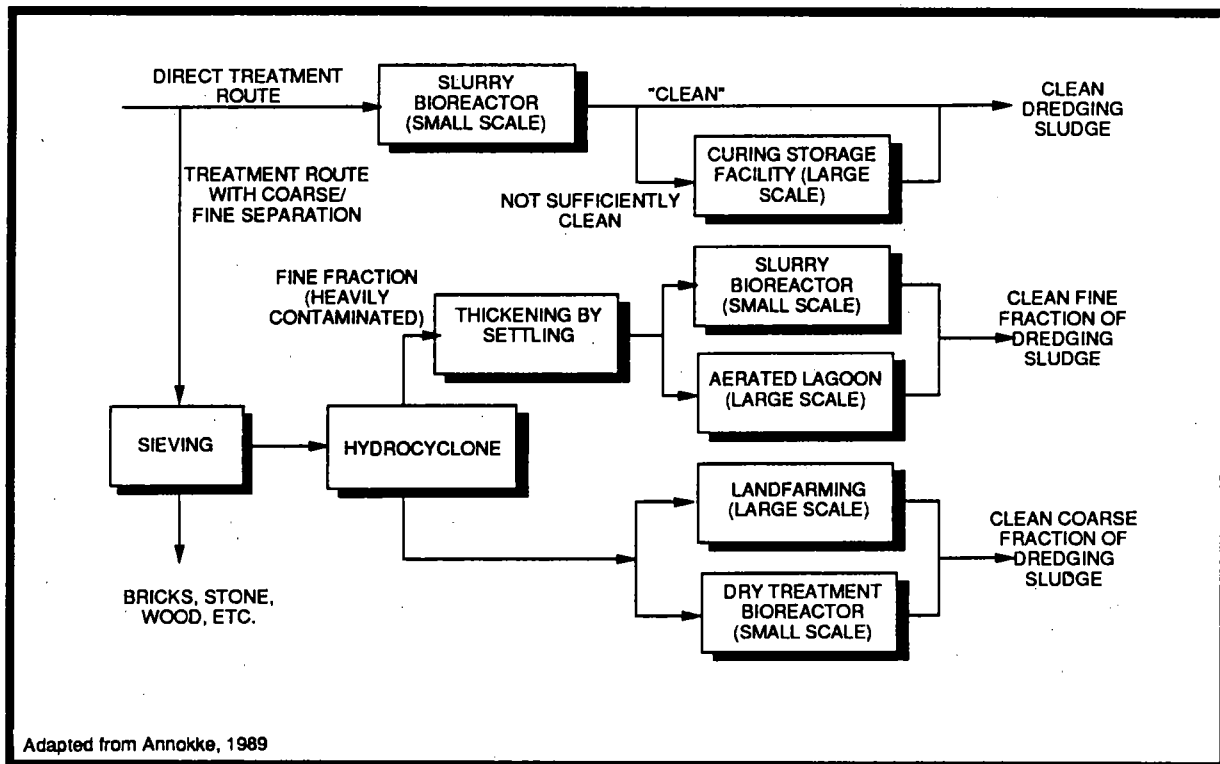
with the name of the technology developer, the site and scale of demonstration and the type of contamination.

Field tests of composting for remediation of lagoon sediment contaminated with trinitrotoluene (TNT) were conducted at an ammunitions plant in Louisiana, United States. Results demonstrated that contaminant concentrations decreased from 12 000 ppm to 3 ppm (USEPA, 1991b).

Since biological sediment treatments are relatively inexpensive and treated sediment destined for reuse should be more environmentally acceptable than sediment treated by physical, chemical or thermal processes, Dutch research has focused on two treatment routes in recent years--one for small-scale field operations and one for large-scale operations (Van Veen, 1988).

The Netherlands Organization for Applied Research (TNO) has developed a wet and a dry bioreactor to treat contaminated soil and dredged material containing mineral oils, polychlorinated aromatics and other nonchlorinated hydrocarbons. The dry bioreactor is similar to composting, and the wet bioreactor is similar to an aerobic activated sludge system. The bioreactors have been operating on a laboratory scale, and pilot-scale experiments with a throughput of 11 tons per day have been conducted. Treatment costs are estimated at US\$45 per ton (Averett et al., 1990).

Figure 4.10 shows Dutch processing routes for sediment decontamination by biodegradation. These routes are currently being tested in the laboratory and on a bench and pilot scale.



**Figure 4.10 Dutch processing routes for sediment decontamination by biodegradation**

As Figure 4.10 shows, the first route uses bioreactors (maximum capacity of 500 cubic metres) operating in batch mode for small-scale operations. This route calls for intensive treatment in a very short time and does not require particle separation by hydrocyclones. In the processing route for large-scale operations, treatment begins by coarse/fine separation. The fine fraction is then treated in aerated lagoons. The coarse fraction can be landfarmed, which generally requires a relatively long treatment time, addition of nutrients and regular stirring of the sediment to introduce additional oxygen.

In landfarming tests of material contaminated by PAHs, oils and chlorinated hydrocarbons, dredged material from the Geul and Zierikzee harbours was spread in a thin layer (about 30 cm thick) at a specially designed dumping site. After one year, 60 to 80 percent of the PAHs had degraded. Costs of this type of treatment range from US\$25 and US\$60 per in situ cubic metre (Dillen & Bruggeman, 1992).



Laboratory-scale tests of sediment biodegradation using slurry bioreactors demonstrate the technology yields acceptable contaminant degradation. The process is only economical however when sediment bioreactor residence times are very short (a few days to a week). Unfortunately, residence times of one to two months are required to achieve acceptable degradation percentages even when bacteria are added and temperature is increased. The Dutch government therefore abandoned the research on treating sediment in slurry bioreactors at the laboratory stage. Treatment costs for residence times of four, seven and thirty days are respectively US\$70, 100 and 375 per cubic metre of treated sediment (50 percent dry matter) (Dillen & Bruggeman, 1992).

Tests using aerated lagoons to achieve biological degradation of PAHs and light oils in contaminated sediment after separation by hydrocyclone demonstrated a 70 to 80 percent decrease in contaminant concentrations in sediment from the Geul Harbour and a 30 percent drop in contaminant concentrations in sediment from the Zierikke Harbour. Treatment costs for residence times of two, four and eight months are respectively US\$7, US\$12 and US\$20 per cubic metre of treated light fraction (10 percent dry matter).

Sediment biotreatment research in the Netherlands also demonstrated that biotechnologies leave residual concentrations of contaminants too high to sediment quality goals for the year 2000 set by the Dutch government for PAHs and oils. Research continues to try to lower residual concentrations to acceptable levels.

Radian Corporation (1989) conducted a bench-scale aerobic biodegradation study for PCB removal on sediment from the New Bedford Harbour Superfund site in Massachusetts. Results showed an overall PCB reduction, but preferential reduction in concentrations of di- and tri-isomer groups in the active reactors compared to uniform concentration reduction of all groups in the control reactors (Averett et al., 1990).

The company Heacon N.V. conducted full-scale demonstrations of in situ biotreatment of sediment in a number of Belgian harbours (see Table 4.4). Results of these tests are not yet available.

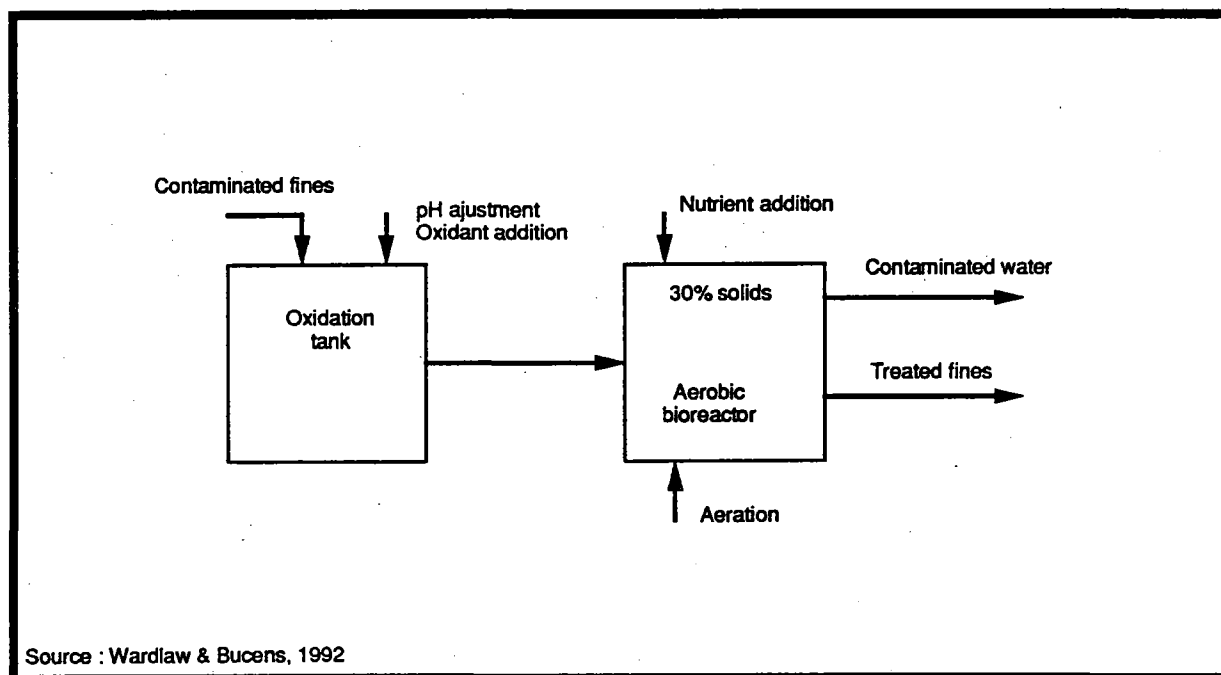
The Dearborn Environmental Consulting Group of Mississauga, Ontario, conducted bench-scale biodegradation tests (composting) on sediment contaminated by PAHs and chlorophenols from the Hamilton, Thunder Bay and St. Marys River harbours. Preliminary results show a significant reduction in PAHs when surfactants and biodegradable organic matter are used (Wastewater Technology Centre, 1992b). Pilot-scale tests of sediment from the Hamilton Harbour were conducted in the fall of 1992. These demonstration projects were funded by the Great Lakes Environment Office through Environment Canada's Great Lakes Cleanup Fund.

Another biotreatment process (slurry bioreactor) financed by the Great Lakes Cleanup Fund was tested on sediment from the Toronto Harbour in the summer of 1992. The bioreactor used for the tests was designed by SNC-Lavalin to accelerate biodegradation and give high destruction efficiencies even for chlorinated hydrocarbons of high molecular weight. The first step is chemical oxidation to oxidize high molecular weight organics to lower molecular weight species that biodegrade more readily and rapidly.

As Figure 4.11 shows, the sediment to be treated is first placed in a tank for pH adjustment and oxidant addition. The slurry is then passed to the bioreactors where it is aerobically biodegraded by nutrient addition and aeration for at least four weeks (Wardlaw and Bucens, 1992).

This process was the last stage in the treatment train used by the Toronto Harbour Commission; the first two stages were washing and metal extraction. Section 4.8 herein gives more detailed information on the treatment train used by the Commission.

Sediment pretreatment prior to biodegradation is more and more becoming common practice to eliminate contaminants that resist biodegradation or inhibit microorganism activity (heavy metals, for example).



**Figure 4.11 SNC-Lavalin bioreactor process scheme**

The Bio-Clean biological treatment process developed by the U.S. firm Encore Environmental and suggested for treatment of Hudson River sediment (United States) highly contaminated by PCBs calls for treatment of dredged sediment in a series of nine continuously operating reactors on barges, eliminating the need to transport contaminated sediment long distances. The process uses naturally-occurring bacteria to degrade organic contaminants. It is a batch process involving extraction, sterilization, and solubilization of contaminants using high temperature, high pH, and biodegradation. Estimated treatment costs range from US\$130 to US\$270 per cubic yard (Averett et al., 1990; USEPA, 1991b).

**4.3.7 Technologies under demonstration for sediment treatment.** Table 4.5 lists biotechnologies recommended for Great Lakes sediment remediation demonstration projects on the basis of the technology selection and evaluation criteria used by the USEPA and the USACE (see Chapter 3 herein). The table also lists biotechnologies being researched in Canada and the Netherlands.

**Table 4.5      Biotechnologies under demonstration for Great Lakes sediment remediation and in Europe**

Technology	Developer*	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Biodegradation • Aerobic & anaerobic	Not specified	U.S.	Buffalo River	Bench	PAHs, oils and greases PCBs, organo-chlorines PCBs PCBs	USEPA, 1992a
			Ashtabula River	Bench		
			Saginaw Bay	Bench		
			Sheboygan Harbour	Bench		
Biodegradation • Landfarming • Aerated lagoon	Netherlands Organization for Applied Scientific Research (TNO) Development Program Treatment Processes for Polluted Aquatic Sediment (DTPP)	Holland	Rotterdam & Hamburg harbours	Full	Organics	Annokke, 1989
		Holland	De Geul & Zierickzee harbours	Full	PAHs, oils & chlorinated hydrocarbons	Dillen & Bruggeman, 1992
Biodegradation • Composting	Dearborn Environmental Consulting Group	Canada	Thunder Bay, Hamilton & Sault St. Marie harbours,	Pilot	Chlorophenols, PAHs	Environ-ment Canada, 1993
Biodegradation • Bioreactor	Institute of Gas Technology	Canada	Hamilton Harbour	Bench	Chlorophenols, PAHs	Environ-ment Canada, 1993
	SNC-Lavalin	Canada	Toronto Harbour	Pilot	PAHs	
Biodegradation • In situ anaerobic	Michigan Biotechnology Institute	U.S.	Not specified	Laboratory	PCBs	Samson, 1992

\* See Appendix C for telephone numbers and addresses of developers.

As shown in Table 4.3, the biotechnologies recommended for Great Lakes sediment remediation demonstration projects are bioreactor processes and other aerobic or anaerobic treatments. Costs, destruction efficiencies and implementability of these technologies, apart from the bioreactor processes (their application to sediment has not yet been demonstrated), compare well with those of other technologies considered--composting, anaerobic digestion and enzyme processes (limitations of these technologies for sediment treatment are described above).

Given the considerable potential of bioremediation technologies, the USEPA has invested tens of millions of dollars in basic research annually. For example, the Michigan Biotechnology Institute was granted \$15 million to study anaerobic organochlorine biodegradation mechanisms (reductive dechlorination) in the hope that an in situ remediation technology for sediment contaminated by PCBs might eventually be developed.

As indicated in Table 4.5, biotechnologies for treatment of contaminated sediment are being tested on a bench and a pilot scale as part of the demonstration projects funded by the Great Lakes Cleanup Fund (Environment Canada, 1993). As the table shows, in addition to the technologies described in the preceding section, a biochemical process developed by the Institute of Gas Technology (IGT) of Chicago is currently under demonstration on a bench scale on sediment from the Hamilton Harbour.

The effectiveness of the IGT biochemical process was demonstrated on a bench scale for treatment of organic compounds (PCBs, PAHs and volatile hydrocarbons) in sludge and soil. The process combines two technologies: pretreatment by chemical oxidation with metallic salts and hydrogen peroxide to produce a hydroxyl radical to modify and degrade organic compounds; and aerobic or anaerobic biological treatment used alone or in sequence depending on contaminants to be treated (USEPA, 1992f).

As Table 4.5 indicates, field-scale bioremediation demonstration projects are under way in Europe (in the Netherlands, Belgium and Germany).

**4.3.8 Technologies recommended for sediment remediation projects.** Table 4.6 lists three off-site and one in situ project using biological technologies to clean up contaminated sediment in the United States. These projects are part of the innovative technologies program. As the table indicates, most of the projects were in the design phase in 1991. Cleanup demonstrations properly speaking were to be completed in the fall of 1992 or the winter of 1993.

Table 4.7 lists thirteen U.S. sites where biotechnologies were planned, considered or applied to clean up contaminated sediment under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), the Resource Conservation and Recovery Act (RCRA) or the Underground Storage Tank (UST) regulation.

**4.3.9 Conclusions.** As the preceding sections show, biotechnologies are promising options for treating most organic sediment contaminants. Heavy metals and certain sediment characteristics (clay content, pH and organic matter content, for example) can limit contaminant bioavailability. Pretreatment technologies can increase bioavailability, by increasing active surface area, adding structuring substances or removing metals (washing processes or other technologies).

To date, biotechnologies for treatment of sediment have been tested mainly in the laboratory or on a bench or pilot scale. Results of such demonstration projects in the United States have however been sufficiently conclusive for biotechnologies to be recommended for cleanup of sites with contaminated sediment. Only after project results have been published will it be possible to specify costs of using biotechnologies to treat sediment and to know whether biodegradation conditions for cleanup of thousands of cubic metres of sediment can be optimized as well as conditions in a pilot or bench scale project.

**Table 4.6 Sediment bioremediation projects under the U.S. innovative technologies program**

Site name & state	Technology	Site description	Media (quantity)	Key contaminants treated	Status	Contact/Phone
L.A. Clarke & Sons, VA	On-site bioremediation (type to be determined)	Wood treating	Soil (73 700 cy), sediment (45 300 cy)	Creosote, PAHs and VOCs (benzene)	Pilot: 1992 Design: winter 1993	Gene Wingert 215-597-1727
Moss-American, WI	Slurry phase treatment of fines from soil washing and sediment	Wood treating	Sediment (5 200 cy), fines from soil (80 000 cy)	PAHs	Design: winter 1993	Betty Levis 312-886-4784
Burlington Northern (Somers Plant), VT	Land treatment	Wood treating	Soil, sediment (11 700 cy combined)	Creosote, PAHs, and SVOCs (phenols)	Design: fall 1992	Jim Harris 406-449-5414
French Limited, TX	In situ lagoon bioremediation	Petrochemical	Sludge, sediment (70 100 cy)	VOCs (BTEX), PAHs, petroleum hydrocarbons, and PCBs	In design	Judith Black 214-655-6735

Source: USEPA, 1991c

**Table 4.7 Sediment bioremediation projects under CERCLA, RCRA and UST programs**

Site name & state	Technology	Media	Key contaminants treated	Status	Contact/phone
Charlestown Navy Yard, MA	In situ	Sediment	PAHs	Pilot: 1991	Steven Carlson 617-242-5680
General Electric, MA	Off site	Sediment, soil	PCBs	Pilot: 1992	Joan Blake 202-382-6236
General Electric, MA	In situ	Sediment	PCBs	Pilot: 1992	Joan Blake 202-382-6236
Pine Street Canal, VT	Soil: in situ Groundwater: fixed-film reactor	Soil, sediment, groundwater	PAHs	Bench: Fall 1990	Ross Gilleland 617-573-5766
Alcoa, NY	Undetermined	Sediment	PCBs	Currently in RI stage	Lisa Carson 212-264-6857
General Motors, NY	Undetermined	Soil, sediment, sludge, groundwater	PCBs, PAHs, volatiles	Treatability studies	Lisa Carson 212-264-6857
Reynolds Metals, NY	Undetermined	Sediment	PCBs	Currently in RI stage	Lisa Carson 212-264-6857
Moss American, WI	Slurry bioreactor using indigenous bacteria	Soil, sediment	PAHs	Pilot: completed Design: summer 1991	Betty Lewis 312-866-4784
Sheboygan River and Sheboygan Harbour, WI	Natural and enhanced biodegradation in enclosed facility; in situ study in capped sediment	Sediment	PCBs	Pilot: 1991	Bonnie Eleder 312-886-4885
St. Louis River, MN	Undetermined	Soil, sediment	PAHs	Treatability studies	Debbie Siebers 312-353-9299
Burlington Northern, MT	In situ	Soil, sediment, groundwater	PAHs, zinc, phenol	Full: 1992	Jim Harris 406-449-5414
J.H. Baxter, CA	Land treatment	Soil, sediment, groundwater	Arsenic, chromium, PCP, PAHs, dioxins, furans, zinc	Treatability studies complete	Mary Masters 415-744-2370
Celanese Fibers Operations, NC	Sequencing batch reactor	Soil, sediment, groundwater	bis(2-ethylhexyl) phthalate	Treatability studies complete	Ken Mallary 404-377-7791

Adapted from USEPA, 1991c



#### **4.4 Physical and chemical extraction**

##### **4.4.1 Principle of treatment**

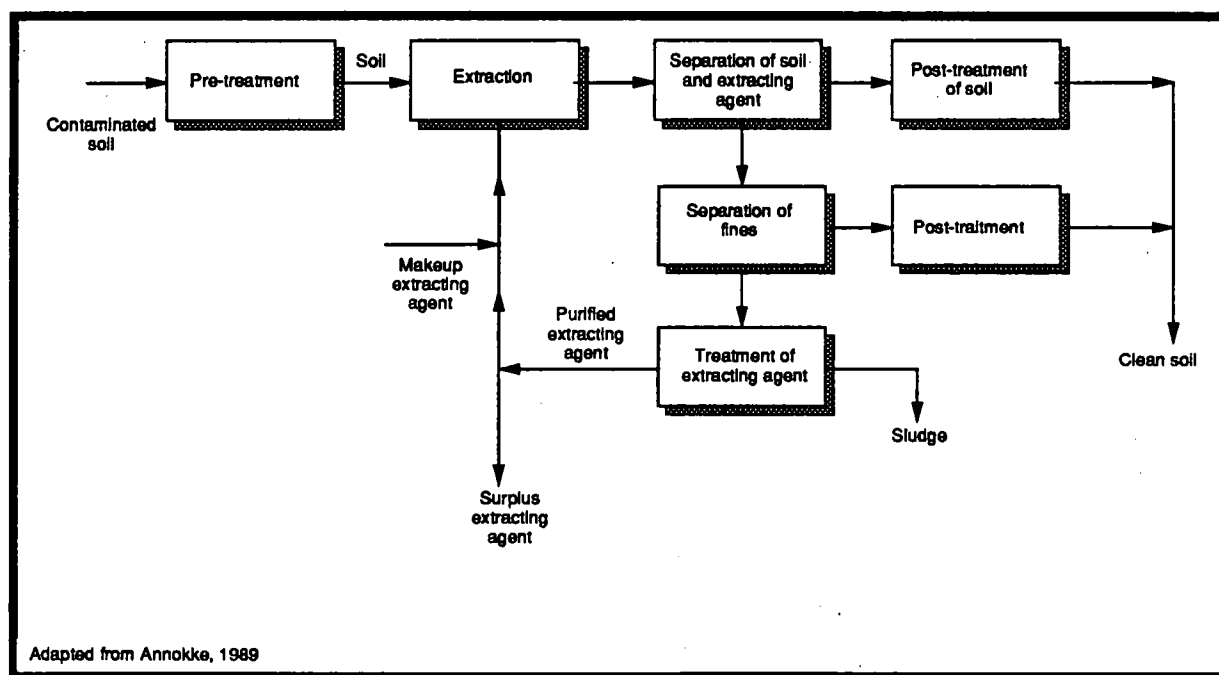
Physical and chemical extractive processes remove contaminants from a medium (soil or sediment, for example) by dissolving them in a fluid (water, for example) which is then recovered or treated. Since organic or metal contaminants are removed but not destroyed or chemically altered, process effluents are much more concentrated with the contaminants than was the original sediment or soil.

As the USEPA mentions, the term "extraction" traditionally refers to chemical extraction. Nowadays, however, the term is increasingly being used for any technology that reduces volume by removing contaminants from one medium and concentrating them in another. With this definition, soil washing is an extraction technology, though traditionally it has been considered separate from chemical extraction (USEPA, 1991b).

Extractive technologies should be viewed as one part of a treatment train since organic contaminants still need to be destroyed or treated by thermal, physical and chemical, or bioremediation processes after extraction. Concentrating contaminants in a smaller volume of sediment or residual can, however, mean significant cost savings (USEPA, 1991b).

Extraction fluids are selected depending on whether organics or inorganics are to be removed. Options include water, acids, bases, complexing and chelating agents, surfactants, kerosene, methanol, ethanol, isopropanol, furfural, dimethylformamide, toluene, dimethyl sulphoxide, ethylene diamine, freon mixture, and carbon dioxide or propane at critical or supercritical pressures and temperatures. Most processes require multiple extraction cycles to achieve high removal efficiencies (Averett et al., 1990).

Figure 4.12 shows a schematic of an extractive process used to treat soil; a similar process should be applicable for sediment.



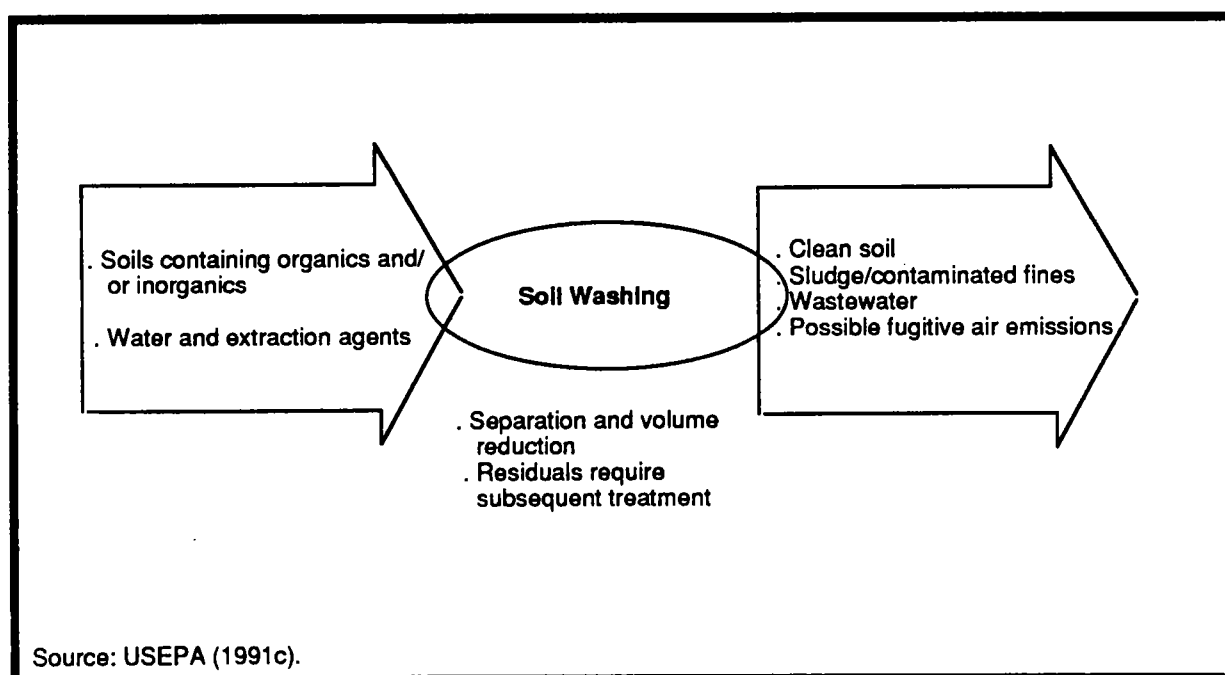
**Figure 4.12 Extraction process scheme**

Soil contaminant extraction technologies can have many applications for treating contaminated sediment. Since sediment remediation usually entails treating large volumes of material with relatively low concentrations of contaminants, extractive technologies are among the most attractive options for sediment treatment because they concentrate contaminants in a small volume of sediment or residual and thus significantly reduce costs (USEPA, 1991a).

#### 4.4.2 Technologies available

**4.4.2.1 Washing.** Washing processes use water and mechanical action to remove contaminants physically attached to particles of soil. The technology exploits the fact that contaminants tend to adhere to organic carbon and the fine soil fraction (silt and clay). Superficial contamination is often removed from the coarse fraction by abrasive scouring (USEPA, 1992c).

Figure 4.13 shows soil washing inputs and products.

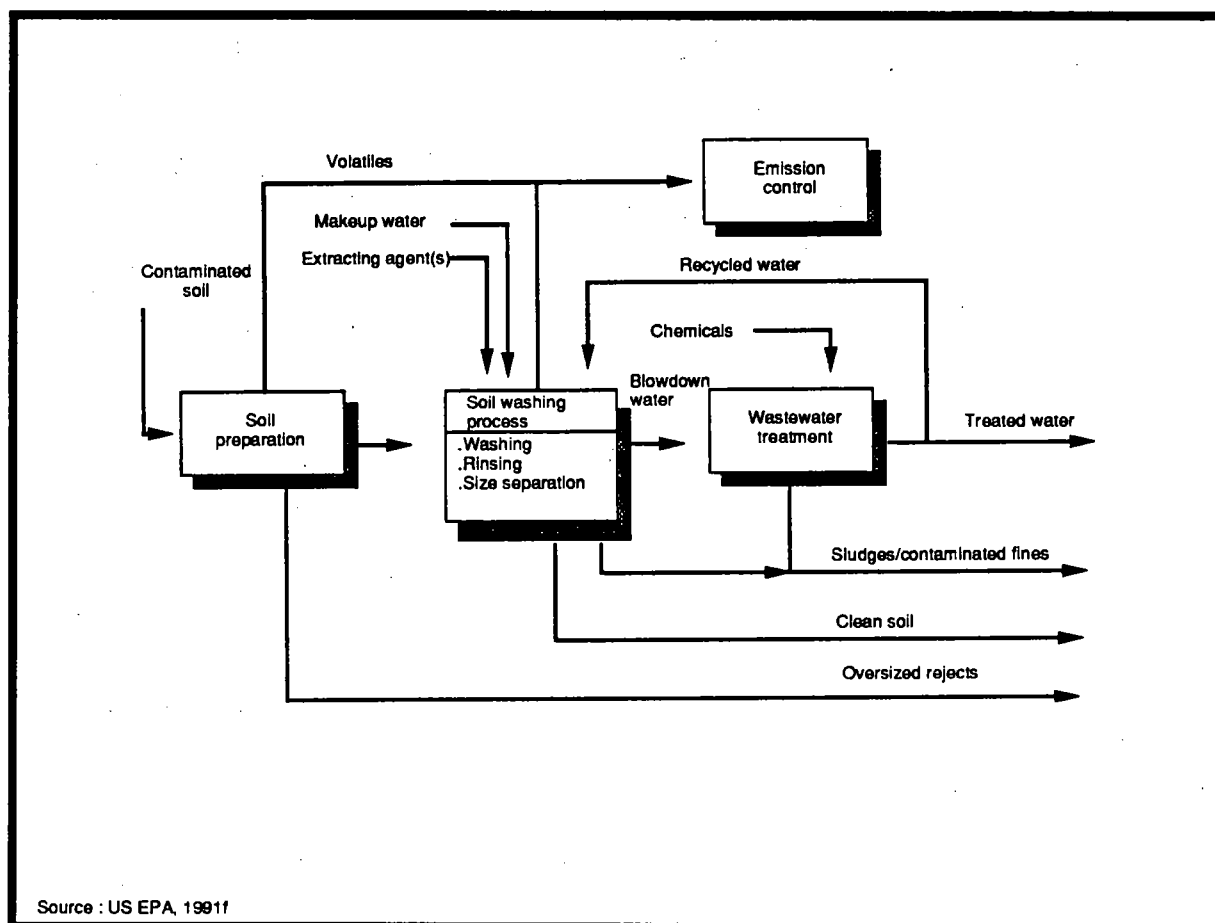


**Figure 4.13 Soil washing inputs and products**

Contaminated soil can be physically cleaned with water enhanced with extraction agents. When the soil is left in situ, the process is called *soil flushing*; when the soil is removed and then placed in contact with the fluid, the process is called *soil washing*.

Composition of the soil-washing fluid depends on contaminants to be removed. The fluid can be pure water or can contain acids (to leach metals or neutralize alkaline soil), bases (to neutralize acid contaminants), chelating agents (to solubilize heavy metals), surfactants (to enhance removal of organic soil contaminants and the capacity of water to emulsify insoluble organic compounds) or reducers (to reduce oxides). Soil contaminants can dissolve, form emulsions or react chemically. When hazardous compounds are extracted, the compounds sometimes react chemically with solutes in the water; in such cases, the treatment is chemical as well as physical.

Figure 4.14 shows a soil washing process scheme.



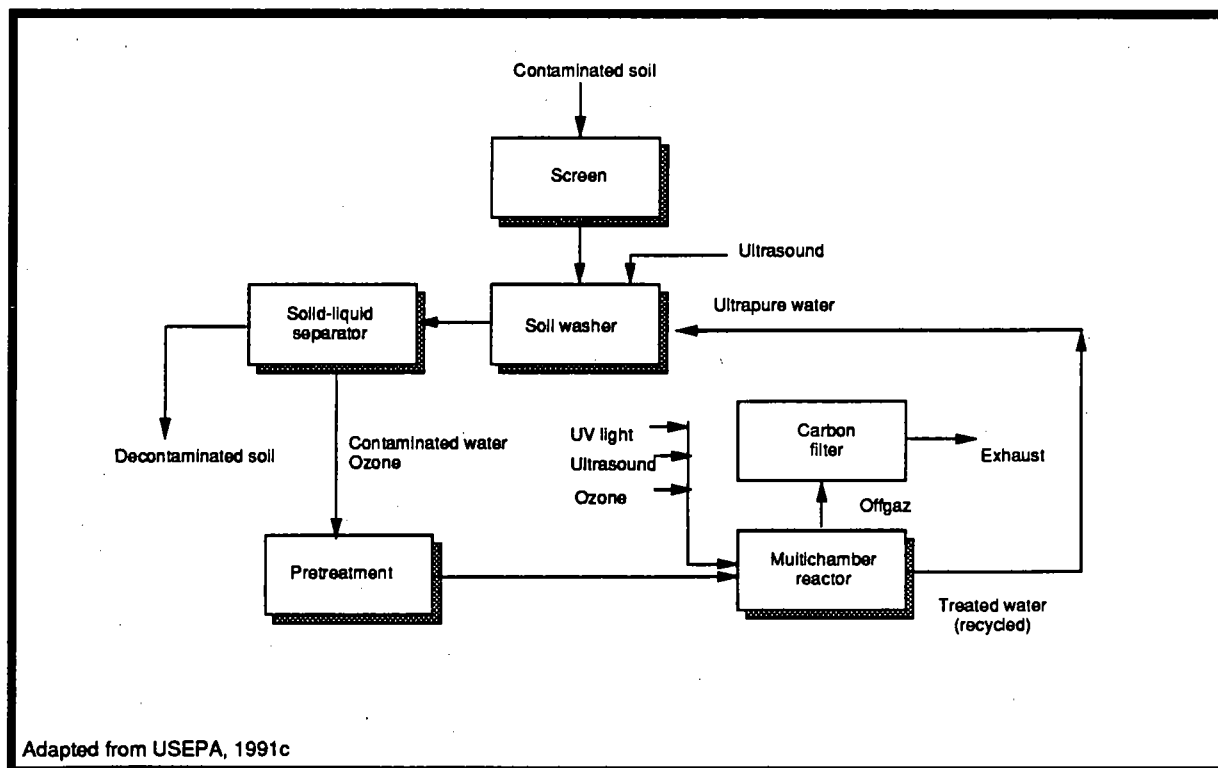
**Figure 4.14 Aqueous soil washing process scheme**

As Figure 4.14 indicates, the blowdown water from the soil washing process must be treated to extract contaminants before it is recycled, released or disposed of. Blowdown water treatments generally include one or more of the following processes: activated carbon filtering to remove organic contaminants; biological treatment for biodegradable organic compounds; sulphide treatment to precipitate metals; additions to break down emulsions; filtration; and reverse osmosis.

A variety of techniques can be used to promote extraction of soil contaminants. One Dutch firm, Bodemsanering Nederland BV, uses high-pressure water jets. A second Dutch firm, Ecotecniek BV, uses hot water. Harbauer, a German firm, submits the mixture of soil and water to intense vibration or oscillation to separate contaminants from soil particles. Other technologies add oxidizers such as hydrogen peroxide or ozone during mixing (Intera Kenting, 1990).

Figure 4.15 shows a soil washing process developed by the U.S. firm Excalibur Enterprises Inc. The process uses a combination of technologies (ultrasound, ultraviolet light and ozone) at different stages to increase extraction efficiency.

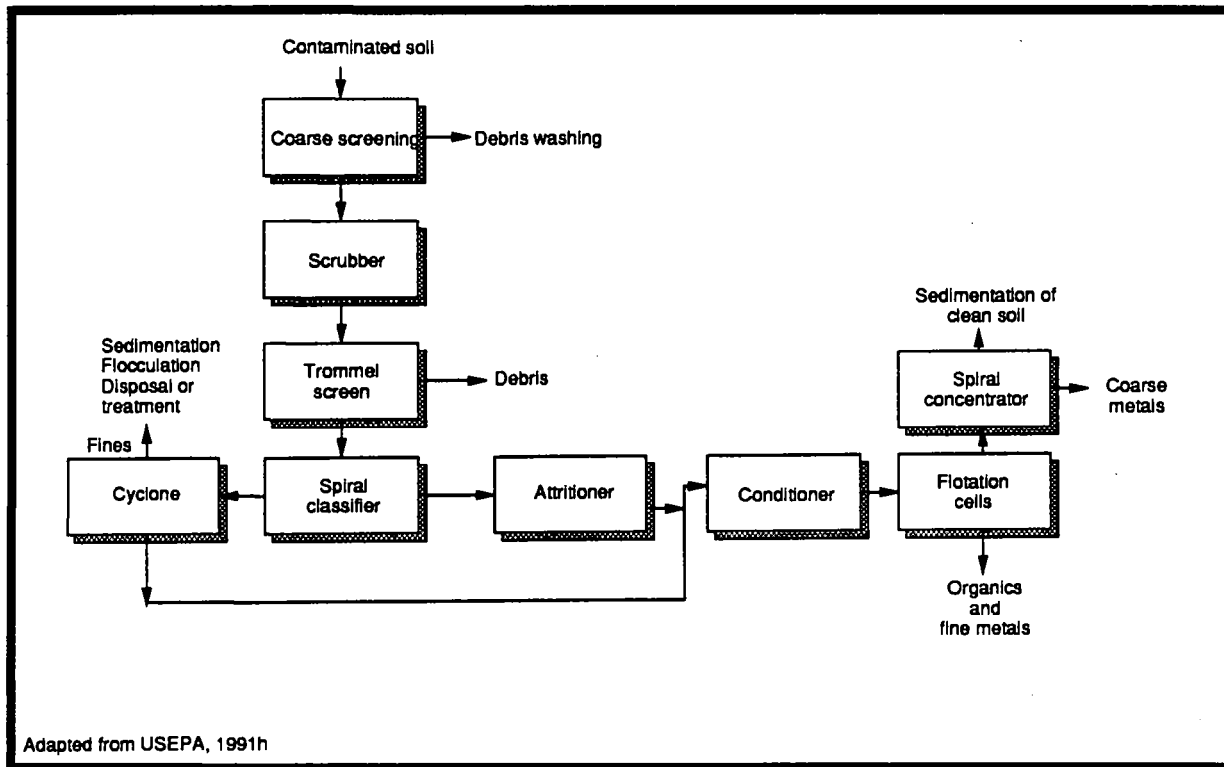
**4.4.2.2 Flotation.** Flotation has been used for more than seventy-five years in the mining industry to extract metals and is now more and more being used to treat soil contaminated by metals and organic compounds. Separation by flotation can take place naturally, without chemical or mechanical treatment, or as a result of physical and chemical treatment. In both cases, less dense matter floats to the surface where it can be skimmed off easily.



**Figure 4.15 Process scheme for soil washing using ultrasound, ultraviolet light and ozone**

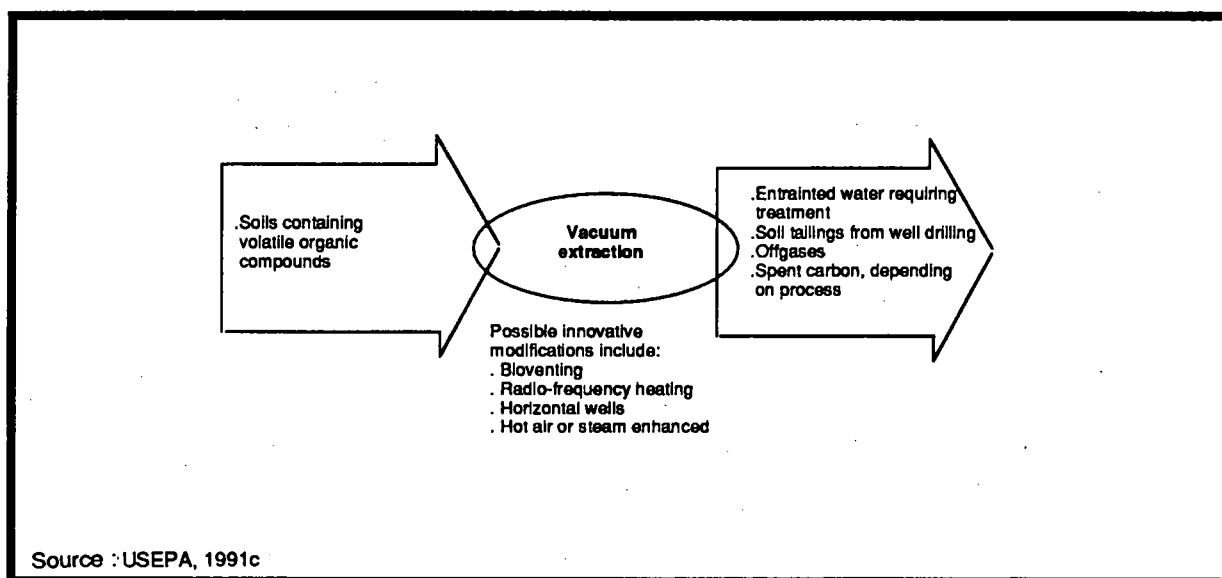
The principle of flotation is well known and is based on particle surface chemistry and electric double layer theory. Contaminated material is screened and then slurried in a tank. Air bubbles are injected into the solution to separate contaminants from soil. Chemicals are sometimes added to facilitate contaminant adsorption onto the air bubbles. The air bubbles with their adsorbed contaminants rise to the surface as foam that is then removed and treated. Energy requirements of this technology are low, and it can treat oils, halogenated organics, cyanides and heavy metals (Intera Kenting, 1990).

Figure 4.16 shows a flotation process scheme.



**Figure 4.16** Process scheme for soil washing by flotation

**4.4.2.3 Vacuum extraction.** With this technology, a vacuum is applied to a series of extraction wells to create air flow through the vadose zone (the zone just above the water table). As the air moves through the soil, it strips volatile contaminants from soil and pore water. Since the process draws volatile organic compounds from the soil, vapours withdrawn must be treated. Figure 4.17 shows process inputs and products as well as possible process modifications.

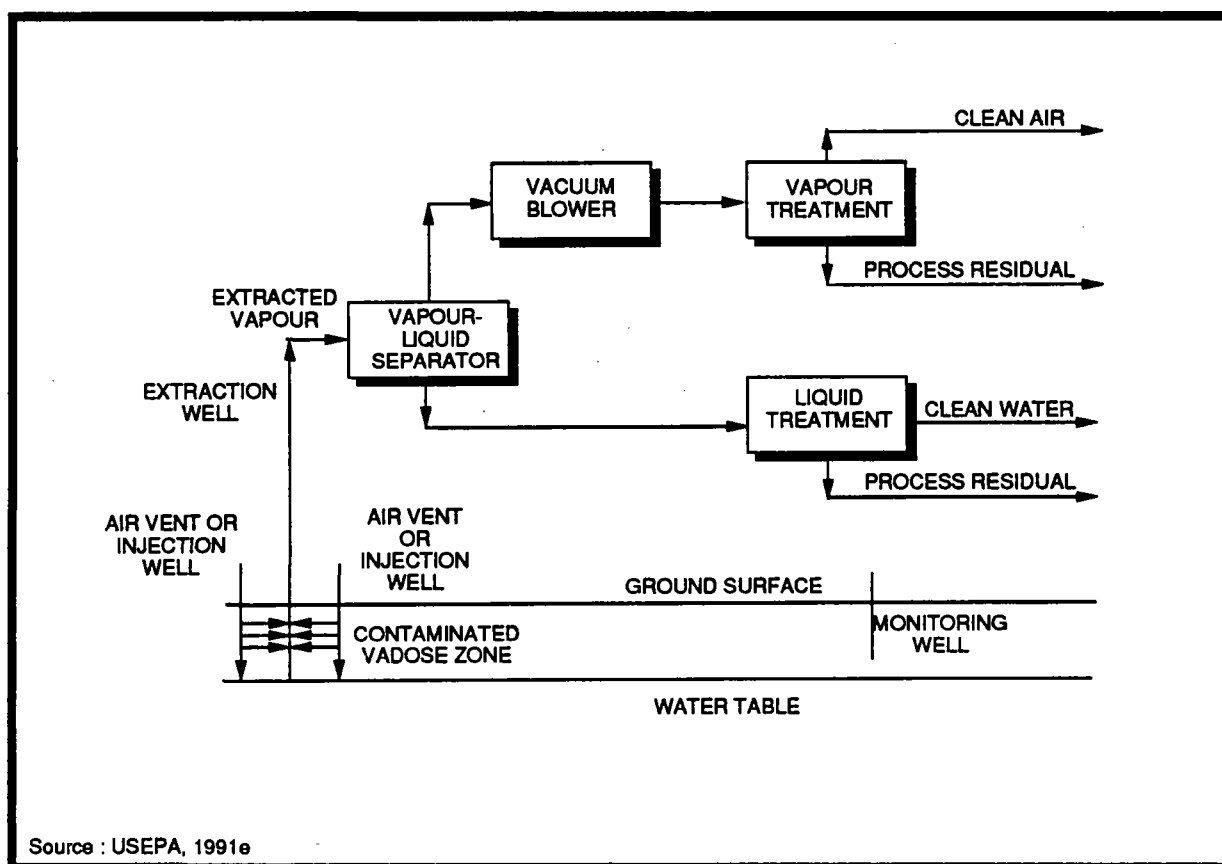


**Figure 4.17 Vacuum extraction inputs and products**

As Figure 4.17 shows, vacuum extraction efficiency can be thermally enhanced by injecting hot air or steam directly into the soil (to provoke vaporization of volatile and semivolatile organic compounds) or by radio-frequency heating, bioventing or injecting air in horizontal wells.

Figure 4.18 shows a vacuum extraction process scheme.





**Figure 4.18 Vacuum extraction process scheme**

As Figure 4.18 shows, vacuum extraction technologies require the following components in addition to an impermeable cap on the treatment site: air injection and extraction wells, underground pipe system in a permeable medium, vapour-liquid separator, vacuum blower, vapour and liquid treatment systems and monitoring well.

These technologies have limited applications for treatment of contaminated sediment.

**4.4.2.4 Solvent extraction.** Contaminants are dissolved in solvent which is then recovered and treated. When solvents are used to leach solid or sludge material, the process is called leaching (Manahan, 1990).

Solvent extraction technologies remove organic compounds rather than metals. These liquid-solid and liquid-liquid extraction processes are performed off site. They are based on the principle that it is easier to eliminate contaminants from solvents with treatment technologies available than to eliminate them from the original media. Solvents used depend on contaminants present, and the spent solvent solution must be treated. Temperature or pressure change is used to separate contaminants from the solvent, which is then recycled (USEPA, 1991c).

Figure 4.19 shows solvent extraction inputs and products.

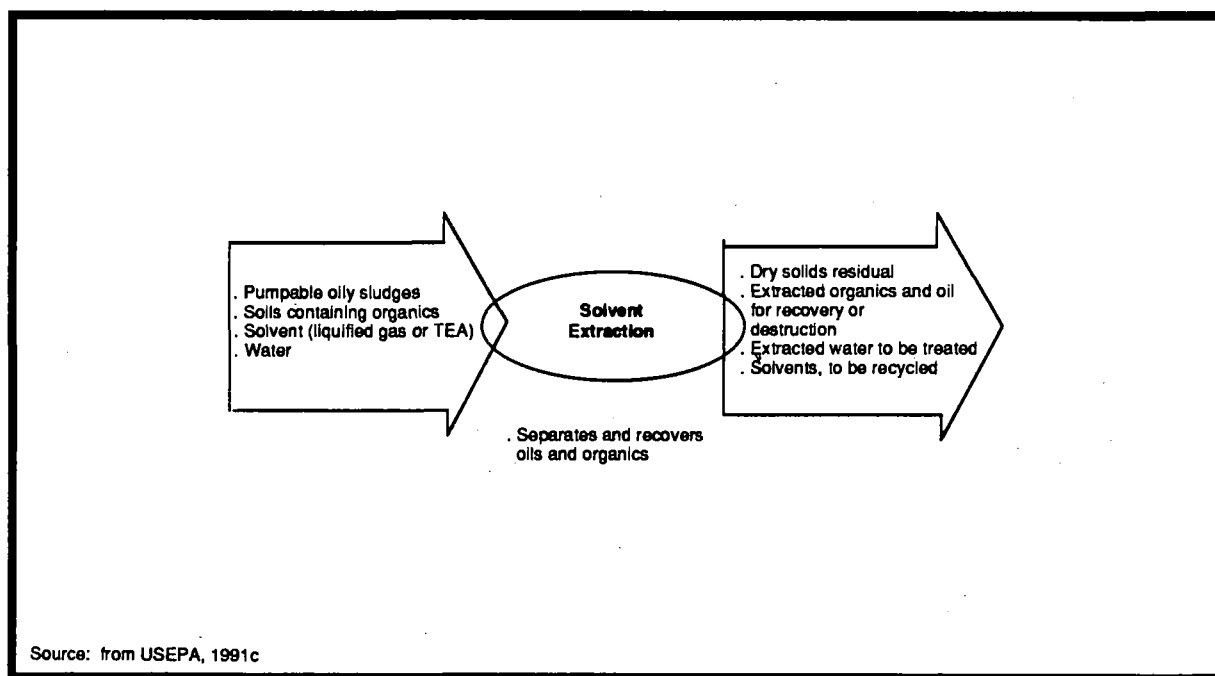


Figure 4.19 Solvent extraction inputs and products

Some solvent extraction processes use heat to promote separation. The acetone-kerosene extraction process developed by the Applied Science Department of New York University, for example, extracts PCBs and other organic contaminants from soil and sediment and concentrates the extract in preparation for chemical destruction. The process separates sediment into a liquid and a solid fraction. The solid fraction is leached with a hydrophillic solvent (acetone) which is then steam stripped from the sediment. The PCBs are treated with a hydrophobic solvent (kerosene) (Averett et al., 1990).

Figure 4.20 shows a solvent extraction process scheme.

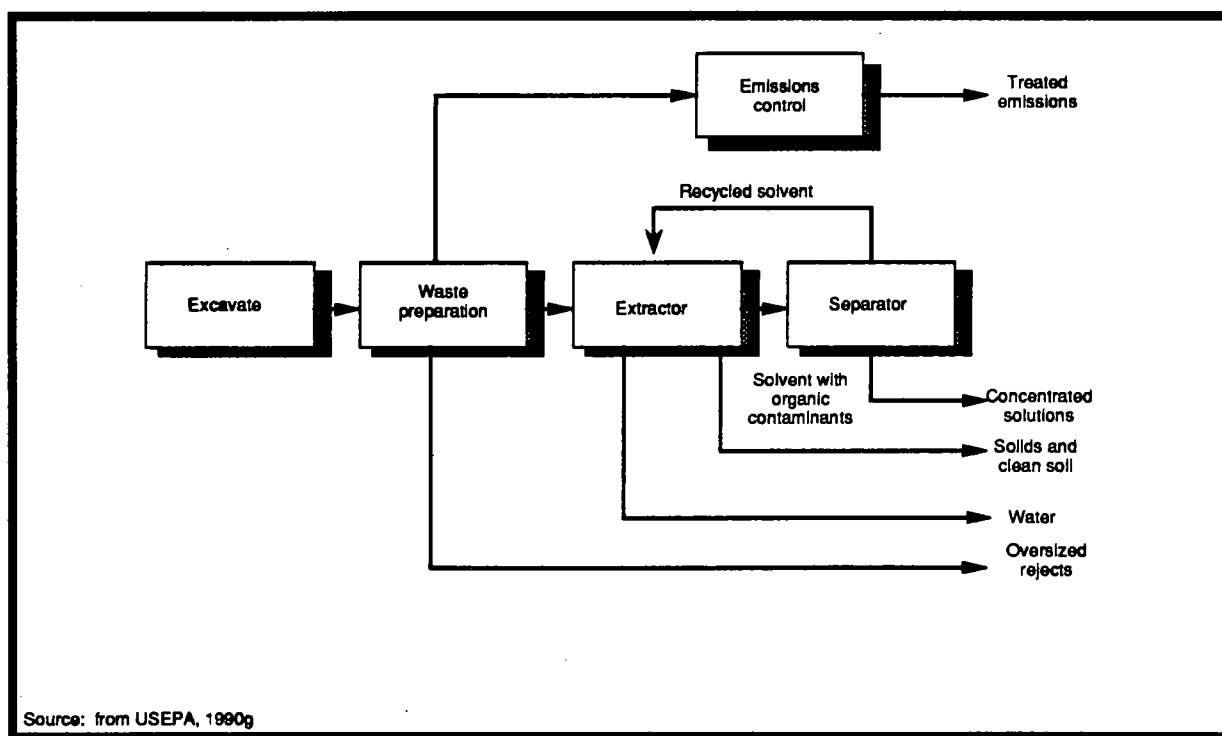


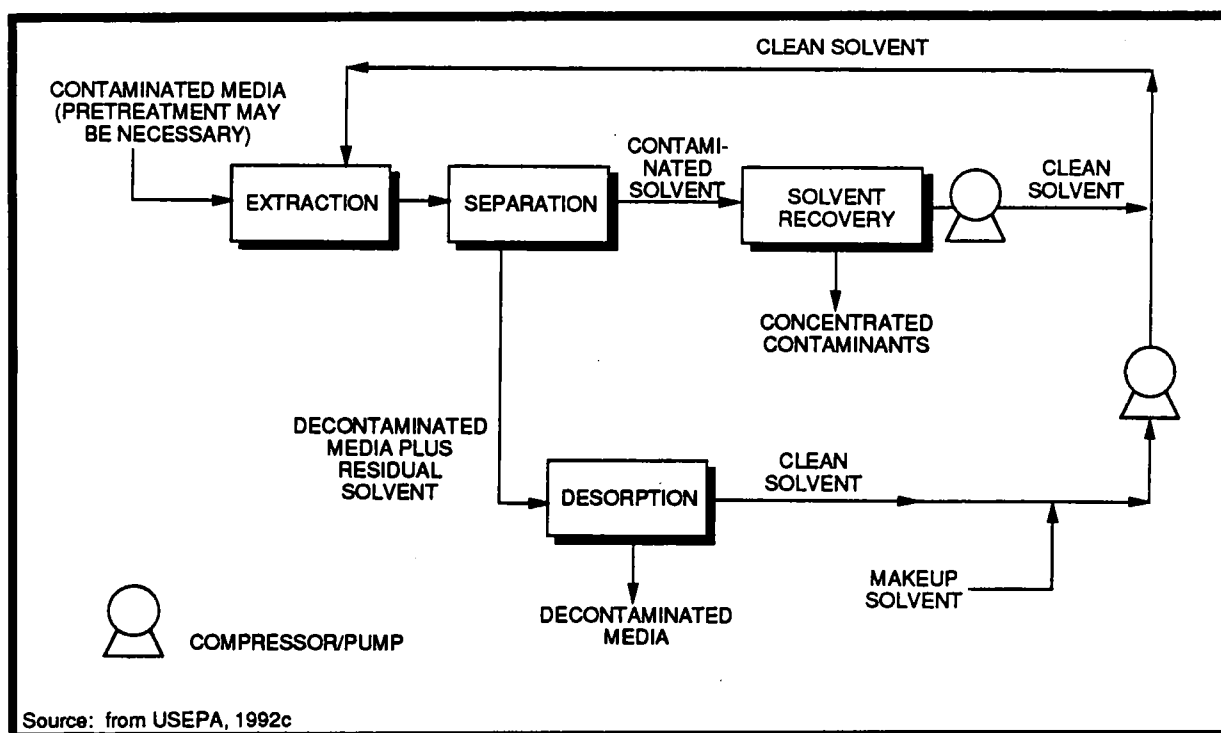
Figure 4.20 Solvent extraction process scheme

**4.4.2.5 Solvent extraction using critical fluid solvents.** One of the most promising approaches to solvent extraction and leaching of hazardous waste uses critical fluids as extraction solvents. Fluids such as carbon dioxide or light hydrocarbons (propane, for example) have properties of liquids as well as gases when at or above critical pressures and temperatures.

Carbon dioxide is commonly used as a solvent to treat wastewater because of its nontoxicity, nonflammability, low cost and low critical point. Light hydrocarbon gases are used as critical fluid solvents for treatment of contaminated soil (Intera Kenting, 1990).

A critical fluid is a fluid at or above its thermodynamic critical temperature and pressure such that density, viscosity, dielectric constant, diffusivity and other properties of the fluid are intermediate between those of a gas and those of a liquid. Under these conditions, variations in temperature and pressure can increase organic compound solubility in the solvent. Reducing temperature or pressure of the solvent-contaminant mixture following extraction results in phase separation of the solvent gas and the contaminant liquid or solid. The solvent gas is then recycled (Intera Kenting, 1990; USEPA, 1992e).

Figure 4.21 shows a critical fluid extraction process scheme.

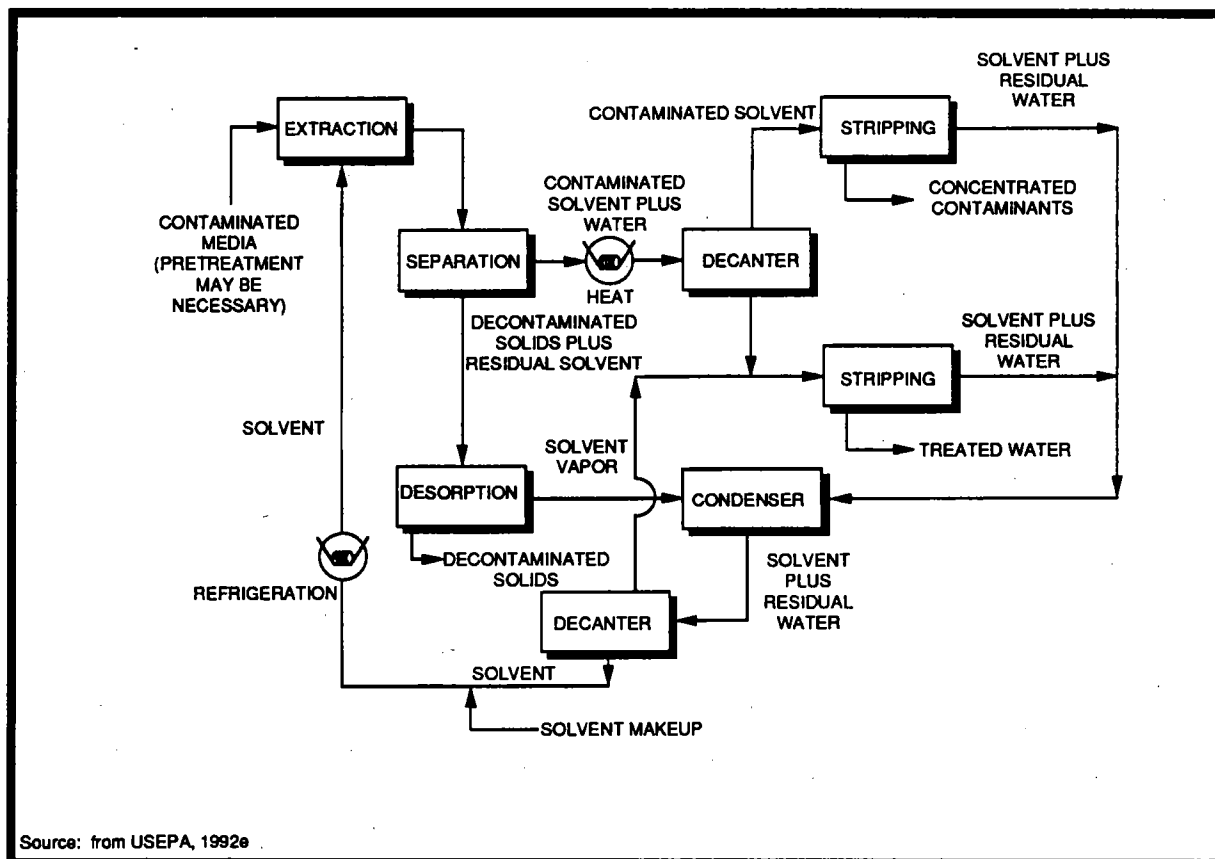


**Figure 4.21 Critical fluid extraction process scheme**

As Figure 4.21 shows, the technology essentially has four steps: solvent extraction, separation, desorption and solvent recovery.

Technologies using supercritical fluids have also been developed. The supercritical fluid most commonly used for extraction is carbon dioxide ( $\text{CO}_2$ ) at a temperature of  $31.1^\circ\text{C}$  and a pressure of 73.8 atmospheres. After a contaminant has been extracted with a supercritical fluid, pressure is dropped to separate contaminant and fluid. The fluid can then be recompressed and recirculated in the extraction system (Manahan, 1990).

Figure 4.22 shows a supercritical fluid extraction process scheme.



**Figure 4.22 Critical Solution Temperature (CST) extraction process scheme**

Supercritical fluid extraction technologies require fluid heating systems, stripping units, condensers and decanters in addition to the components required for critical fluid technologies.

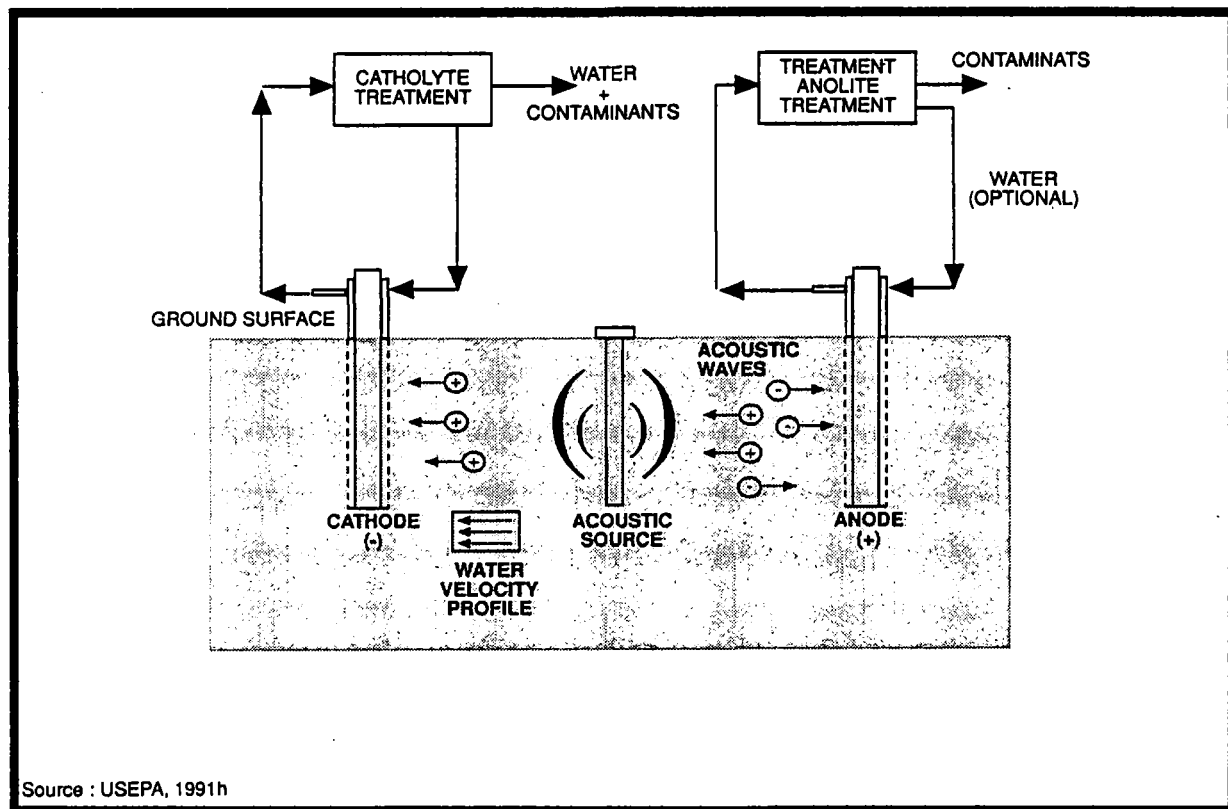
Intensive research over the last few years, generally with CO<sub>2</sub> as the supercritical fluid, has demonstrated the technology can be used for the following applications:

- Removal of organic contaminants from wastewater.
- Extraction of organohalogenated pesticides from soil.
- Extraction of oils from emulsions used in the aluminium and steel industries.
- Regeneration of spent activated carbon.

- Cleaning of used oil contaminated with PCBs, metals and water using ethane under supercritical conditions.

**4.4.2.6 Electric separation and electroacoustic decontamination.** These separation technologies use the principle of the electric field to move positive and negative ions through contaminated material so they can subsequently be removed. Treatment efficiency inevitably depends on the electric properties of the medium treated (USEPA, 1991h). Electroacoustic technologies apply a direct current field and an acoustic field to allow transport of liquids through solids (fine-grained soil).

Figure 4.23 shows the conceptual layout of an electroacoustic soil decontamination process, a technology patented by Batelle Memorial Institute.



**Figure 4.23** Conceptual layout of electroacoustic soil decontamination process

Contaminants that may be treated by electroacoustic soil decontamination include cadmium, chromium, lead, cyanide, chromate, and dichromate. Other effects that may occur during the reaction (besides ion displacement and movement to the electrodes) are ion exchange, development of pH gradients, electrolysis, gas generation, oxidation and reduction reactions, and heat generation. Application of an electric field increases leaching rate. The acoustic field enhances dewatering or leaching of contaminants (Averett et al., 1990).

These technologies are still in the design stage and have not been applied to in situ soil remediation or to contaminated sediment.

**4.4.2.7 Mechanical aeration/extraction.** Air is injected into contaminated soil to transfer volatile organics into the airstream, which is then treated in activated carbon canisters or water scrubbers, or incinerated in an afterburner. Mechanical aeration/extraction strips volatiles such as benzene, toluene, xylene, trichloroethylene, ketone and alcohol from soil. Heating the soil enhances removal of less volatile organics. Mechanical aeration/extraction processes may prove hard to use on contaminated sediment (Averett et al., 1990).

**4.4.3 Applications.** Extraction technologies which have been actively developed for contaminated soil can be selected for removal of organics or inorganics, but seldom can both types of compounds be removed simultaneously.

As Table 4.8 shows, in situ or off-site *soil washing* technologies can treat most organic, inorganic and reactive soil contaminants. Solvent extraction technologies are quite effective for treating most organic contaminants in soil, sludge and sediment but are not effective for metals and other inorganic and reactive compounds (oxidizers or reducers) in these media.



**Table 4.8 Effectiveness of extraction technologies on contaminant groups for different matrices**

Contaminant group	EFFECTIVENESS RATINGS*					
	Soil washing		Soil flushing	Solvent extraction		
	Sandy/ gravelly soil	Silty/ clayey soil	Soil	Soil	Sludge	Sediment
<b>ORGANICS</b>						
Halogenated volatiles	2	1	2	1	1	1
Halogenated semivolatiles	1	1	1	2	1	1
Nonhalogenated volatiles	2	1	1	2	2	1
Nonhalogenated semivolatiles	1	1	2	2	2	1
PCBs	1	1	1	2	2	2
Pesticides (halogenated)	1	1	1	2	1	1
Dioxins/Furans	1	1	1	1	1	1
Organic cyanides	1	1	1	1	1	1
Organic corrosives	1	1	1	1	1	1
<b>INORGANICS</b>						
Volatile metals	2	1	1	0	0	0
Nonvolatile metals	2	1	2	0	0	0
Asbestos	0	0	0	0	0	0
Radioactive materials	1	1	1	0	0	0
Inorganic corrosives	1	1	1	0	0	0
Inorganic cyanides	1	1	1	0	0	0
<b>REACTIVES</b>						
Oxidizers	1	1	1	0	0	0
Reducers	1	1	1	-	-	-

**\*EFFECTIVENESS RATINGS**

- 2 Good to excellent. High probability the technology will be effective.
- 1 Moderate to marginal or potential. Exercise care in choosing the technology. Expert opinion is that the technology will be effective.
- 0 Ineffective. Expert opinion is that the technology cannot be used to treat this type of waste or contaminant.
- X May have adverse effects.

Adapted from USEPA, 1991f; 1991c; 1992e

#### 4.4.4 Strengths, limitations and demonstrated applications of each technology.

Table 4.9 lists strengths, limitations, applications and demonstrations of fifteen physical and chemical technologies for extraction by washing, chelating agents, surfactants, acids or bases, solvents or flotation.

As the table shows, the main strengths of most of the extraction processes are that they can treat a wide range of organic as well as inorganic contaminants without air emissions that are difficult to control and that they can easily be accommodated on fixed or mobile units.

The main disadvantages of these technologies are the substantial sludge they generate, their limited efficiency when fine particles are present and the need to recover and treat spent washing or extraction solutions before disposing of them. Some technologies use flammable chemicals that pose a fire hazard, others require skilled operators. Also, some of the processes are relatively new and have not been demonstrated on a bench or pilot scale.

As Table 4.9 shows, many of the extraction processes are commercially available in Europe as well as in North America and have already been used at numerous sites to clean up soil contaminated with organics and inorganics.

In Europe, especially in the Netherlands, several companies have been offering commercial soil washing facilities for a number of years: Ecotechniek BV, Bodemsanering Netherlands BV, HWZ Bodemsanering BV, Heijman Milieutechniek BV and Hiedemij Froth Flotation in the Netherlands; and Harbauer & Bergmann in Germany (USEPA, 1991c).

The following U.S. vendors have the facilities to conduct pilot-scale tests or carry out soil remediation projects: MTA Remedial Resources Inc., Biotrol Inc., USEPA Risk Reduction Engineering Laboratory and Soil Cleaning Company of America Inc.

In Canada, pilot units combining soil washing technologies and extraction by chelating agents are currently under demonstration for treatment of soil in Ontario and Quebec: one such unit is produced by Tallon Metal Technologies Inc.; another was designed by SNC-Lavalin for the Toronto Harbour Commission.

Table 4.9 Strengths, limitations and contaminated-sediment applications of extraction technologies

Technology	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATIONS
Washing	<ul style="list-style-type: none"> <li>• Demonstrated technology. Commercial units available in Europe.</li> <li>• Can treat a wide range of soil and contaminants.</li> <li>• Enhancements allow treatment of fine particles.</li> <li>• No chemicals required.</li> </ul>	<ul style="list-style-type: none"> <li>• Treated soil and residues may remain difficult to dispose of due to presence of salts or metals.</li> <li>• Spent washing solution requires treatment before disposal.</li> <li>• Efficiency decreases with high fines content.</li> </ul>	<ul style="list-style-type: none"> <li>• Commercial units available in Europe (Netherlands, Germany).</li> <li>• Demonstrated on Superfund sites.</li> </ul>
Surfactant extraction	<ul style="list-style-type: none"> <li>• Can treat a wider variety of contaminants and remove a greater percentage of them than washing alone.</li> <li>• A wise choice of surfactant significantly enhances decontamination.</li> </ul>	<ul style="list-style-type: none"> <li>• Spent washing solution may be difficult to treat.</li> <li>• Not economical if high surfactant concentrations are required.</li> <li>• Many surfactants are themselves pollutants and restrictions may exist on in situ applications.</li> <li>• Limited application to soil of low permeability.</li> </ul>	<ul style="list-style-type: none"> <li>• Commercial units available in the United States and Canada.</li> <li>• Commercial units in operation for several years in Europe, particularly in Germany and the Netherlands.</li> <li>• As effective with metals as with organics.</li> </ul>
Acid/base extraction	<ul style="list-style-type: none"> <li>• Acids and bases are readily available and relatively inexpensive.</li> <li>• Chemical demands for this process are moderate.</li> </ul>	<ul style="list-style-type: none"> <li>• Large quantities of sludge generated when fine particles and humus are removed from soil.</li> <li>• Not recommended with high concentrations of organics (oily material or PAHs).</li> </ul>	<ul style="list-style-type: none"> <li>• At bench- or pilot-scale stage of development; two processes have been demonstrated full scale.</li> <li>• Some units used for remediation projects in the Netherlands.</li> <li>• Fines content in the soil should not exceed 20 percent.</li> </ul>
Chelating agents	<ul style="list-style-type: none"> <li>• Chelating agents are readily available and relatively inexpensive.</li> <li>• More suitable than acid/base extraction for certain types of contaminants.</li> <li>• Demonstrated effective for removal of metal.</li> <li>• Chelating agents have been used to remove radium (226) from contaminated soil in the laboratory.</li> </ul>	<ul style="list-style-type: none"> <li>• Hard to remove contaminants from very fine particles.</li> <li>• Relatively new process not yet fully demonstrated to determine to what substances it applies.</li> <li>• Chelating agents and carrier fluids must be treated.</li> </ul>	<ul style="list-style-type: none"> <li>• Demonstrated on a bench scale.</li> <li>• Processes demonstrated in England on remediation projects.</li> </ul>
Solvent extraction • B.E.S.T. process	<ul style="list-style-type: none"> <li>• Demonstrated technology and commercially available.</li> <li>• Suitable for fine grained materials.</li> <li>• Fixed or mobile units.</li> <li>• Air emissions are controllable.</li> </ul>	<ul style="list-style-type: none"> <li>• The solvent (TEA) is considered dangerous.</li> <li>• The solvent has an offensive odour.</li> <li>• Process water and residues require posttreatment.</li> <li>• Not very effective on coarse particles.</li> </ul>	<ul style="list-style-type: none"> <li>• Demonstrated for treatment of PCB-contaminated soil and sludge (full scale).</li> </ul>
Solvent extraction • Extraksol process	<ul style="list-style-type: none"> <li>• Demonstrated on a full scale for treatment of organic soil contaminants.</li> <li>• Closed system that minimizes or eliminates fugitive emissions.</li> <li>• Suitable for treating coarse and fine materials.</li> </ul>	<ul style="list-style-type: none"> <li>• Solvents used are extremely flammable.</li> <li>• Not effective on gravel with fine-particle porosity.</li> </ul>	<ul style="list-style-type: none"> <li>• Mobile pilot unit used to treat a wide variety of media and contaminants.</li> </ul>

**Table 4.9**      **Strengths, limitations and contaminated-soil applications of extraction technologies**  
(continued)

Technology	STRENGTHS	LIMITATIONS	Applications/demonstrations
Low energy solvent extraction process	<ul style="list-style-type: none"> <li>Operates at ambient temperatures.</li> <li>Simple and relatively inexpensive process using solvents and standard equipment.</li> </ul>	<ul style="list-style-type: none"> <li>Only demonstrated on a bench scale.</li> <li>Solvents used pose a fire hazard.</li> <li>Not very effective on large particles.</li> <li>Disposal or incineration of kerosene/organics phase likely to be expensive.</li> </ul>	<ul style="list-style-type: none"> <li>Pilot-scale demonstration on PCBs.</li> <li>Can treat a wide variety of volatile and semi-volatile organics.</li> </ul>
ENSR solvent extraction process	<ul style="list-style-type: none"> <li>Can remove a wide range of organics.</li> <li>No pretreatment required.</li> <li>Not affected by moisture or clay content.</li> </ul>	<ul style="list-style-type: none"> <li>PCB residues must be incinerated or otherwise treated.</li> </ul>	<ul style="list-style-type: none"> <li>Technology designed to treat PCBs but capable of treating a wide range of organic compounds.</li> <li>Processes demonstrated on pilot or bench scale.</li> </ul>
Carver-Greenfield process	<ul style="list-style-type: none"> <li>Has been applied to a variety of wastes from several industries including municipal wastewater sludge, paper mill sludge, and pharmaceutical plant sludge.</li> </ul>	<ul style="list-style-type: none"> <li>Energy intensive process involving evaporation, distillation and steam stripping which will escalate costs.</li> <li>Very complex process.</li> </ul>	<ul style="list-style-type: none"> <li>Bench-scale tested.</li> <li>Industrial applications demonstrated on a pilot scale.</li> </ul>
BP Oil solvent extraction process	<ul style="list-style-type: none"> <li>Treats organic and inorganic compounds simultaneously.</li> <li>Improves efficiency of fixation processes by removing organics from the soil/sludge.</li> <li>No uncontrollable emissions.</li> <li>Can be designed as a mobile or fixed system.</li> </ul>	<ul style="list-style-type: none"> <li>Has never been used for remediation.</li> <li>Residue is a solidified mass which must be landfilled.</li> <li>Inorganic constituents may make disposal difficult and expensive.</li> </ul>	<ul style="list-style-type: none"> <li>Pilot-scale tests performed at refineries.</li> <li>Full-scale tests under way.</li> </ul>
Accurex solvent extraction process	<ul style="list-style-type: none"> <li>Relatively simple process.</li> <li>Mobile or fixed units.</li> </ul>	<ul style="list-style-type: none"> <li>Uses highly volatile solvents requiring air emission control.</li> <li>Bench-scale tested only.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated on a bench scale for PCBs and hydrocarbons.</li> </ul>
Soilex process	<ul style="list-style-type: none"> <li>Insufficient information available to determine the advantages of this process.</li> </ul>	<ul style="list-style-type: none"> <li>New technology, tested on a pilot-scale only.</li> </ul>	<ul style="list-style-type: none"> <li>Insufficient information.</li> </ul>
Hot toluene extraction	<ul style="list-style-type: none"> <li>Air emissions are minimal and can be controlled.</li> <li>Very effective in removing hydrocarbons.</li> </ul>	<ul style="list-style-type: none"> <li>Safety hazard for operators (hot toluene).</li> <li>In pilot stage of development.</li> </ul>	<ul style="list-style-type: none"> <li>Used for hydrocarbons in separators and at the bottoms of tanks.</li> </ul>
CF Systems extraction	<ul style="list-style-type: none"> <li>Effectiveness of full-scale system very well-documented.</li> <li>Can treat a variety of media and contaminants.</li> <li>Possibilities for considerably reducing residue contamination.</li> <li>Air emissions highly unlikely and fugitive emissions are easily controlled.</li> </ul>	<ul style="list-style-type: none"> <li>Requires a completely enclosed system (tightly sealed pumps, tanks, vessels and piping) which can add considerably to costs.</li> <li>High pressure system requires trained operators.</li> <li>Wastewater must be treated.</li> </ul>	<ul style="list-style-type: none"> <li>Commercial system available.</li> <li>Tested for sediment, skimmers, tank bottoms, separators, paint waste, tar, synthetic rubber, used oil and soil contaminated with creosote, dioxins and furans.</li> </ul>
Flotation	<ul style="list-style-type: none"> <li>Used in the mining industry for several years.</li> <li>Used recently to treat soil contaminated with organics and heavy metals.</li> <li>High treatment capability and low use of energy.</li> </ul>	<ul style="list-style-type: none"> <li>May generate large quantities of sludge.</li> </ul>	<ul style="list-style-type: none"> <li>Commercial units available in the Netherlands since 1983.</li> <li>Can treat oils, HMA, organochlorine compounds, wax, paint waste, pesticides, cyanide, heavy metals, PAHs.</li> <li>Pilot-scale unit in Alberta.</li> </ul>

Adapted from CH2M Hill Engineering Ltd., 1991

The St. Lawrence Centre is funding demonstration of a technology that decontaminates soil by leaching hydrocarbons and pentachlorophenols under constant high pressure. The leaching is performed in a reactor called Hydromet developed by the firm Géocycle Inc.

The following U.S. and Canadian companies offer solvent extraction technologies: CF Systems Corporation (CF Systems process), Resources Conservation Company (B.E.S.T. process), Sanexen Environmental Services (EXTRAKSOL process), Dehydrotech Carver-Greenfield process), Harmon Environmental Services and Acurex Corporation (Acurex process), Applied Remediation Technology Inc. (LEEP process) and BP Oil (BP process).

**4.4.5 Strengths and limitations for sediment treatment.** Although extraction technologies have been used for a number of years to treat contaminated soil, their application to sediment has been limited to date to laboratory, bench-scale and pilot-scale projects--at least in North America (see Table 4.10). Until these technologies are applied to full-scale treatment projects, their feasibility for treating contaminated sediment cannot be properly assessed. This is why the USACE and the USEPA are conducting demonstration projects on contaminated sediment from the Great Lakes.

Since extraction technologies generally are not very efficient for treating soil with a high percentage of clay and silt--often the case with sediment--they may prove difficult to apply to sediment. The toxicity of residual solvents in sediment may also prove problematical.

**4.4.6 Technologies demonstrated for sediment remediation.** Table 4.11 lists extraction technologies demonstrated on different scales for treatment of contaminated sediment. The following paragraphs describe these technologies and, when available in the literature, give demonstrated treatment efficiencies.

Table 4.10 Anticipated performance of extraction technologies applied to sediment remediation

PROCESS	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABILITY	PERFORMANCE RATINGS**		
				Effectiveness	Implementability	Cost
<b>Acid leaching</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	3	2	2
<b>Acurex (hexane/feron)</b>	<b>Pilot</b>	<b>No</b>	<b>Proprietary</b>	3	1	2
<b>B.E.S.T. (TEA)</b>	<b>Demonstrated</b>	<b>Bench</b>	<b>Proprietary</b>	4	3	2
<b>Biotrol soil washing process</b>	<b>Pilot</b>	<b>No</b>	<b>Proprietary</b>	2	2	2
<b>CF Systems - CO<sub>2</sub></b>	<b>Pilot</b>	<b>No</b>	<b>Proprietary</b>	3	1	2
<b>CF Systems - Propane</b>	<b>Pilot</b>	<b>Pilot</b>	<b>Proprietary</b>	3	2	2
<b>CROW process</b>	<b>Conceptual</b>	<b>No</b>	<b>Proprietary</b>	2	1	2
<b>Electroacoustic soil decontamination</b>	<b>Conceptual</b>	<b>No</b>	<b>Emerging</b>	2	2	1
<b>EPA mobile soil washing unit</b>	<b>Pilot</b>	<b>No</b>	<b>Available</b>	2	2	2
<b>Harbauer semibatch soil washing</b>	<b>Pilot</b>	<b>No</b>	<b>Foreign</b>	3	1	2
<b>Harmon Env. Serv. soil washing</b>	<b>Bench</b>	<b>No</b>	<b>Proprietary</b>	3	1	2
<b>Heidemij mobile soil washing</b>	<b>Pilot</b>	<b>No</b>	<b>Foreign</b>	2	1	2
<b>In situ vacuum and steam</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	2	1	2
<b>Integrated vapour and steam vacuum stripping</b>	<b>Demonstrated</b>	<b>No</b>	<b>Proprietary</b>	2	1	1
<b>Low energy (acetone/kerosene)</b>	<b>Conceptual</b>	<b>Bench</b>	<b>Emerging</b>	3	2	2
<b>Mechanical aeration/extraction</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	2	2	2
<b>MTA remedial res. soil washing</b>	<b>Demonstrated</b>	<b>No</b>	<b>Proprietary</b>	2	2	2
<b>OH Materials (methanol)</b>	<b>Pilot</b>	<b>No</b>	<b>Available</b>	3	1	2
<b>Oil CREP (on site)</b>	<b>Pilot</b>	<b>No</b>	<b>Foreign</b>	2	1	2
<b>Soilex (kerosene)</b>	<b>Pilot</b>	<b>No</b>	<b>Available</b>	3	2	1
<b>Steam stripping</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	2	1	2
<b>Surfactants</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	3	2	2

## Notes

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

Adapted from Averett et al., 1990

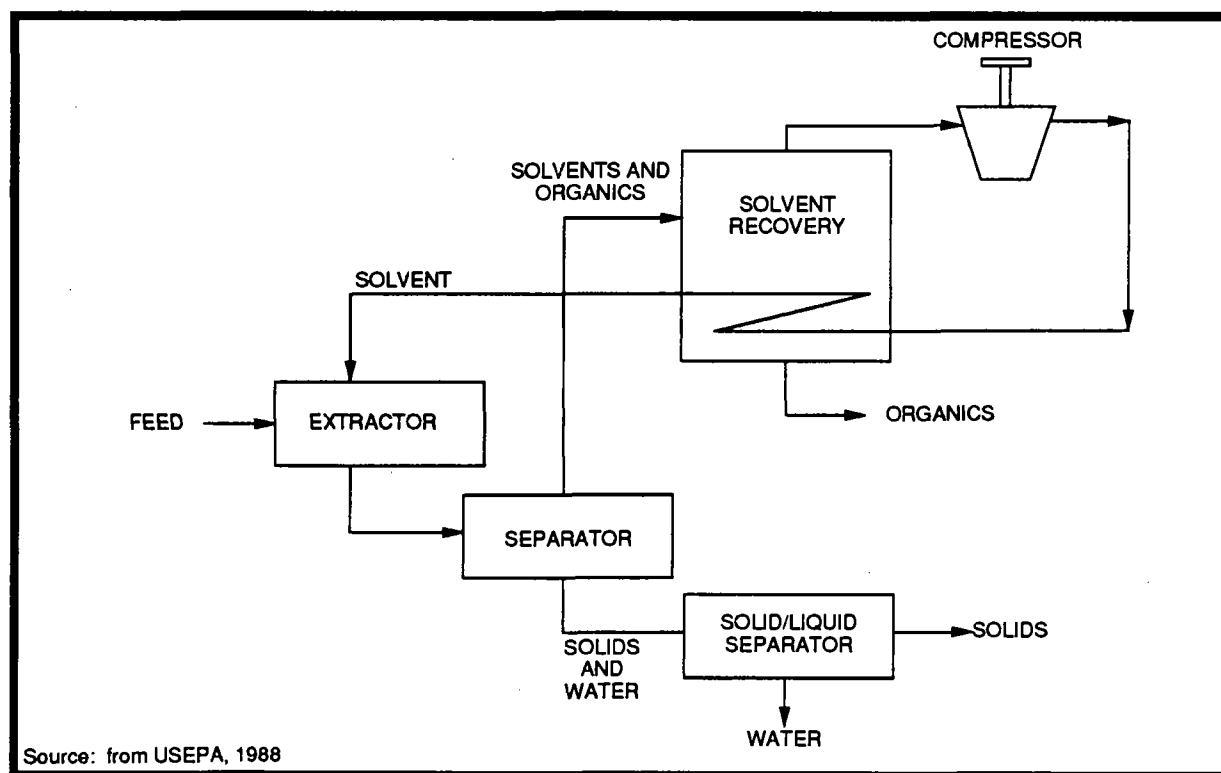
**Table 4.11 Extraction technologies demonstrated for sediment remediation**

Technology	Developer*	Place of Demonstration		Scale of Demonstration	Type of Contamination	Reference
		Country	Site			
Chemical extraction of organics • CF Systems	CF Systems Corporation	U.S.	New Bedford Harbour, MA	Pilot	PCBs, PAHs, VOCs, oils and greases	USEPA, 1991b Averett et al., 1990
Chemical extraction of organics • B.E.S.T.	Resources Conservation Corporation	U.S.	Hermantown, MN	Bench	PCBs, Hydrocarbons and organics with high molecular weight	USEPA, 1991b
		U.S.	New Bedford Harbour, MA	Bench	PCBs, PAHs, VOCs, oils & greases	Averett et al., 1990
		U.S.	Indiana Canal & Harbour, IN	Bench	PCBs	Averett et al., 1990
Chemical extraction of organics • LEEP	Art International Corporation	U.S.	Waukegan Harbour, IL	Bench	PCBs	Averett et al., 1990
Extraction by washing	Several treatment companies: Nine plants for sediment	Europe		Commercial	Metals and organics	Averett et al., 1990
Physical/chemical extraction • Flotation/ separation	Public Works and Water Management of the Netherlands	Netherlands	Geul Harbour, Oosterschelde, Apeldoorn Canal	Full	Heavy metals and organic contaminants	Dillen & Bruggeman, 1992

\* See Appendix C for telephone numbers and addresses of developers.

**CF Systems (propane).** CF Systems has developed a continuous system using compressed gases (carbon dioxide or propane) at critical pressures and temperatures to extract organic contaminants as varied as PCBs, PCPs, PAHs, fuels, oils, organic acids and chlorinated solvents. Operating pressures and temperatures are above critical point so the solvent displays physical properties between those of the solvent's liquid and gaseous states. The process can be used to treat soil as well as very fine particle wastes such as sediment and separator sludge. Heavy metals and inorganics are not amenable to treatment with this system (CH2M Hill Engineering Ltd., 1992).

Carbon dioxide is mainly used to treat aqueous solutions of hazardous solvents and oxygenated compounds. Propane is used to treat sediment, soil and sludge containing PCBs and other organics--carbon tetrachloride, chloroform, benzene, naphthalene, gasoline, grease, xylene, toluene, acetone, butanol, phenol, heptane and other alcohols (Averett et al., 1990).



**Figure 4.24** CF Systems critical fluid extraction process scheme



The contaminated soil or sediment is first screened to remove large particles and then, as Figure 4.24 shows, pumped to a series of extraction stages. Exact number of extraction stages depends on type of waste and degree of contamination. Compressed gas at or above critical point is injected into the reactor counter current. At the end of each extraction stage, the waste mixture is pumped to a decanter to separate the water-solid phase from the solvent-organic waste. Decanter effluent goes to a dewatering step (solid-liquid separator) where water is extracted and partially recycled into the process.

The cleaned soil or sediment is removed from the system. The solvent-organic phase is treated to remove water and then sent to a recovery step where the solvent is vaporized by releasing pressure and then recovered, recompressed and reused within the system. The liquid organic-contaminant fraction is removed and treated (CH2M Hill Engineering Ltd., 1992)

Pilot-scale tests were conducted on sediment from New Bedford Harbour, Massachusetts. Sediment containing 350 ppm PCBs were extracted to 10 ppm after ten passes through the unit. Extraction efficiencies of 90 to 98 percent were achieved on sediment with PCB concentrations of 350 ppm to 2 575 ppm. Laboratory tests showed 99.9 percent removal of volatile and semivolatile organics in aqueous and semisolid wastes. Treatment costs should range from US\$150 to US\$450 per ton (Averett et al., 1990).

Though PCB concentrations did not drop below 10 ppm, results were still well above acceptable levels according to the interim sediment quality criteria described in Chapter 2. Treated sediment will, nevertheless, have to be shipped to a containment site.

**B.E.S.T. process (Best Extraction Sludge Treatment).** The B.E.S.T. process, marketed by Resources Conservation Company, is a patented solvent extraction technology that uses triethylamine (TEA) as a solvent to extract organic compounds. TEA is an aliphatic amine produced when ethyl alcohol reacts with ammonia. The key to the B.E.S.T. process is TEA's inverse immiscibility: at temperatures below 18°C, TEA is completely soluble in water. Above 18°C TEA and water are only partially miscible. This means chilled TEA is simultaneously miscible with oil and water.

The flowchart illustrates the process of hazardous waste treatment, storage, and disposal. It begins with 'RAW WASTE' entering a dashed box labeled 'FRONTEND NEUTRALIZATION'. The output goes to 'SLUDGE STORAGE', then to a central unit labeled 'SOLVENT' which contains 'COLD END EXTRACTION' and 'HOT END SEPARATION'. This unit also receives inputs from 'POWER', 'STEAM', 'AIR', and 'INSTRUMENTATION' (grouped in a dashed box labeled 'PERIPHERAL UTILITIES') and 'COOLING WATER'. The 'SOLVENT' unit produces three outputs: 'WATER PRODUCT', 'OIL PRODUCT', and 'SOLIDS PRODUCT'. A legend indicates that dashed lines represent 'SITE SPECIFIC' components.

**Figure 4.25 B.E.S.T. extraction process scheme**

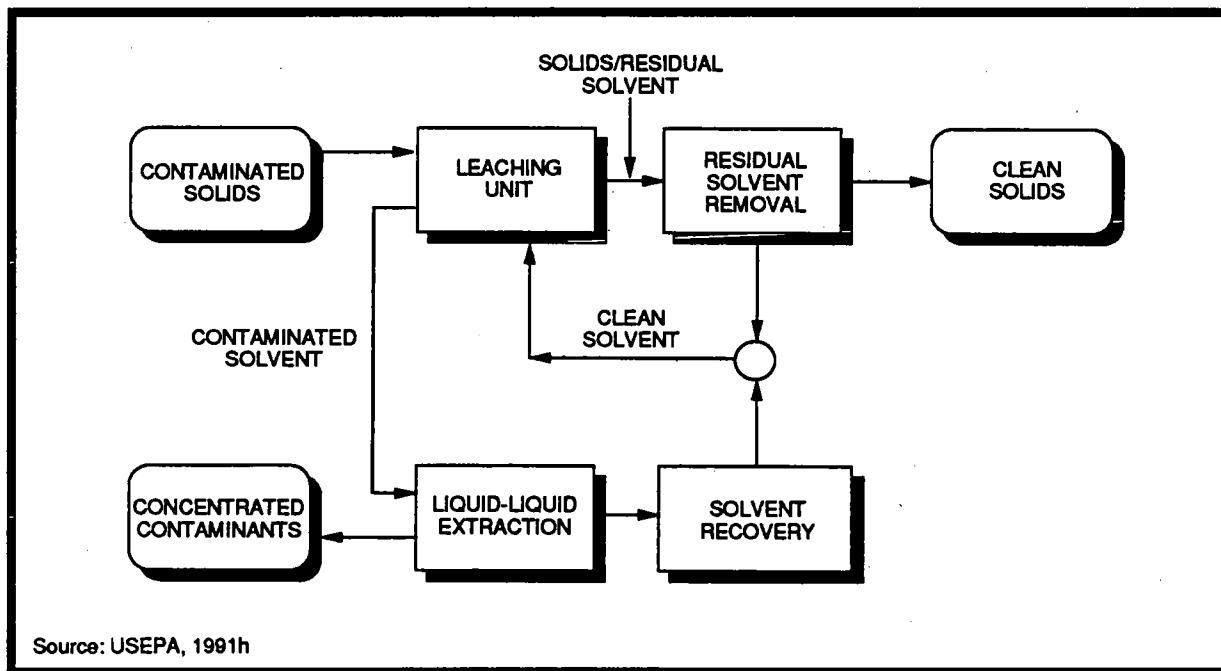
The B.E.S.T. process separates contaminants and sediment into three fractions: a solids fraction containing inorganic contaminants (such as heavy metals); an oil fraction containing organic contaminants (such as PCBs); and a water fraction containing other residual contaminants. The process does not by itself destroy contaminants, but it can substantially reduce the volume of sediment that must be treated. Biological treatment or carbon adsorption may be necessary to remove residual organics. If soluble metals are present, precipitation or other removal processes are required.

The B.E.S.T. technology was bench-scale tested on harbour sediment from New Bedford, Massachusetts. A PCB removal efficiency of 99.1 percent was achieved on moderately contaminated sediment (400 ppm PCB). Treatment costs were lowered by using centrifugation to minimize volume of feed material. Estimated cost for treatment of New Bedford Harbour sediment is US\$57 to US\$73 per cubic yard of sediment. The B.E.S.T. technology is also being considered for cleanup of the Hudson River, which is highly contaminated by PCBs (Averett et al., 1990).

The B.E.S.T. technology has also been bench-scale tested on sediment samples from the Indiana Harbour and Canal. A system designed to treat an average 520 cubic metres per day with peak throughput of 675 cubic metres per day should cost US\$133.30 per cubic metre to operate.

**Low Energy Extraction Process (LEEP).** This is a solvent extraction process that removes PCBs and some other organic contaminants. Solvents such as methanol yield satisfactory results, but even better results can be obtained with a mixture of solvents (acetone and kerosene, for example), depending on soil and contaminant characteristics.

Figure 4.26 shows a schematic of the technology.



**Figure 4.26 LEEP technology process schematic**

Studies on PCB-contaminated sediment from Waukegan Harbour, Illinois, confirmed the applicability of LEEP technology to this type of material. Cost of treatment with this acetone-kerosene extraction process is estimated at US\$41 per cubic yard of sediment using equipment with a throughput of 260 to 750 cubic yards of sediment per day (Averett et al., 1990).

**European soil washing plants.** Commercial soil washing plants have been treating soil contaminated by heavy metals and organics in Europe since 1982. Of seventeen plants in operation in 1991, nine were capable of treating contaminated sediment. Throughputs range from 10 to 130 tons of sediment per hour (USEPA, 1991b).

**Extraction technologies developed in the Netherlands.** Technologies that use solvents as extracting agents to remove heavy metals from sediment have been tested in the Netherlands. The following solvents have been used: hydrochloric acid (HCl), complexing agents and biologically produced sulphuric acid ( $H_2SO_4$ ).

The tests show that high removal rates can be achieved with these technologies and that aeration of the sediment-solvent mixture considerably accelerates the reaction and increases efficiency. These technologies require a lot of chemicals, however, and they generate residues contaminated by heavy metals which have to be treated before disposal.

Further research and design refinements are required before full-scale sediment cleanup demonstration projects can be undertaken (Dillen and Bruggeman, 1992).

**4.4.7 Technologies under demonstration for sediment treatment.** The USEPA and the USACE considered and evaluated twenty-one extraction technologies. Of these technologies, they recommended five for Great Lakes sediment remediation demonstration projects: acid leaching, B.E.S.T., CF Systems, low-energy and surfactant processes. As already mentioned, most of these technologies have already been conclusively demonstrated on contaminated sediment. Acid leaching was retained because of the limited availability of other processes for removing heavy metals from sediment.

Table 4.12 lists sites where demonstration projects have been conducted in the United States and specifies type of contamination at the site. The table also lists extraction technologies under demonstration in Canada through the Great Lakes Cleanup Fund.

Table 4.12 Extraction technologies under demonstration for Great Lakes sediment remediation

Technology	Developer*	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Chemical extraction of organics • B.E.S.T.	Resources Conservation Corporation	U.S.	Buffalo River Great Calumet River Saginaw Bay	Bench Bench/pilot Bench	PAHs PCBs, PAHs, oils & greases PCBs	USEPA, 1992a
Chemical extraction of organics • Acetone	Ram-Tech	U.S.	Sheboygan Harbour	Bench	PCBs	USEPA, 1992a
Aqueous surfactant extraction	Not specified	U.S.	Sheboygan Harbour	Bench	PCBs	USEPA, 1992a
Physical/chemical extraction • Bergmann	Bergmann USA Inc.	U.S.	Buffalo River Great Calumet River Saginaw Bay	Bench	PAHs PCBs, PAHs, oils & greases PCBs	USEPA, 1992a
		Canada	Toronto Harbour	Pilot		Environment Canada, 1993
Chelation • Metanetix	Toronto Harbour Commission	Canada	Toronto Harbour	Pilot	Heavy metals	Environment Canada, 1993
Sequential leaching • Beak	Beak Consultants Ltd.	Canada	Welland Canal	Bench	PAHs	Environment Canada, 1993
Washing • Biogenesis	BioGenetics Enterprises Inc.	Canada	Thunder Bay Harbour	Bench	PAHs, creosotes and phenols	Environment Canada, 1993
Washing • ALTECH	ALTECH Consulting Ltd.	Canada	Welland Canal	Bench	PAHs	Environment Canada, 1993
Metal leaching • COGNIS Terra Met	COGNIS Inc.	Canada	St. Marys River	Bench	Heavy metals	Environment Canada, 1993
Metals extraction • Tallon	Tallon Metal Technologies Inc.	Canada	Hamilton Harbour	Bench/Pilot	Heavy metals & hydrocarbons	Environment Canada, 1993

\* See Appendix C for telephone numbers and addresses of developers.

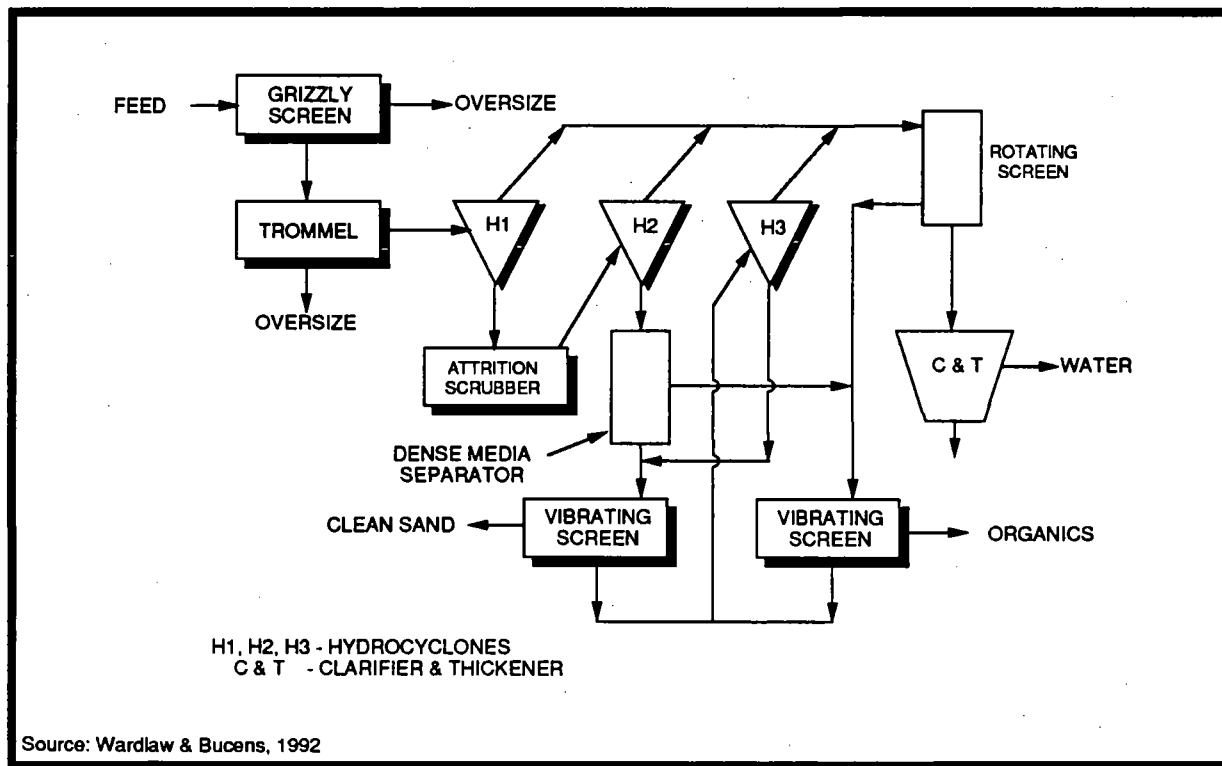
The B.E.S.T. process has already been described (section 4.4.6). Other solvent extraction technologies under demonstration for remediation of Great Lakes sediment are similar. These are briefly described below.

**Bergmann washing process.** Bergmann USA is a subsidiary of the Dutch firm Bergmann B.V. which owns a number of commercial soil washing facilities in Europe. The U.S. subsidiary has already conducted several demonstration projects in the U.S. and Canada with facilities capable of processing 5 to 10 tons per hour.

The Bergmann soil washing process uses physical and chemical separation technologies to remove organic and inorganic contaminants from soil or residues. The process reduces the volume of contaminated soil by about 80 percent.

The technology is based on the assumption that most sediment contaminants are concentrated in two fractions--organic matter (leaves, roots and so forth) and fine particles (less than 63 microns)--and that the larger granular- particle fraction (clean sand and gravel) is generally less contaminated (USEPA, 1992c).

Figure 4.27 shows a soil washing process scheme.



**Figure 4.27** Bergmann soil washing process scheme

The sediment is first run through a grizzly screen and a Trommel to separate out particles of more than 6 mm. It is then passed through three hydrocyclones in series. A dense media separator facilitates removal of organic particles (specific gravity less than 1.6) from the sandy fraction. An attrition scrubber releases contaminants bound to the surface of grains of sand by causing particles to scrub against one another. Surfactants, acids and bases can be added in the scrubber to facilitate contaminant desorption. Lastly, vibrating and rotating screens separate clean sand and organics, and a clarifier separates fine particles by flocculation with polymers (USEPA, 1992c).

The Bergmann process can be used to remove organics as well as inorganics from soil and sediment with a clay-and-silt content of less than 40 percent and an organic-solids content of less than 20 percent.

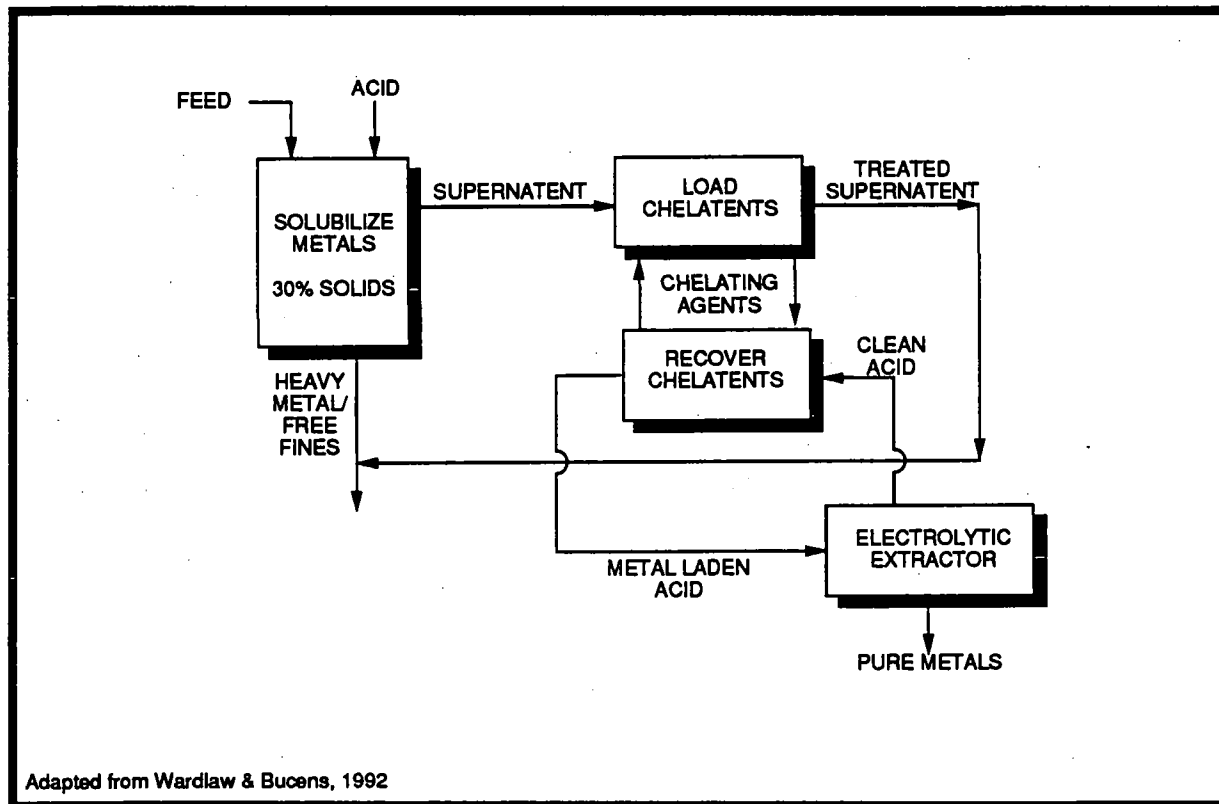


As Table 4.12 indicates, the Bergmann process has been tested in the United States on sediment from Saginaw Bay, Lake Huron, Michigan, and in Canada on sediment from the Toronto Harbour. Test results will be available in 1993.

**Metanetix process.** This process was developed by DeVoe Environmental Laboratories to extract metal from incinerator ash and other solid mineral matrices. Worldwide rights to the technology now belong to the Toronto Harbour Commission.

The Metanetix process is capable of selective and nonselective extraction of heavy metals. The process solubilizes metals bound to the contaminated solid matrix and then extracts the metal ions (hydroxide, oxide) from solution using chelating agents. The acidification and chelation steps are designed for maximum removal of target metals and minimum effect on metals deemed inoffensive. The innovative aspects of the process are its patented chelating agents and reactor design (Wardlaw and Bucens, 1992).

Figure 4.28 shows a schematic of the Metanetix metal extraction process.



**Figure 4.28 Metanetix process scheme**

As Figure 4.28 shows, fine sludge is sent first to primary reactors where it is mixed with selected acids (to solubilize metals) and with a chelating agent (to complex the metals once they are solubilized). Acids and acid concentrations are chosen to maximize heavy metal extraction without dissolving metals not considered contaminants.

The solubilized metals are then pumped into the metal adsorption reactor where the sludge comes in contact counter current with the chelating agent. The sludge leaves the reactor free of heavy metals, but the chelating agent leaves the reactor laden with them. The metal-laden chelating agent passes through a regeneration reactor where it comes in contact with regenerating acids that solubilize the heavy metals until the chelating agent is completely regenerated. The heavy metals are then recovered electrolytically (SNC-Lavalin, 1992). If metal concentrations are high enough, a pure metal byproduct can be obtained (Wardlaw and Bucens, 1992).

As Table 4.12 indicates, many other extraction technologies have been bench-scale tested under the Contaminated Sediment Treatment Technology Program of the Great Lakes Cleanup Fund. The following sections briefly describe technologies for which test results are to be published in the very near future.

**Sequential Metal Leaching System (SMLS).** The Sequential Metal Leaching System, developed by Beak Consultants Ltd. and Guelph University, Ontario, was bench-scale tested on Hamilton Harbour sediment. The process extracts metals by sequential leaching with an oxidizing agent, hydrochloric acid and a chelating agent such as ethyl diamine tetra acetic acid. The leaching agents are placed in contact with the sediment in a slurry reactor. After each leaching stage the slurry is dewatered (Wastewater Technology Centre, 1992a).

**Biogenesis soil washing process.** Developed by the U.S. firm BioGenesis Enterprises Inc. to treat organic compounds, this soil washing process uses patented chemicals, a specialized truck, oil-water separators, filters, a bioreactor and water. The patented chemicals encapsulate hydrocarbons and enhance their bioavailability. Oils freed from the soil may be reclaimed, and the oil/water/fines slurries are processed in the filters and a bioreactor (for coarse material) or in hydrocyclone separators and a three-phase centrifuge (Wastewater Technology Centre, 1992a).

Throughput is 25 tons to 30 tons per hour when feed is soil contaminated by 5 000 ppm hydrocarbons. A single washing removes 85 to 99 percent of hydrocarbons when contaminant concentrations do not exceed 15 000 ppm. Several washing cycles are required when contamination levels are higher. As Table 4.12 indicates, the process was bench-scale tested on Thunder Bay Harbour sediment highly contaminated by creosotes, chlorophenols and HAPs (Environment Canada, 1993).

**Altech Mobile Soil Washer.** A commercial mobile soil washer developed by ALTECH Consulting Ltd. of Willowdale, Ontario, to treat organic and inorganic contaminants was bench-scale tested on sediment from the Welland Canal, Ontario (Environment Canada, 1993.) The process uses vigorous mechanical agitation of slurry to extract adsorbed

contaminants from particles. This is followed by solid/liquid separation and treatment of the water phase. Carbon adsorption units control emissions of VOCs. (Wastewater Technology Centre, 1992a).

**COGNIS TerraMet™ metal extraction unit.** The COGNIS TerraMet™ technology is a two-stage process designed to treat contaminated soil, sediment and so forth containing metals and organics (Environment Canada, 1993). Metals are first removed with leaching agents either by reduction or by ion exchange. The process is designed so that both leachant and extractant are fully regenerated and recycled. Organic contaminants are destroyed by bioremediation in a bioreactor or, when conditions are favourable, by landfarming or composting (Wastewater Technology Centre, 1992a).

The process has been bench-scale tested for different matrices, including mercury-contaminated soil and soil from battery recycling sites, zinc works, munitions testing sites, and spent oil recycling plants. Metals treated include cadmium, copper, mercury, lead and zinc. The process was bench-scale tested on sediment from the Saint Marys River in Ontario (Environment Canada, 1993).

**Tallon Metal Technologies extraction facility.** The firm Tallon Metal Technologies Inc. of Guelph, Ontario, has a commercial unit for extracting metals from soil or liquids. The process employs a series of extraction and hydrometallurgic recovery systems that use a combination of nontoxic organic and inorganic leaching agents with adsorbents called Vitrokele™ (Wastewater Technology Centre, 1992a). This technology has been used in the mining and plating industries and is now under demonstration on a bench-scale and a pilot scale on sediment from Hamilton Harbour (Environment Canada, 1993).

According to the USEPA and the USACE, demonstration projects have been undertaken with these washing processes because technical feasibility of most extraction processes is hard to evaluate for want of real-scale remediation projects. Demonstration projects should identify problems with sediment handling, solvent recovery and residual solvent toxicity. Costs are not well documented but are expected to exceed US\$100 per cubic yard (Averett et al., 1990).

**4.4.8 Technologies recommended for sediment remediation projects.** In 1990, soil washing technologies were selected for soil remediation at sixteen U.S. Superfund sites contaminated by at least one of the following: PAHs, PCPs, metals, lead, pesticides and VOCs. Of the sixteen sites, five also contained contaminated sediment (USEPA, 1991b). Table 4.13 briefly describes these sites.

Solvent extraction technologies were selected for seven contaminated soil remediation projects between 1982 and 1990. Contaminated sediment was present at one of the seven sites (Table 4.13).

**4.4.9 Conclusions.** As the preceding sections show, physical and chemical extraction technologies can easily be developed for mobile or fixed facilities. Extraction technologies can remove organic contaminants as well as heavy metals from sediment without air emissions that are difficult to control. With most processes, multiple extraction cycles may nevertheless be required to achieve high removal efficiencies, especially when the soil or sediment contains a high percentage of silt or clay.

Because extraction technologies concentrate contaminants in a small volume of matrix to be treated, they can have many applications for contaminated sediment treatment, which usually entails treating large volumes of material with relatively low concentrations of contaminants. The residual volumes generally have to be treated by destructive technologies (incineration, for example) in the case of organic contamination, or by immobilization technologies, where heavy metals are present. Some advanced technologies (the Metanetix process for example) use chelating agents to extract and recover metals from contaminated sediment.

To date, extraction technologies have been applied to contaminated sediment only in the laboratory and on a bench and pilot scale, at least in North America. Though there are a number of commercial units in Europe capable of treating sediment, they do not seem to be commonly used for sediment remediation. Until extraction technologies are used for projects that call for clean up of thousands of cubic metres of sediment, their technical, economic and environmental feasibility will remain hard to evaluate.

Table 4.13 U.S. Superfund sediment remediation projects using extraction technologies

Site name & state	Technology	Site description	Media (quantity)	Key contaminants treated	Status	Contacts/phone
King of Prussia, NJ	Washing	Recycling facilities	Soil, sediment & sludge (20 150 cy*)	Metals (chromium, copper, silver)	Design in summer 1993	Jim Hahnenberg 212-264-5387
Myers Property, NJ	Washing preceded by dechlorination	Pesticide manufacturing	Soil & sediment (50 000 cy)	Metals (aluminium, cadmium, silver, chromium, sodium)	Predesign	John Prince 212-264-1213
Vineland Chemical, NJ	Washing	Pesticide manufacturing	Sediment (62 600 cy)	Arsenic	Predesign	Matthew Westgate 212-264-3406
United Scrap Lead, OH	Washing	Battery recycling	Sediment (45 500 cy) soil (45 500 cy)	Lead, arsenic	Design	Anita Boseman 312-886-6941
Koppers (Oroville Plant), CA	Washing	Wood treating	Soil & sediment (200 000 cy)	PAHs, SVOCs (PCPs), dioxins	Design in summer 1992	Fred Schauffler 415-744-2365
O'Connor, ME	Solvent extraction	Recycling electric transformers	Soil & sediment (23 500 cy)	PCBs, PAHs, lead	Design in spring 1993	Mike Jasinski 617-573-5786

\* cy: cubic yard

Adapted from USEPA, 1991c

## 4.5 Chemical treatment

**4.5.1 Principle of treatment.** Chemical treatment technologies use chlorine displacement, oxidation, or reduction to destroy, detoxify or remove contaminants found in contaminated media.

Chemical treatment technologies include oxidation-reduction, dechlorination, hydrolysis, electrolysis and photolysis.

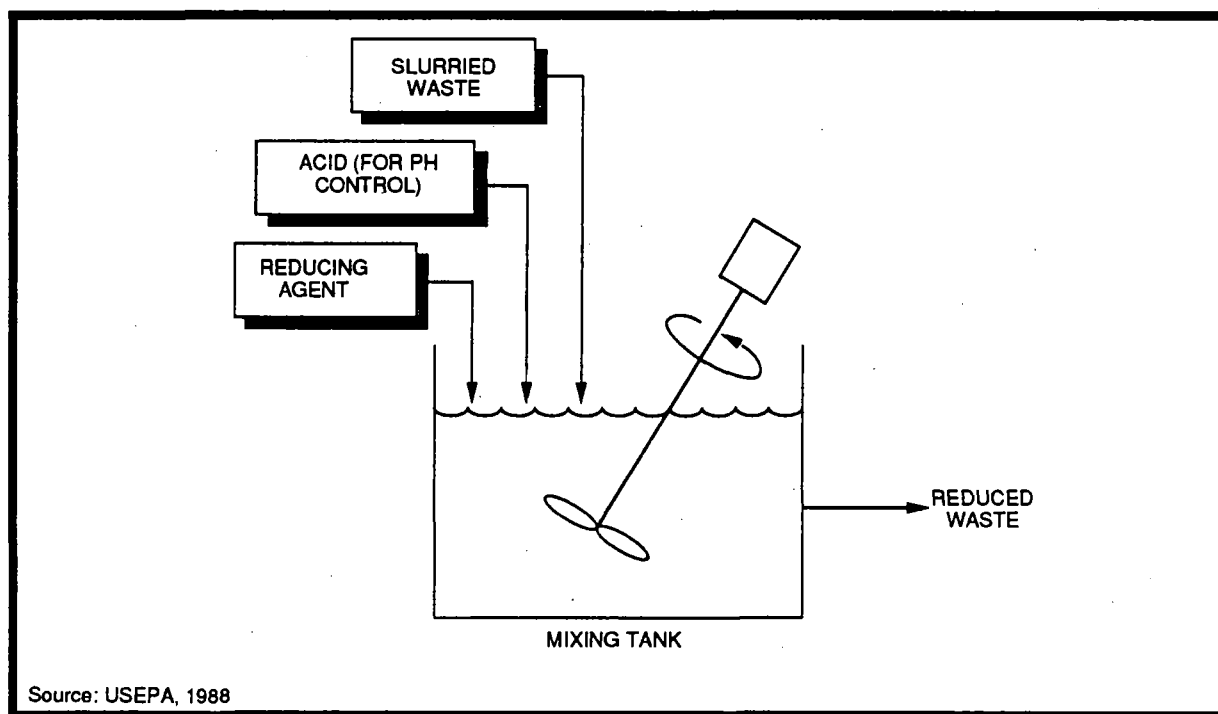
According to Manahan (1990), application of chemical treatment technologies to waste cleanup depends on the chemical properties of the contaminants in the waste media: acid-base, precipitation and complexing properties as well as redox potential, reactivity, inflammability/combustibility, corrosivity and compatibility with other contaminants. These properties and possible chemical reactions significantly affect selection of any of the following methods of chemical treatment:

- Acid/base neutralization.
- Chemical precipitation.
- Chemical flocculation.
- Oxidation.
- Reduction.
- Chemical extraction and leaching.
- Ion exchange.

## 4.5.2 Available technologies

**4.5.2.1 Reduction/oxidation.** Chemical reduction/oxidation reactions (redox) can be used to destroy hazardous compounds or to convert them to less toxic substances. When waste contaminant and reagents react, oxidation level of one substance increases and that of another decreases.

The redox process consists of pH adjustment, addition of reducing agents, mixing and treatment to remove or precipitate oxidized or reduced products. Figure 4.29 shows inputs and products of redox processes.



**Figure 4.29 Inputs and products of chemical reduction/oxidation**



The redox process is often used to *reduce* hexavalent chromium ( $\text{Cr}^{+6}$ ) to trivalent chromium, which is less toxic and easier to chemically precipitate. The process is also used to treat waste contaminated by mercury, silver or lead. Common reducing agents include alkali metals (sodium or potassium), sulphur dioxide, sulphite salts, ferrous sulphate, iron, aluminum, zinc, and sodium borohydrides.

Chemical *oxidation* is used mainly to treat cyanides and wastewater containing oxidizable organics such as aldehydes, mercaptans, phenols, benzidine, unsaturated acids and certain pesticides. The main commercially available reagents are potassium permanganate, hydrogen peroxide, hypochlorites and chlorine gas.

Figure 4.30 shows a chemical oxidation process scheme.

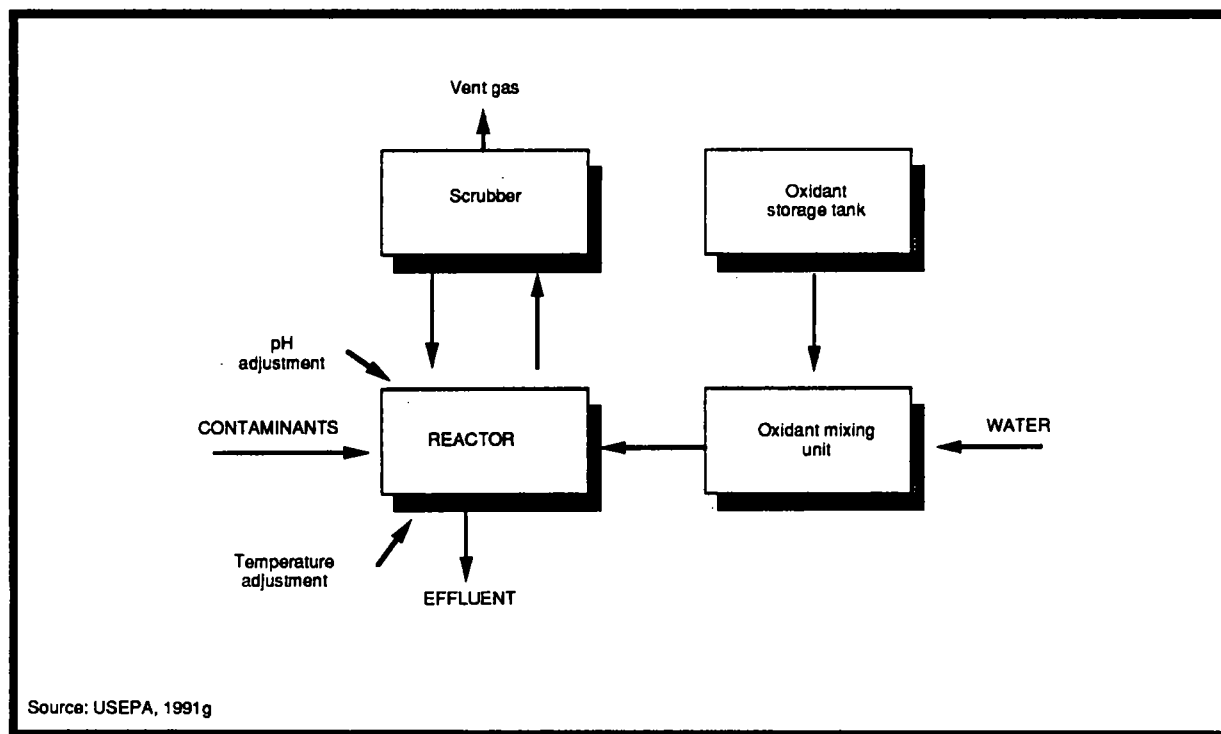


Figure 4.30 Chemical oxidation process scheme

The redox process generates solid/liquid effluents that must be treated by one or more of the following processes: chemical precipitation, filtration, sedimentation, evaporation, biological treatment or activated carbon adsorption. Since hydrochloric acid is sometimes produced when chlorinated organics are treated, leaching tests must be performed on solid residues to determine whether stabilization is required before disposal.

Chemical oxidation of organics is a technology that transforms, degrades or immobilizes contaminants in soil by removing electrons to increase the oxidation state of an atom. Complete contaminant degradation (to carbon dioxide and water) depends on oxidant concentrations, pH, oxidation potential and formation of stable intermediates. Toxic products may form if the reaction is not completed.

Oxidation may be used as a pretreatment to biological treatment of waste streams containing oxidizable organics such as aldehydes, phenols, and benzidine. Oxidation has limited application for slurries, tars and sludge.

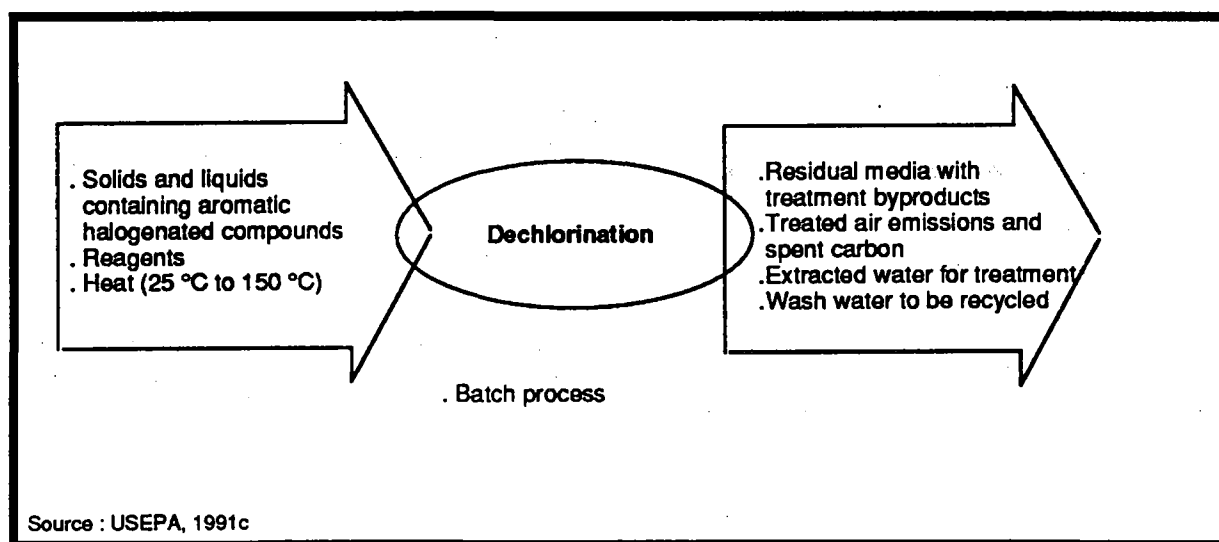
Organic contaminants in soil and groundwater can be oxidized in situ by using strong reagents such as ozone and hydrogen peroxide. Other reagents such as calcium hypochlorite, potassium permanganate, sodium hypochlorite, fluorine and chlorine gases can also be used. These oxidants can be applied in water solutions by spreading them directly on the soil surface, injecting them into the subsurface, or placing them in injection wells. These options are adaptable to dredged material in confined disposal facilities.

**4.5.2.2 Dechlorination.** Dechlorination includes any nucleophilic substitution chemical technology that removes or replaces chlorine atoms in hazardous compounds. Hazardous chlorinated compounds formed during the reaction may have to be treated subsequently.

Nucleophilic substitution can be used in waste treatment to chemically remove chlorine from organic (aromatic) compounds using the electron donating principle under favourable conditions. Since nucleophilic substitution depends upon high pH, the reaction should proceed in alkaline conditions. The most effective nucleophilic substitution agents are

undoubtedly alkali metal hydroxides in polyethylene glycol (APEG) or in polyethylene glycol methyl ether (APEGM).

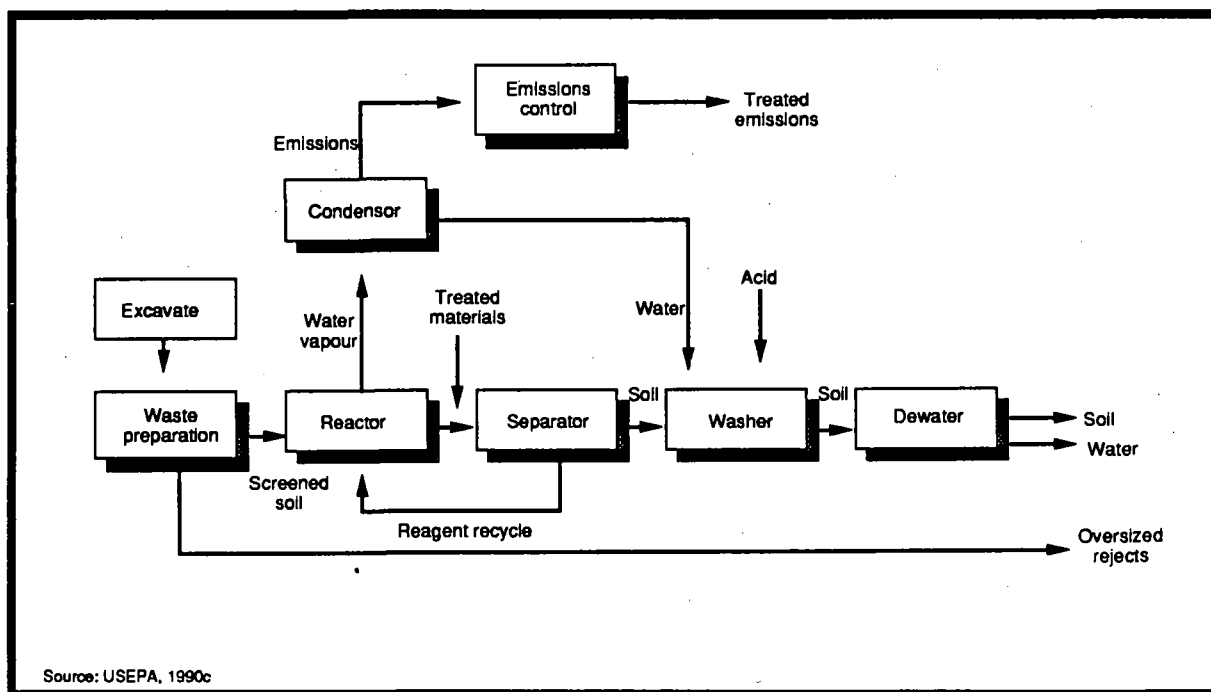
Figure 4.31 shows dechlorination inputs and products.



**Figure 4.31 Inputs and products of dechlorination**

KPEG (potassium hydroxide/polyethylene glycol), the most commonly used APEG reagent, reduces the toxicity of chlorinated hydrocarbons (such as PCBs) by removing chlorine atoms and replacing them with alkali metals (potassium, for example). Specific KPEG reagents exist for solids, liquids and sludge. KPEG is generally used on waste oils containing dioxins and diesel fuel containing PCBs, dioxins and chlorobenzenes. KPEG reduces toxicity but increases the volume of waste. Byproducts include chloride salts, polymers and heavy metals. Further treatment must be supplied by oxidation, biodegradation, carbon adsorption or incineration (Averett et al., 1990).

Figure 4.32 shows an APEG dechlorination process scheme.



**Figure 4.32 APEG dechlorination process scheme**

As Figure 4.32 shows, waste feed is first screened to remove debris and large objects. Reagents are then mixed with contaminated soil in the reactor and the mixture is heated to between 100°C and 180°C. The reaction proceeds for 4 to 5 hours and then the treated soil is sent to a separator where the reagent is recovered. Water vaporized during the reaction is condensed and then recycled through the washing process or sent to a water treatment system. Carbon filters trap volatile substances. Upon leaving the separator, treated soil is neutralized by addition of acid and then dewatered before disposal (USEPA, 1991c).

Another dechlorination process evaluated by the USEPA and the USACE for cleanup of Great Lakes sediment is *thionation*. In this process, sulphur displaces chlorine in organic molecules. Still in the early design stages, the method should be able to degrade organic contaminants. Sulphur and sodium carbonate react with p-dichlorobenzene between 150°C and 170°C to remove chlorine, leaving an insoluble polymer, sodium chloride, and carbon dioxide. This process has limited applicability to sediment however (Averett et al., 1990).

**4.5.2.3 Hydrolysis.** Many organic and inorganic compounds are dangerous because of their strong reaction in the presence of water; this reaction is called hydrolysis. In some cases, the reaction can even cause a fire or explosion or generate a dangerous gas ( $H_2$ , for example), an explosive gas, a toxic gas or a corrosive gas ( $HCl$ ).

One way of treating certain chemical compounds that are highly reactive with water is to subject them to hydrolysis under controlled conditions. Among inorganic contaminants that can be treated by hydrolysis are metals that react with water: metal carbides (calcium carbide), hydrides (sodium aluminum hydride,  $NaAlH_4$ ), amides (sodium amide,  $NaNH_2$ ), alkoxides (sodium ethoxide,  $NaOC_2H_5$ ) and halides (silicon tetrachloride,  $SiCl_4$ ).

Hydrolysis occurs when a compound undergoes bond breakage and dissolves into a water-ionic solution mixture. Breakage can be achieved by adding chemicals, irradiation (photolysis) or enzymatic bond cleavage. Hydrolysis can be carried out as a batch process in open tanks or by continuous flow in large towers. Hydrolysis can treat liquids, gases, or solids contaminated with aliphatics and aromatics such as esters, phosphates, and nitrates, but is not suitable for treating inorganic contaminants.

Toxic byproducts may form depending on materials used in the reaction. Applicability of hydrolysis to contaminated sediment is limited (Averett et al., 1990).

**4.5.2.4 Electrolysis.** Electrolysis involves applying electricity from an external source to electrodes to electrochemically reduce and oxidize dissolved chemical constituents. One of the dissolved constituents (generally a metal ion) is reduced by the electrons at the cathode and another is oxidized at the anode. When treating hazardous waste, electrolysis is usually used to recover metals.

**4.5.2.5 Photolysis.** Photolysis is a process that uses photons from short-wave light or ultraviolet radiation to chemically decompose contaminants (photodecomposition of atmospheric nitrogen dioxide, for example, which produces reactive oxygen atoms that trigger smog formation). This technology is still in the bench-scale stage of development.

**4.5.3 Applications.** Demonstrated or anticipated effectiveness of chemical technologies on general contaminant groups for various matrices is shown in Table 4.14. As the table indicates, chemical oxidation and dechlorination can treat a wide range of organic contaminants in liquids, soil, sludge or sediment. Oxidation/reduction technologies can treat metals and inorganic cyanides. Dechlorination processes are not designed to treat inorganics.

With the exception of chemical oxidation, which can treat reactive contaminants (reducers), the chemical technologies listed cannot treat reactive contaminants in any matrix.

**4.5.4 Strengths, limitations and demonstrated applications of each technology.** As Table 4.15 shows, the main strength of chemical dechlorination is that it yields soluble compounds less toxic than the original contaminant by altering contaminant molecular structure in a reduction reaction that removes chlorine atoms. With these processes there is no risk of producing dioxins or furans during the reaction.

Dechlorination can take place as an in situ process (APEG) or as an aboveground process (APEG, EcoLogic and radiolytic and electrochemical dechlorination). Some of the processes however are still in the design stage (radiolytic and electrochemical dechlorination) and require trained operators (CH2M Hill Engineering Ltd., 1992).

The APEG and EcoLogic processes have already been conclusively bench-scale tested on a wide variety of chlorinated soil contaminants--PAHs, PCBs, dioxins and furans, among others.

Oxidation processes that work by addition of electrically negative species (such as chlorine, hydroxyl and oxygen) or by loss of hydrogen have been applied to wastewater. Reactions are generally very rapid and good process control is essential to ensure oxidation of organic contaminants does not yield other organic compounds that are even more toxic or more resistant to treatment than the original contaminants.

**Table 4.14 Effectiveness of chemical treatment technologies on contaminant groups for different matrices**

Contaminant group	EFFECTIVENESS RATINGS*						
	Chemical oxidation		Glycol dechlorination	Chemical dechlorination APEG			
	Liquids	Soil/sludge	Soil/waste	Sediment	Oils	Soil	Sludge
<b>ORGANICS</b>							
Halogenated volatiles	2	1	1	1	1	1	1
Halogenated semivolatiles	2	1	1	1	1	1	1
Nonhalogenated volatiles	2	1	0	0	0	0	0
Nonhalogenated semivolatiles	2	1	0	0	0	0	0
PCBs	2	0	2	2	2	2	2
Pesticides (halogenated)	2	1	1	1	2	2	1
Dioxins/furans	1	0	2	2	2	2	2
Organic cyanides	2	2	0	0	0	0	0
Organic corrosives	1	1	0	0	0	0	0
<b>INORGANICS</b>							
Volatile metals	2	1	0	0	0	0	0
Nonvolatile metals	2	1	0	0	0	0	0
Asbestos	0	0	0	0	0	0	0
Radioactive materials	0	0	0	0	0	0	0
Inorganic corrosives	0	0	0	0	0	0	0
Inorganic cyanides	2	1	0	0	0	0	0
<b>REACTIVES</b>							
Oxidizers	0	0	0	0	0	0	0
Reducers	2	1	0	0	0	0	0

**\* EFFECTIVENESS RATINGS**

- 2 Good to excellent. High probability the technology will be effective.
- 1 Marginal to moderate or potential. Exercise care in choosing the technology. Expert opinion is that the technology will be effective.
- 0 Ineffective. Expert opinion is that the technology cannot be used to treat this type of waste or contaminant.
- X May have adverse effects.

Adapted from USEPA, 1990c & 1991c

Table 4.15 Strengths, limitations and contaminated-soil applications of chemical technologies

TECHNOLOGY	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATIONS
Dechlorination • APEG process	<ul style="list-style-type: none"> <li>Products of dechlorination are less toxic and usually biodegradable.</li> <li>Reagents used are nontoxic and relatively easy to synthesize.</li> <li>Technology can be applied in situ or off site.</li> <li>Mobile treatment units.</li> </ul>	<ul style="list-style-type: none"> <li>Soil pH must be monitored and must be neutralized if reagents are present.</li> <li>Process becomes less effective in clay-rich or organic-rich soil.</li> <li>In situ treatment is only effective for surface soil because of the method of application.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated on a bench and pilot scale for soil contaminated with PCBs and dioxins.</li> </ul>
Dechlorination • EcoLogic process	<ul style="list-style-type: none"> <li>Can treat a variety of halogenated compounds in a variety of soils.</li> <li>Removal rate of 99.999 percent at bench-scale.</li> <li>Mobile units.</li> <li>Suitable for high volume, long-run jobs as well as short-term projects.</li> <li>Because of the absence of oxygen, no dioxins or furans are produced.</li> </ul>	<ul style="list-style-type: none"> <li>Skilled operators are required because of the complexity of the process and the monitoring system.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated on a bench scale for a variety of organic contaminants such as PAHs, PCBs, dioxins, furans and derivatives of these compounds.</li> <li>Designed to treat soil, sediment, sludge and leachate from sanitary landfill.</li> </ul>
Dechlorination • Radiolytic process	<ul style="list-style-type: none"> <li>Because of the absence of air, no dioxins or furans are produced.</li> <li>On-line process monitoring ensures complete destruction.</li> <li>Applicable to waste containing PCBs and similar compounds.</li> </ul>	<ul style="list-style-type: none"> <li>Process in the early design phase.</li> <li>Very little data on effectiveness and impacts.</li> </ul>	<ul style="list-style-type: none"> <li>In early stages of development.</li> <li>Experiments conducted by Atomic Energy of Canada.</li> </ul>
Dechlorination • Electrochemical process	<ul style="list-style-type: none"> <li>Relatively good results detoxifying pentachlorophenols.</li> </ul>	<ul style="list-style-type: none"> <li>Not directly applicable to soil.</li> <li>Requires an extraction step which increases treatment costs.</li> <li>Process in the early design phase.</li> </ul>	<ul style="list-style-type: none"> <li>In early stage of development by the government of the Netherlands.</li> </ul>
Oxidation reactions • Chlorine dioxide	<ul style="list-style-type: none"> <li>Does not produce toxic halogenated organics.</li> <li>Reaction products are nontoxic organics and salts.</li> <li>Chlorine dioxide can be produced on site by reacting chlorine with sodium hypochlorite.</li> </ul>	<ul style="list-style-type: none"> <li>Has not been demonstrated for soil remediation.</li> <li>More data is required before full-scale application is possible.</li> </ul>	<ul style="list-style-type: none"> <li>Used to treat aqueous waste contaminated with cyanides.</li> <li>Application to soil should be simple.</li> <li>Recommended for USEPA Superfund projects.</li> </ul>
Oxidation reactions • Soil catalyzed reactions	<ul style="list-style-type: none"> <li>Organophosphorous and carbonate pesticides can be degraded by hydrolysis under alkaline conditions.</li> <li>Process verified in the field for several classes of contaminants, including s-triazines and organophosphate compounds.</li> <li>Toxic concentrations may also be reduced by attenuation with added soil.</li> </ul>	<ul style="list-style-type: none"> <li>Oxidation of organic contaminants can produce compounds more toxic than initial contaminants.</li> <li>Decreased moisture can retard microbial activity or increase ventilation of volatile organic compounds.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated treatability for several classes of chemicals (triazines, organophosphates and ethyl parathion).</li> </ul>
Oxidation reactions • Hydrogen peroxide	<ul style="list-style-type: none"> <li>Readily available oxidizer of demonstrated efficiency.</li> <li>Relatively inexpensive.</li> <li>Very rapid reaction.</li> </ul>	<ul style="list-style-type: none"> <li>Highly exothermic reactions with possible volatilization of lighter hydrocarbons before they can be oxidized by the peroxide.</li> <li>Possible noxious odours from intermediate products.</li> <li>Evolution of these compounds can be controlled but at high cost.</li> <li>Cost of chemicals is high since the oxidant is nonselective and may oxidize compounds which are not targeted.</li> <li>May oxidize essential organic compounds in the soil.</li> </ul>	<ul style="list-style-type: none"> <li>Used to remediate a site contaminated by formaldehyde.</li> <li>Used on a bench-scale for PCP-contaminated soil.</li> </ul>
Oxidation reactions • Ozone	<ul style="list-style-type: none"> <li>Very rapid reaction.</li> <li>Intermediates are biodegradable and normally less toxic than similar compounds.</li> </ul>	<ul style="list-style-type: none"> <li>Must be produced on site because of its short half-life, and this is very expensive.</li> <li>Oxidation of pesticides sometimes produces substances more toxic than initial compounds.</li> </ul>	<ul style="list-style-type: none"> <li>Fuels, mineral oils and PAHs.</li> <li>Also effective in treating aromatic and aliphatic hydrocarbons.</li> <li>Used in Germany to treat soil and groundwater.</li> </ul>

Adapted from CH2M Hill Engineering Ltd., 1991



**4.5.5 Strengths and limitations for sediment treatment.** To date, few chemical destruction technologies have been used to treat heavy metals or organic contaminants in sediment. According to Averett et al (1990) and the USEPA (1991b), several of the processes have been laboratory tested but only *nucleophilic substitution (dechlorination)* using potassium hydroxide and polyethylene glycol (KPEG) has been tested on a bench scale (in the early 1990s) as indicated in Table 4.16.

*Oxidation of inorganics* is applicable to a limited number of compounds. Two potential applications for contaminated sediment are oxidation of cyanide to less toxic cyanate and conversion of arsenites to less soluble arsenates. Other compounds may, however, become more mobile under oxidized conditions, precluding application of the process to many contaminated sediment problems.

*Oxidation of inorganics* can be achieved by natural aeration of sediment or by adding oxidants such as ozone, hydrogen peroxide, potassium permanganate or chlorine gas. Aerating sediment over long periods is not a practical solution, however, and adding oxidants to sediment can result in formation of toxic byproducts (Averett et al., 1990).

*Organics contaminants* in soil and groundwater can be oxidized in situ using strong reagents like ozone and hydrogen peroxide. As the oxydants can be applied in water solutions by spreading directly onto the soil surface, injecting into the subsurface, or placing into injection wells, these options are adaptable to dredge material in a CDF (Averett et al. 1990).

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The Dutch began researching sediment remediation technologies in 1989. They discovered that adding hydrogen peroxide to dredged material to oxidize organic contaminants did not yield expected results. They therefore abandoned the development of this technology in the laboratory stage.

Table 4.16 Anticipated performance of chemical technologies applied to sediment remediation

TECHNOLOGY	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABILITY	PERFORMANCE RATING**		
				EFFEC-TIVENESS	IMPLEMENT-ABILITY	COST
<b>Chelation*</b>	<b>Demonstrated</b>	<b>No</b>	<b>Available</b>	3	2	2
Chemical hydrolysis	Conceptual	No	Emerging	2	1	2
Nucleophilic substitution	Pilot	<b>Bench</b>	<b>Proprietary</b>	4	2	2
Oxidation of metals (inorganic)	Conceptual	No	Emerging	2	1	2
<b>Oxidation of organics</b>	<b>Pilot</b>	<b>No</b>	<b>Available</b>	3	2	2
Reduction of metals	Conceptual	No	Emerging	2	1	2
Reduction of organics	Conceptual	No	Emerging	1	1	2
Thionation	Conceptual	No	Emerging	1	1	2

Notes

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

Adapted from Averett et al., 1990

Before the *APEG dechlorination process* can be applied on a full scale to contaminated sediment, the following problems must be solved: mixer design for mass transfer; reaction kinetics and solids separation; reagent recovery and disposal; solids disposal; and treatment of organic compounds remaining in the solids after dechlorination.

*Radiant energy photolysis* processes use radiant energy from sunlight or ultraviolet lamps to photodegrade organic contaminants. Since ultraviolet light cannot penetrate sediment or opaque solutions, contaminants must first be extracted from the sediment before that are subjected to ultraviolet rays. These technologies have not been demonstrated on a full scale and are still conceptual (Averett et al., 1990).

4.5.6      **Technologies demonstrated for sediment remediation.** Table 4.17 lists chemical technologies which have been demonstrated for remediation of contaminated sediment. For each technology, the name of the developer, the place and scale of demonstration and the types of contaminants treated are listed. As of 1992, only the KPEG dechlorination process and the EcoLogic thermochemical process had been demonstrated effective for treating sediment.

The KPEG process developed by Galson Research Corporation and described above was bench-scale tested on sediment from New Bedford Harbour in Massachusetts. PCB concentrations of 6 000 to 7 500 ppm were reduced to 4 ppm in 12 h at 165°C and residual recovery was 98 percent. Treatment costs should range from US\$146 to US\$175 per cubic yard (Averett et al., 1990).

**Table 4.17 Chemical technologies demonstrated for sediment remediation**

Technology	Developer	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Dechlorination • EcoLogic process	EcoLogic	Canada	Hamilton Harbour, ON	Laboratory & pilot	PCBs, PAHs, heavy metals	WTC, 1992b
			Thunder Bay Harbour, ON	Bench	PCBs, PAHs, heavy metals	
Dechlorination • APEG process	Galson Research Corporation	U.S.	New Bedford Harbour, MA	Bench	PCBs	USEPA, 1991b

\* See Appendix C for addresses and telephone numbers of developers.

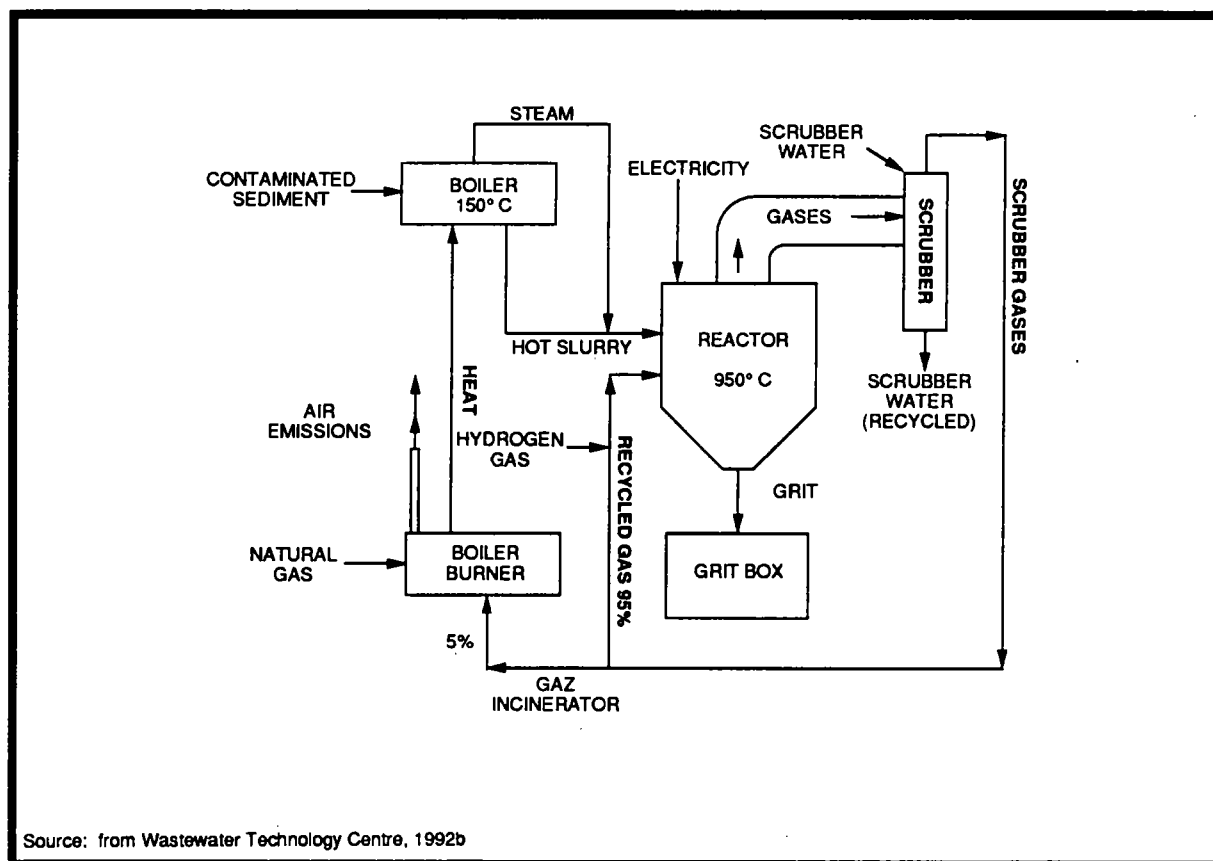
ELI Ecologic International Inc. of Rockwood, Ontario, developed the Ecologic dechlorination process, which uses hydrogen at high temperatures.

Working from the principle that at elevated temperatures (850°C or more) hydrogen in the gas phase reacts with organic molecules to form smaller, lighter and less toxic molecules, the company ELI Ecologic in 1986 developed a unconventional incinerator for aqueous wastes.

Water, which can be used as reducing agent and as a source of hydrogen, enhances the reaction. And since hydrogen creates an atmosphere that excludes presence of free oxygen, no dioxins or furans are formed. In addition, when hydrogen is used as the active reducing agent, a gas of low molecular weight is produced without forming the heavy hydrocarbons generally associated with pyrolytic processes.

Figure 4.33 shows a schematic of the EcoLogic process. In this process, waste is first preheated with steam to 150°C and then pumped around the ceramic tubes of the reactor to cause volatile organic compounds (VOCs) to volatilize. Heavy particles drop to the bottom of the reactor and fine fractions rise up with the gases. Gases pass through a scrubber to remove hydrogen chloride and fine particles. Ninety-seven percent of the gases are recirculated, and the other three percent are diverted to preheat the waste feed. Process residues consist of grits from the reactor, calcium chloride and particulate sludge from the scrubber, and condensed water sludge (Cambel and Hallet, 1992; Wastewater Technology Centre, 1992b).

Results of about one hundred tests conducted over two years show destruction efficiencies of 99.9999 percent or more. In addition, the technology can treat a wide range of contaminated matrices: soil, sediment, liquid, gas, industrial effluent, landfill leachate, sludge from aerated lagoons, PCB-contaminated waste, chlorinated solvents, contaminated oils and waste from the dry cleaning industries, from wood treating plants, paint factories, pulp and paper mills, chemical plants and plastics plants.



**Figure 4.33 EcoLogic process scheme**

Contaminants that the Ecologic process can treat include chlorinated and nonchlorinated compounds as well as volatile and nonvolatile compounds: PCBs, HAPs, chlorophenols, pesticides and herbicides (organics and organometallics), solvents, benzene-toluene, ethylbenzene and xylene.

Treatment costs are expected to range from US\$250 to US\$300 per ton for a commercial unit with a throughput of 100 tons per day.

A full-scale demonstration unit with a throughput of 5 to 7 tons per day was used to treat 20 cubic metres of Hamilton Harbour sediment contaminated by PAHs (3 to 26 100 ppm) and PCBs (110 to 500 ppm). Tests showed destruction efficiency was 99.9999 percent. The

demonstration project was supervised by the Wastewater Centre and funded by the Environment Canada (through the Great Lakes Cleanup Fund) and the Ontario Department of the Environment (Wastewater Technology Centre, 1992b).

**4.5.7 Technologies under demonstration for sediment treatment.** Eight chemical processes were recommended by the USEPA and the USACE for cleanup of Great Lakes sediment. However, given the limited applications to date, the complexity as well as the expected treatment costs of the processes, only chemical (KPEG process) and thermal nucleophilic substitution (EcoLogic process) technologies have been selected for demonstration projects (Table 4.18).

Nevertheless, as Table 4.16 indicates, technologies for oxidation of organics using chelating agents have been selected as alternative solutions for future demonstration projects.

**4.5.8 Technologies selected for sediment remediation projects.** In 1992, chemical dechlorination technologies were selected for only one sediment remediation project, at a site in New Jersey where soil and sediment were contaminated by semivolatile organic compounds (hexachlorobenzene), DDT, dioxins, TCDD, DDD and DDE. This project is still in the design stage (USEPA, 1991c).

**4.5.9 Conclusions.** As the sections above show, chemical technologies have been used mainly in industry. Few have been applied to or demonstrated for treatment of organic compounds and heavy metals in sediment.

As of 1992, only dechlorination technologies and the EcoLogic process developed by a Canadian firm had been demonstrated effective on a bench and pilot scale for treatment of sediment contaminated by organic compounds. To date, dechlorination technology has been applied in the U.S. at only one site significantly contaminated by a variety of organic compounds.

Table 4.18 Chemical technologies under demonstration for Great Lakes sediment remediation

Technology	Developer	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Dechlorination EcoLogic process	EcoLogic	U.S.	Sheboygan Harbour	Bench	PCBs	USEPA, 1992a
Chemical dechlorination KPEG process	Galson Research Corporation	U.S.	Asthabula River Great Calumet River Sheboygan Harbour	Bench	PCBs	USEPA, 1992a

\* See Appendix C for addresses and telephone numbers of developers.



Most of these technologies were developed by the chemical industry to treat a limited number of chemical compounds present mainly in water. With contaminated sediment, however, identification of a particular chemical reaction that can treat a specific contaminant is often difficult. A reaction that treats one contaminant, for example, often increases the mobility of others.

Large-scale application of chemical technologies to sediment remediation may prove long and difficult because of materials handling and process control requirements that have not been fully demonstrated. There is not much information available on costs for these processes and they are thus difficult to quantify. Costs are, nevertheless, expected to exceed US\$100 per cubic yard.

## 4.6 Thermal treatment

Thermal technologies use heat to destroy, encapsulate, desorb or volatilize contaminants. The most common processes are incineration, which destroys organic contaminants by combustion (aerobic conditions) and pyrolysis which destroys organic contaminants in the absence of oxygen (anaerobic conditions). Intensive research is currently being conducted on new technologies that encapsulate contaminants in a molten slag or salt or use heat to desorb contaminants from soil without directly destroying them.

**4.6.1 Principle of treatment.** *Incineration* is the burning of waste in the presence of oxygen. Incineration volatilizes and/or destroys organic contaminants in liquids, sludge, slurries and solids. Metals, radionuclides and volatile compounds which are not treated accumulate in the ash byproduct or are released in the gas stream. Depending on waste treated, pollution control equipment for offgas may be necessary; this can include quench chambers, baghouse filters, gas absorbers and mist eliminators (CH2M Hill Engineering Ltd., 1992).

*High-temperature thermal processes* generally include incineration, pyrolysis, vitrification and any other process that requires heating soil or sediment several hundreds or thousands of degrees. These processes are generally among the most effective in destroying organic contaminants, but they are also among the most costly. In addition, they are not well perceived by the public.

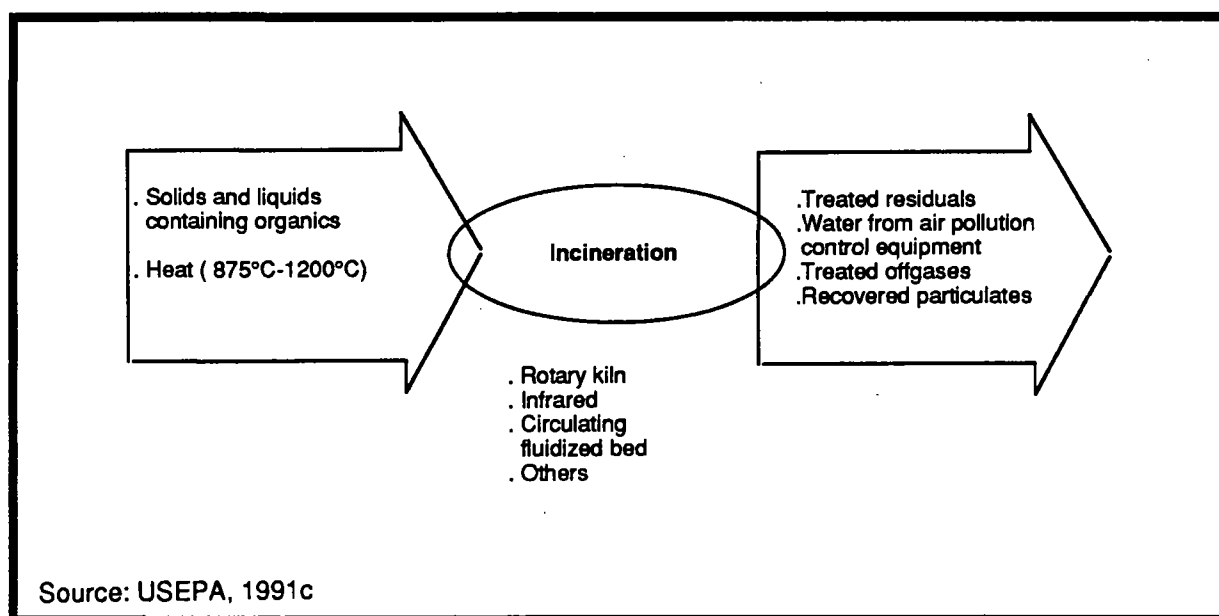
*Low-temperature thermal processes* include desorption, low-temperature thermal stripping, wet air oxidation and desorption-pyrolysis processes such as AOSTRA-Taciuk.

*Vitrification* technologies convert waste to molten material at very high temperatures. Inorganics are thus immobilized in a glassy slag and organics are destroyed by the high temperatures. *Desorption* technologies do not destroy contaminants; they volatilize them or concentrate them in another form for subsequent treatment (CH2M Hill Engineering Ltd., 1992).

## 4.6.2 Technologies available

**4.6.2.1 Incineration.** Incineration technologies use temperatures ranging from 871°C to 1204°C to volatilize and burn (in the presence of oxygen) organic constituents in hazardous wastes. Efficiencies often exceed 99.99 percent.

Figure 4.34 shows incineration inputs and products.

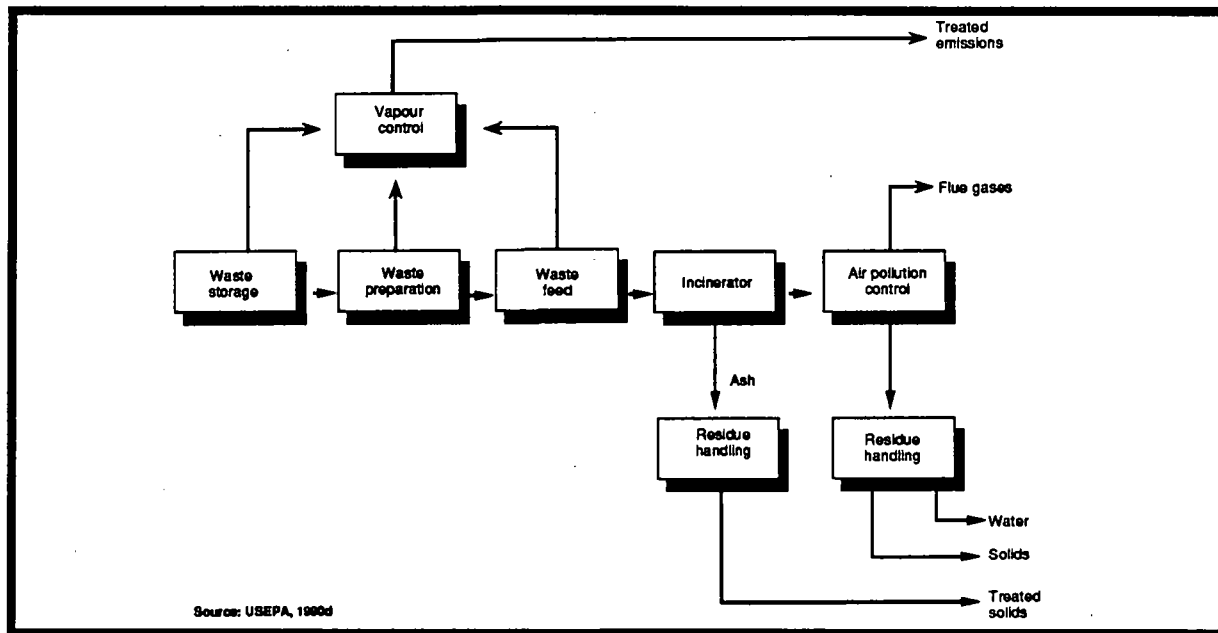


**Figure 4.34 Incineration inputs and products**

As Figure 4.34 suggests, there are a number of different incinerators for destruction of hazardous organic waste on the market: rotary kilns, fluidized bed incinerators, circulating bed combustors, infrared furnaces, liquid injection incinerators, enhanced incinerators and industrial kilns or boilers.

In addition, mobile/transportable incineration units have been demonstrated effective for treating soil, sediment, sludge and liquid contaminated mainly by organics such as halogenated volatiles and semivolatiles, PCBs, pesticides, dioxins and furans, organic cyanides and corrosive organics (USEPA, 1991c).

Figure 4.35 shows a process schematic for a mobile incineration unit.



**Figure 4.35 Mobile incineration unit process scheme**

Main components of an incineration unit are generally as follows:

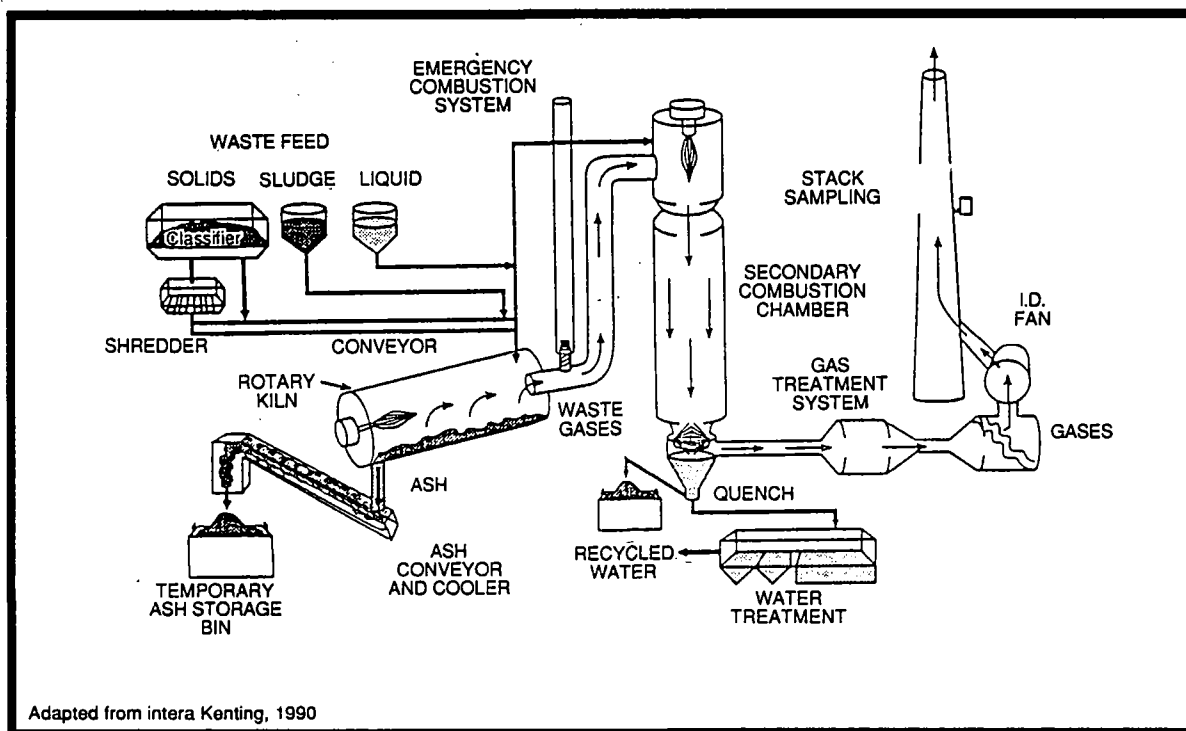
- Waste preparation: classification, screening, mixing and so forth.
- Feed: conveyor belt, screw conveyor and so forth.
- Incinerator: rotary kiln, circulating fluidized bed incinerator, or infrared furnace.
- Air pollution control equipment: postcombustion chamber, separation cyclone, baghouse, electrostatic precipitator, packed scrubber and so forth.
- Residue handling: disposal or immobilization of ash, and disposal or treatment of liquid waste and air pollution control residues.

The following paragraphs briefly describe the different types of incineration processes currently on the market.

**Rotary kilns.** Rotary kilns use direct or indirect heat to vaporize contaminants at temperatures ranging from 200°C to 700°C. Offgases are then incinerated in an afterburner at temperatures ranging from 750°C to 1300°C. All Dutch plants that remediate contaminated soil by thermal destruction work on this principle (Annokke, 1989). Rotary kilns are a well-proven technology used in Sweden and Germany as well as in North America.

In the United States, the main vendors of this type of incinerator are Weston Services Inc., Ensco, IT Corporation, Haztox, Vesta, OH Materials and Von Roll Inc. (Intera Kenting, 1990).

Figure 4.36 shows a cross section of a rotary kiln incinerator.



**Figure 4.36** Cross section of rotary kiln incinerator

**Circulating fluidized bed incineration.** Developed in the United States by Waste-Tech Inc. and Combustion Engineering, fluidized bed incineration treats halogenated or nonhalogenated solids, sludge and liquids in a controlled atmosphere with excess oxygen (Petitpas, 1990).

To facilitate transfer of energy to the waste to be incinerated, the waste is placed on a bed of inert material (often sand). Combustion air is introduced at the bottom of the bed and forced upward. Heat is supplied by heat released by combustion and by supplementary fuel when necessary. In the secondary combustion chamber, complete combustion of contaminants is achieved in a retention time of two seconds. Exhaust gas is sent through air pollution control equipment for cleaning before release into the atmosphere. A variation of this technology marketed by Ogden Environmental Services uses a circulating bed combustor.

Figure 4.37 shows a cross section of a circulating bed combustor.

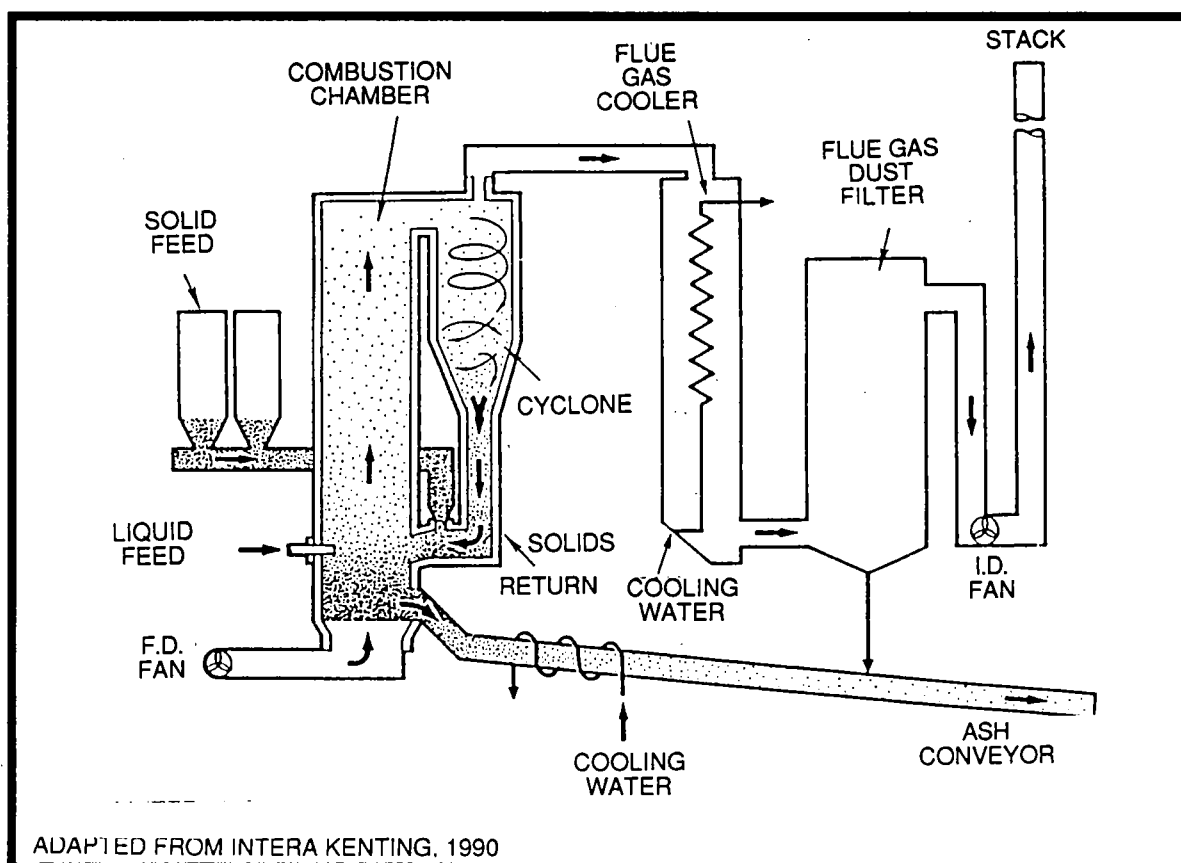
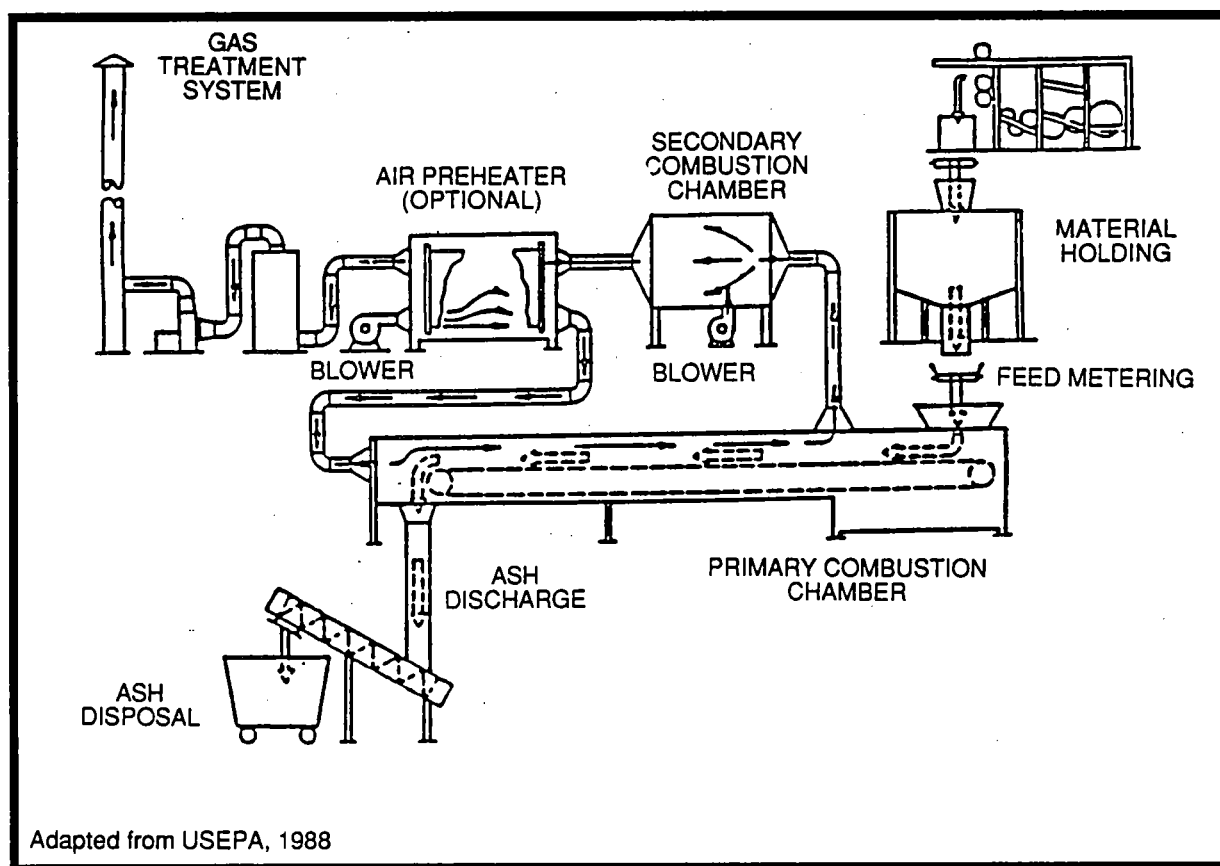


Figure 4.37 Cross section of a circulating bed combustor

The circulating bed combustor uses high air velocity to create a highly turbulent combustion zone that is very effective for destroying contaminants. Because of the high degree

of turbulence and the relatively long retention time, organic compounds can be incinerated at lower temperatures than in rotary kilns (800°C to 850°C). And lower operating temperatures mean fewer nitrogen oxide ( $\text{NO}_x$ ) emissions and less ash sintering. Dry lime is added to the feed to eliminate acid gases in the combustion chamber so offgas need not be neutralized.

**Infrared incineration.** This technology was designed to treat contaminated solids and soil. Figure 4.38 shows a cross section of an infrared incinerator.



**Figure 4.38** Cross section of infrared incinerator

The infrared incineration unit comprises a waste feed system, a primary combustion chamber heated by infrared energy (1000°C), a secondary combustion chamber (1260°C) heated by propane and a gas treatment system. Required destruction efficiency for PCBs (99.9999 percent) can be achieved with this process (Intera Kenting, 1990).

The SHIRCO process is marketed by a number of companies, among them OH Materials Inc., Haztec Inc. and Riedel Environmental Technologies Inc. OH Materials successfully treated PCB-contaminated waste from the Canadian base at Goose Bay with this type of incinerator.

**Liquid injection incineration.** Liquid injection incineration cannot be used for soil remediation.

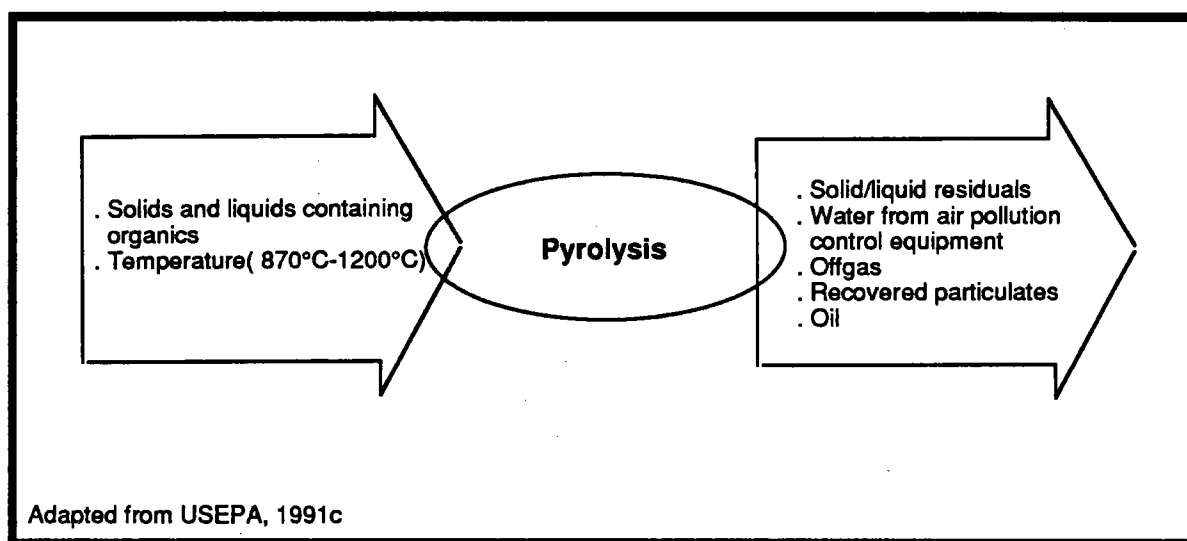
**Industrial processes.** Incineration processes used in industry to destroy hazardous waste--multiple hearth incinerators, cement kilns, lime kilns and industrial boilers--have limited applications for soil remediation because the facilities are not transportable and are not designed to handle or treat this type of waste.

**Enhanced incinerators.** The U.S. firm American Combustion Technologies Inc. developed the Pyretron Oxygen Burner, an oxygen-air-fuel burner that uses advanced fuel injection and mixing concepts to burn solid waste or sludge (CH2M Hill Engineering Ltd., 1992).

**4.6.2.2 Pyrolysis.** Pyrolysis is a thermal process that chemically decomposes organic compounds in the absence of oxygen. Since in practice it is not possible to create an atmosphere completely free of oxygen, some oxidation does take place. If volatiles or semivolatiles are present, thermal desorption occurs.

Figure 4.39 shows pyrolysis inputs and products.

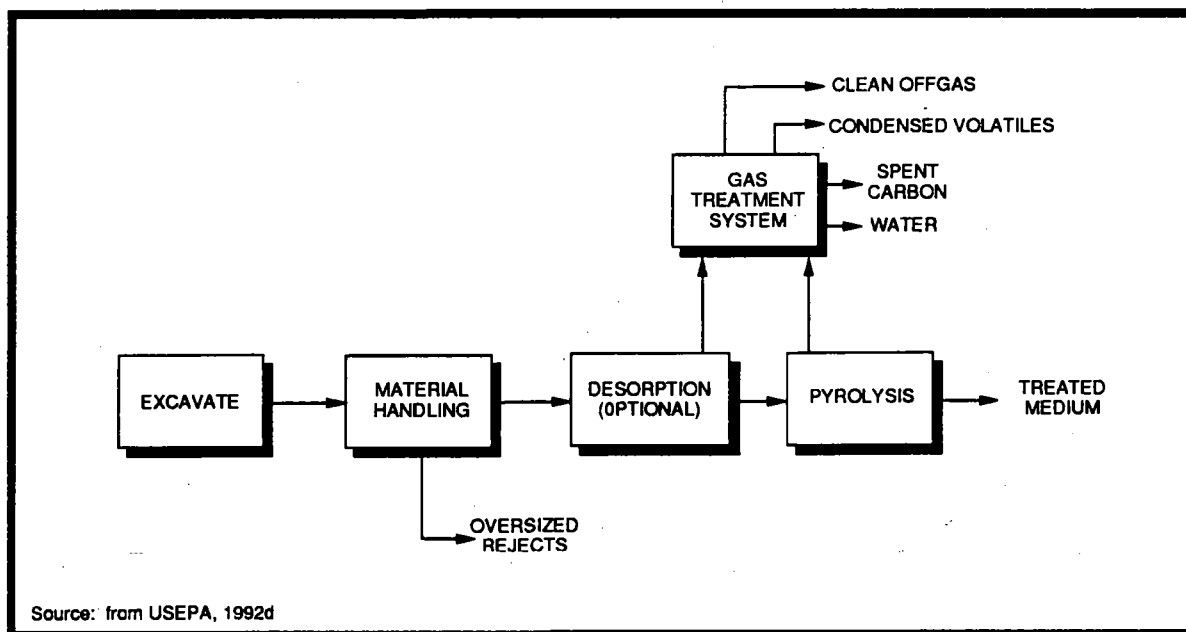




**Figure 4.39 Pyrolysis inputs and products**

Pyrolysis of organics generates offgases such as  $\text{CO}_2$ , hydrogen, methane and other hydrocarbons of low molecular weight as well as a solid residue (coke) containing fixed carbon and ash. When the gases cool they form a residue of tar and oil. Temperatures in the primary combustion chamber range from  $500^\circ\text{C}$  to  $750^\circ\text{C}$ . Temperature in the secondary combustion chamber is set at  $1200^\circ\text{C}$  (Petitpas, 1990).

Figure 4.40 shows a pyrolysis process scheme.



**Figure 4.40 Pyrolysis process scheme**

As with many treatment processes, the feed must first be screened to remove branches, rocks and so forth. Pyrolysis systems generally include a desorption stage prior to pyrolysis. Since pyrolysis transforms organic compounds into coke and gaseous components, offgas must be treated by condensation, some other cleaning system or incineration followed by offgas treatment (USEPA, 1992d).

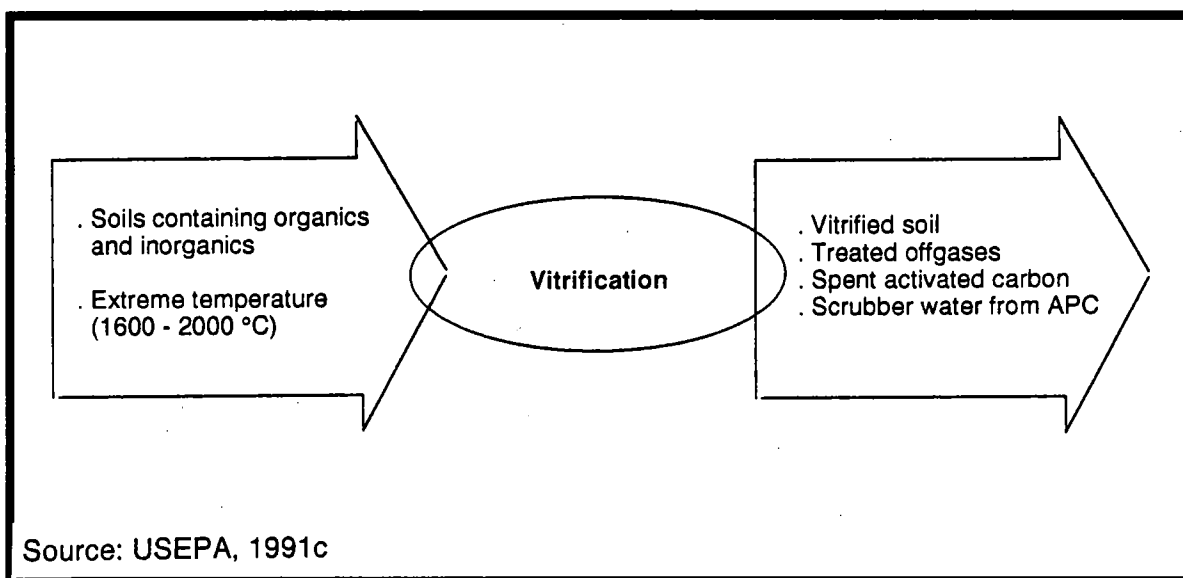
Liquid waste from the gas treatment system may contain metals and organic compounds and must be treated by one or more of the following procedures: neutralization, chemical precipitation, settling or filtration.

In addition, ash and treated soil/solids may also contain heavy metals and have to be treated by stabilization/solidification if leachate standards are not met.

Two U.S. companies operate pyrolysis units, TDI Thermal Dynamics (HT-V thermal distillation system) and SoilTech Inc. (a unit that uses a Canadian anaerobic thermal process known as AOSTRA-Taciuk).

**4.6.2.3 Vittrification.** Vittrification technologies are used for waste containing mainly metals and material with a high silicate content. These technologies generally use heat generated by electricity to melt contaminated soil and sludge into a stable crystalline product that resists leaching. Wastes are heated to temperatures ranging from 1600°C to 2000°C, that is, well above the melting point of soil (USEPA, 1992b).

Figure 4.41 shows vittrification inputs and products.



**Figure 4.41 Vittrification inputs and products**

Vitrification destroys organics at high temperatures and immobilizes metals in a glassy structure composed of molten silicates. Certain vittrification processes transform waste into a material that resembles ceramic by a variety of methods:

- a) High temperature slagging incineration (1200°C).
- b) Plasma reactor (10 000 °C to 20 000°C).
- c) Flame reactor (2000°C).
- d) Electric reactor (2200°C).

e) Cyclone combustor.

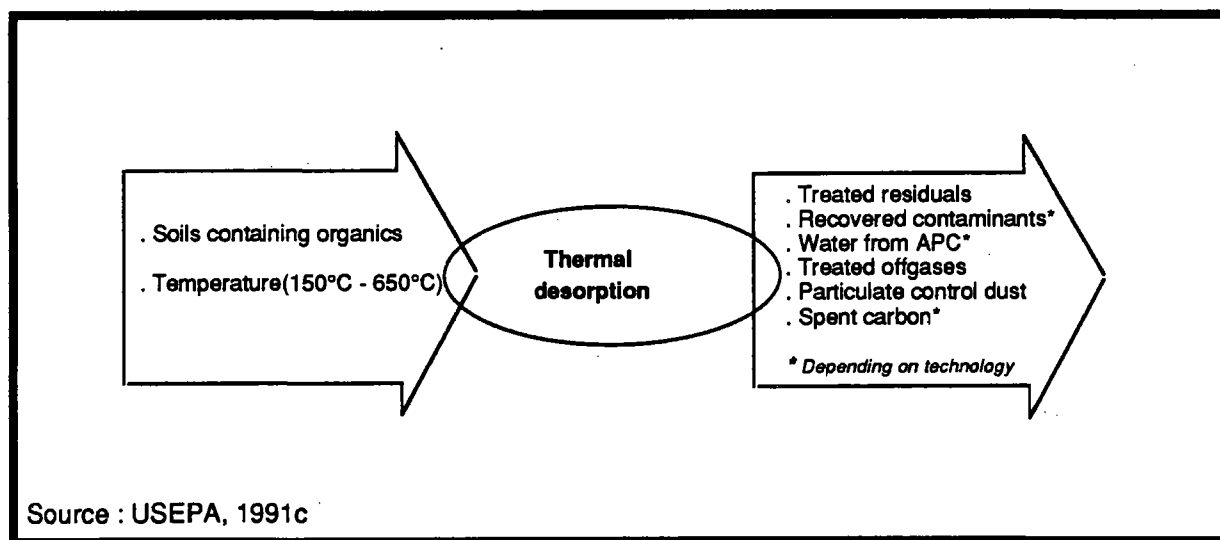
High temperature slagging is a proven technology. Plasma and flame reactor technologies are at the demonstration stage, and electric reactor and cyclone combustor are emerging technologies (CH2M Hill Engineering Ltd., 1992).

Some vitrification processes include gas treatment systems that liquify and recover volatilized compounds by carbon adsorption, flameless low-temperature catalytic processes or incineration of organics. Vitrification technologies that incorporate such gas treatment systems can treat metals as well as organics.

**4.6.2.4 Molten salt.** With molten salt incineration, waste is mixed with air and then placed on a bed of molten salt (sodium carbonate). Temperature of the salt is maintained at 800°C to 1000°C. Hydrocarbons are oxidized to carbon dioxide and water. Phosphorus, sulphur, arsenic and halogens react with the sodium carbonate to form other salts. This process is still in the experimental stage (CH2M Hill Engineering Ltd., 1992).

**4.6.2.5 Desorption.** Desorption technologies use heat in a controlled environment to vaporize organic compounds in contaminated media. Inert gases are sometimes used as the transfer medium for the vaporized compounds.

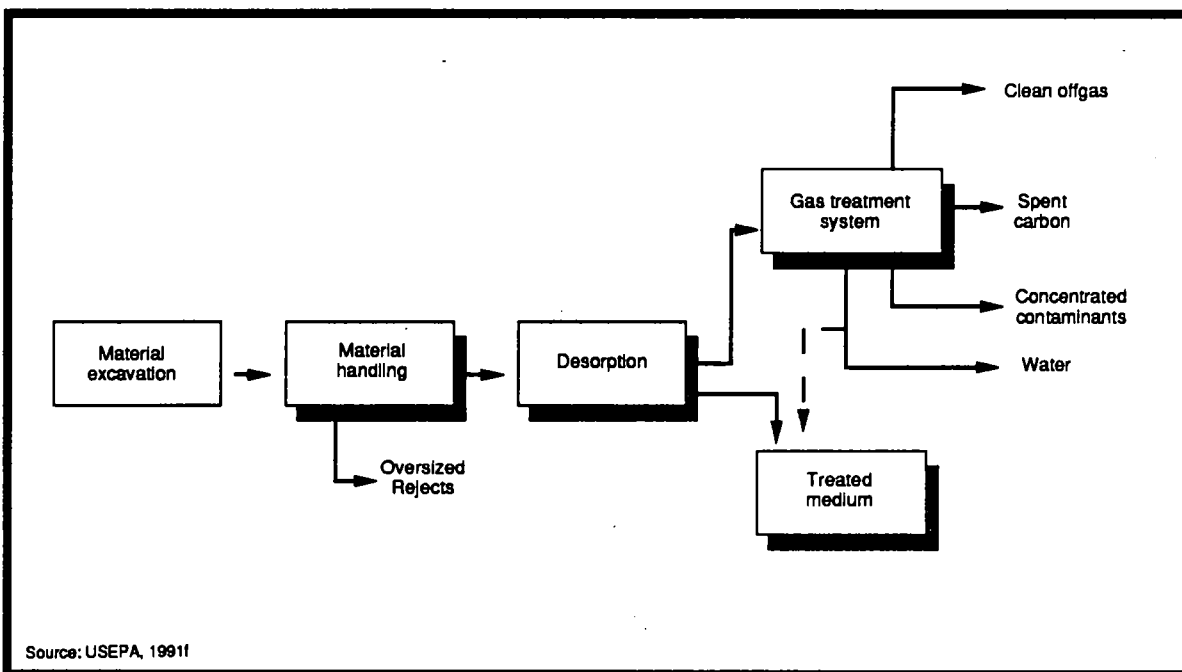
Figure 4.42 shows thermal desorption inputs and products.



**Figure 4.42 Thermal desorption inputs and products**

Thermal desorption processes are planned and designed to avoid combustion (absence of oxygen) of contaminants in the primary unit. These technologies use lower temperatures than incineration technologies (150°C to 650°C). Higher temperatures may be used in the absence of oxygen in the desorption unit. Offgas is further treated in systems that condense and recover volatiles, capture them in activated carbon adsorption units or destroy them by catalysis or flaring. Dust and particulates may be controlled with cyclones, baghouses or venturi scrubbers. Acid vapours may also require treatment (USEPA, 1991c).

Figure 4.43 shows a thermal desorption process scheme.



**Figure 4.43 Thermal desorption process scheme**

According to the USEPA, desorption technologies can be categorized as follows:

- Directly heated desorption
- Indirectly heated desorption
- In situ steam extraction

**Directly heated desorption.** Directly heated desorption technologies use a fuel burner which may be internal or external to the primary heating chamber. Internally fired units resemble rotary kilns; heated air is forced counter-current through the soil. The units operate at temperatures of less than 426°C and have generally been used only for treatment of nonchlorinated organics. The U.S. companies OH Materials Inc. and Canonie Environmental operate directly heated desorption systems (USEPA 1991c).

**Indirectly heated desorption.** These processes transfer heat through metal surfaces to waste. Operating temperature is about 315°C, which means less particulate carryover and less exhaust gas requiring further treatment. Vaporized contaminants are removed from the reactor using a sweep gas with low oxygen content to prevent oxidation (combustion and explosion). Desorbed organics may be condensed and/or removed by carbon adsorption (USEPA, 1991c).

Weston Services Inc. and the U.S. Army Toxic and Hazardous Materials Agency have indirectly heated desorption units operating at temperatures of about 232°C. Chemical Waste Management's X\*TRAX System and SoilTech's AOSTRA Taciuk Processor operate at higher temperatures (above 315°C).

**In situ steam extraction.** With this process, hot air and steam are injected into the ground through drillholes. Volatile organics are stripped from soil and groundwater and collected at the surface for treatment.

**4.6.2.6 Wet air oxidation.** Wet air oxidation technologies oxidize organics and inorganics in an aqueous environment at temperatures of 250°C to 325°C and pressures up to 3000 psig. The technology was developed about thirty years ago and has been used successfully to treat sludge from municipal wastewater plants.

Tests were conducted at temperatures exceeding the critical point of water to limit amount of water evaporated. Compressed air or pure oxygen can serve as a source of oxygen for the oxidant in wet air oxidation processes. These processes are not appropriate for large volume of waste and solids or viscous liquids. (Averett et al., 1990).

**4.6.3 Applications.** As Table 4.19 indicates, high temperature (incineration and vitrification) and low temperature (desorption) thermal technologies have been demonstrated effective or are expected to be effective on most organic contaminants and for most matrices (soil, sludge and sediment).

As for inorganics, thermal desorption processes can only remove volatile metals, whereas vitrification removes other inorganic contaminants but not volatile metals. Apart from inorganic cyanides, incineration cannot treat inorganic contaminants.

Only incineration and vitrification have been demonstrated marginally to moderately or potentially effective on reactive contaminants.

As Table 4.19 indicates, pyrolysis is applicable to a wide range of organic contaminants present in soil, sediment and oily sludge. Performance data are available for PCBs, dioxins, PAHs and many other organic compounds. Pyrolysis is not however designed to destroy or physically remove inorganics; some volatile metals will nevertheless vaporize because of the high process temperatures, but they will not be destroyed (USEPA, 1992d).

Wet air oxydion is used primarily to treat biological wastewater treatment sludges and has potentiel application to concentrate liquid or sludge waste streams containing organic and inorganic waste (including halogenated organics, inorganic/organic cyanide and phenols inorganic/organic sludge) that are not readily biodegradable (USEPA, 1988).



Table 4.19 Effectiveness of thermal treatment technologies on contaminant groups for different matrices

Contaminant group	EFFECTIVENESS RATINGS*										
	Incineration			Pyrolysis		Vitrification	Thermal desorption				Wet air oxidation
	Soil/ sediment	Sludge	Liquid	Soil	Sediment/ sludge	Soil/ sludge	Soil	Sludge	Sediment	Fiber cakes	Sludge
<b>Organics</b>											
Halogenated volatiles	2	2	2	1	1	1	2	1	1	2	1
Halogenated semivolatiles	2	2	2	1	1	1	2	1	1	2	1
Nonhalogenated volatiles	2	2	2	1	2	1	2	1	1	2	1
Nonhalogenated semivolatiles	2	2	2	2	2	1	2	1	1	2	1
PCBs	2	2	2	2	2	1	2	1	1	1	1
Dioxins/furans	1	2	2	1	1	1	2	1	1	1	1
Pesticides (halogenated)	2	2	2	1	2	1	2	1	1	1	1
Organic cyanide	1	1	1	1	1	1	1	1	1	1	1
Organic corrosives	1	1	1	0	0	1	0	0	0	0	1
<b>Inorganics</b>											
Volatile metals	0	0	0	0	0	X	2	1	1	1	0
Nonvolatile metals	0	0	0	0	0	1	0	0	0	0	0
Asbestos	0	0	0	0	0	2	0	0	0	0	2
Radioactive materials	0	0	0	0	0	1	0	0	0	0	0
Inorganic corrosives	0	0	0	0	0	1	0	0	0	0	1
Inorganic cyanides	1	1	1	0	0	1	0	0	0	0	1
<b>Reactives</b>											
Oxidizers	1	1	1	0	0	1	0	0	0	0	-
Reducers	1	1	1	0	0	1	0	0	0	0	-

**EFFECTIVENESS RATINGS\***

2 Good to excellent. High probability the technology will be effective.

1 Marginal to moderate or potential. Exercise care in choosing the technology. Expert opinion is that the technology will be effective.

0 Ineffective. Expert opinion is that the technology cannot be used to treat this type of waste or contaminant.

X May have adverse effects.

Adapted from USEPA, 1988, 1990d 1991c, 1991d and 1992d

**4.6.4 Strengths, limitations and demonstrated applications of each technology.** Table 4.20 lists the main strengths, limitations and applications or demonstrations of thirteen conventional chemical thermal technologies for treating contaminated matrices.

As the table shows, incineration technologies can treat a wide variety of organic contaminants in solids, sludge, waste and liquid effluent. Rotary kiln, fluidized bed and infrared incinerators are technologies proven throughout the world. Treatment costs are relatively high, however, and disposal of treatment residues is often problematic.

A recent survey in the United States shows nine vendors of rotary kiln incinerators, four vendors of infrared furnaces and one vendor of fluidized beds. In 1990, 55 incinerators were approved for off-site waste incineration and 59 for on-site use. However, there is now a limited capacity for off-site incineration of soil. (USEPA, 1991c)

In Canada, in 1992, only the provinces of Alberta (Swan Hills), Ontario (Sarnia) and Quebec (Ville Mercier) had incinerators for treatment of hazardous waste. The Ville Mercier facility is a liquid injection incinerator and cannot therefore treat soil. In New Brunswick, soil contaminated by certain metals is accepted by two smelters (Brunswick and Belledune); soil contaminated by hydrocarbons can be sent for incineration to five approved sites (one in Fredericton, one in Bathurst, one in St. John and two in Moncton) (Crittenden, 1992).

Rotary kiln, infrared and fluidized bed incinerators have been demonstrated effective for treatment of soil.

**Table 4.20**      **Strengths, limitations and contaminated-soil applications of conventional thermal technologies**

TECHNOLOGY	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATIONS
Rotary kiln	<ul style="list-style-type: none"> <li>Proven technology for organics.</li> <li>Transportable and mobile units available.</li> <li>Can treat a variety of media (sand, clay, solids and liquids).</li> </ul>	<ul style="list-style-type: none"> <li>Cost is prohibitive (US\$235 to US\$1176/h).</li> <li>Ash may be hazardous.</li> </ul>	<ul style="list-style-type: none"> <li>Proven technologies (the Netherlands, Sweden, Germany and North America).</li> </ul>
Fluidized beds and circulating bed combustors	<ul style="list-style-type: none"> <li>Afterburner not required due to turbulence.</li> <li>Auxiliary fuel not required to maintain combustion.</li> </ul>	<ul style="list-style-type: none"> <li>Ash byproduct may be hazardous.</li> <li>Cost is prohibitive (US\$118 - US\$353/h).</li> <li>Pretreatment of waste required.</li> </ul>	<ul style="list-style-type: none"> <li>Technologies currently in use in Europe but yet to be demonstrated in North America.</li> </ul>
Infrared incinerators	<ul style="list-style-type: none"> <li>Transportable units are available.</li> <li>Conveyor belt provides constant feed.</li> <li>Little auxiliary fuel required.</li> <li>Fewer particulate emissions than with other types of incinerators.</li> </ul>	<ul style="list-style-type: none"> <li>Electric power required.</li> <li>Ash may be hazardous.</li> <li>High cost (US\$425/h).</li> <li>Pretreatment of waste required.</li> </ul>	<ul style="list-style-type: none"> <li>Approved technologies (U.S.).</li> <li>Technologies used at several Superfund sites.</li> </ul>
Industrial processes <ul style="list-style-type: none"> <li>Multiple hearth kiln</li> <li>Cement kilns</li> <li>Lime kilns</li> <li>Boilers</li> </ul>	<ul style="list-style-type: none"> <li>Technology available in industry.</li> <li>Some technologies can incinerate sludge as well as domestic and industrial waste.</li> </ul>	<ul style="list-style-type: none"> <li>Equipment generally not transportable.</li> <li>Waste with low heat content and high metal and chlorine content is generally undesirable.</li> </ul>	<ul style="list-style-type: none"> <li>Technologies widely used to destroy municipal and industrial wastes.</li> <li>Technologies use waste as reserve fuel.</li> </ul>
Enhanced incinerators	<ul style="list-style-type: none"> <li>High throughput rate and low fuel consumption.</li> <li>High removal efficiencies.</li> <li>Low cost.</li> </ul>	<ul style="list-style-type: none"> <li>May generate NO<sub>x</sub>.</li> <li>Produces slag because of high temperatures.</li> </ul>	<ul style="list-style-type: none"> <li>Pyretron oxygen burner demonstrated at a Superfund site.</li> </ul>
Pyrolysis	<ul style="list-style-type: none"> <li>Heat from secondary combustion chamber can be recovered.</li> <li>System is totally enclosed and offgas is combusted in an afterburner.</li> </ul>	<ul style="list-style-type: none"> <li>Residual ash must be treated for nonvolatiles before disposal.</li> <li>Waste containing metals or salts is not destroyed and is present in the ash.</li> </ul>	<ul style="list-style-type: none"> <li>Technology demonstrated for liquids, sludge and soil contaminated with volatile organics.</li> </ul>
Vitrification <ul style="list-style-type: none"> <li>High temperature slagging incinerators</li> </ul>	<ul style="list-style-type: none"> <li>Inorganics immobilized in slag.</li> <li>Efficient for removal of highly toxic and radioactive waste.</li> </ul>	<ul style="list-style-type: none"> <li>Pretreatment of waste required.</li> <li>Unit is not portable.</li> <li>Low throughput (0.06 t/h).</li> <li>High cost (US\$4000/h).</li> </ul>	<ul style="list-style-type: none"> <li>Technology currently used in Belgium and Japan for radioactive waste.</li> </ul>
Vitrification <ul style="list-style-type: none"> <li>Plasma reactor</li> </ul>	<ul style="list-style-type: none"> <li>Inorganics immobilized in slag.</li> <li>High removal efficiencies.</li> <li>Can be used for liquid waste.</li> </ul>	<ul style="list-style-type: none"> <li>Electric power required.</li> <li>Feed rates low.</li> </ul>	<ul style="list-style-type: none"> <li>Technology under demonstration in the Superfund program.</li> </ul>
Vitrification <ul style="list-style-type: none"> <li>Flame reactor</li> </ul>	<ul style="list-style-type: none"> <li>High throughput.</li> <li>Metal oxides are recovered.</li> </ul>	<ul style="list-style-type: none"> <li>Pretreatment of waste required.</li> </ul>	<ul style="list-style-type: none"> <li>Technology under demonstration in the Superfund program.</li> </ul>
Vitrification <ul style="list-style-type: none"> <li>Electric reactor</li> </ul>	<ul style="list-style-type: none"> <li>Organics are destroyed.</li> <li>Inorganics are immobilized.</li> </ul>	<ul style="list-style-type: none"> <li>Pretreatment of waste required.</li> <li>High capital costs.</li> <li>Energy-intensive.</li> </ul>	<ul style="list-style-type: none"> <li>Technology demonstrated on a pilot scale only.</li> </ul>
Vitrification <ul style="list-style-type: none"> <li>Cyclone combustor</li> </ul>	<ul style="list-style-type: none"> <li>Products of incomplete combustion are entrapped in slag.</li> </ul>	<ul style="list-style-type: none"> <li>Little information available about the technology.</li> </ul>	<ul style="list-style-type: none"> <li>Technology under development for the Superfund program; pilot-scale tests planned.</li> </ul>
In situ vitrification	<ul style="list-style-type: none"> <li>On site process that does not require excavation.</li> <li>Depths up to 5 m can be treated.</li> <li>Product is chemically inert and structurally stable.</li> </ul>	<ul style="list-style-type: none"> <li>Offgas treatment required.</li> <li>Volume reduction may occur (shumping).</li> <li>Metal objects and debris interfere with current flow.</li> </ul>	<ul style="list-style-type: none"> <li>Technology demonstrated on a field scale on radioactive waste.</li> <li>Pilot scale tests in progress on PCBs, dioxins and metal waste.</li> </ul>

Adapted from CH2M Hill Engineering Ltd (1991)

Conventional industrial processes (multiple hearth incinerators, cement kilns and boilers) are available technologies widely used to treat a great variety of waste. Because of equipment requirements, however, these processes are hard to bring on site. Enhanced incinerator technologies appear very promising at the moment because they cut costs of thermal treatment.

Pyrolysis has been demonstrated effective in treating liquids, sludge and soil contaminated by volatile organic compounds. This technology is attractive because reactions take place in a completely enclosed system and heat can be recovered. Pyrolysis does not, however, destroy metals or salts, which turn up in the ash.

Vitrification converts waste into a molten material that turns into a glass slag upon cooling. The advantage of this technology is that organics are destroyed by the high reaction temperatures or are burned in afterburners. Inorganics and products of incomplete combustion are immobilized in the slag (CH2M Hill Engineering Ltd., 1992). However, many vitrification processes require waste pretreatment, which means treatment costs are relatively high, and few of the technologies have been demonstrated on contaminated soil.

Table 4.21 lists the main strengths, limitations, applications and demonstrations of three unconventional high-temperature thermal technologies (molten salt, high temperature/high pressure steam and clay pretreatment) and six unconventional low-temperature thermal technologies (desorption, AOSTRA-Taciuk, valorization of chlorinated residues, mercury roasting, radio frequency heating and in situ steam heating).

The three unconventional high temperature technologies are attractive because, unlike conventional incineration, air emissions are not a problem. These technologies are still in the experimental stage however and can only treat relatively few matrices and contaminants.

The AOSTRA-Taciuk process, demonstrated effective for removing hydrocarbons from bituminous sands in western Canada, has been conclusively tested in the United States and Canada for remediation of contaminated soil and treatment of hazardous waste.

Clay pretreatment is a thermal technology demonstrated in Germany for treatment of sediment contaminated by heavy metals. With this technology, described in section 4.6.6 below, treated sediment can be reused, which cuts treatment costs.

**Table 4.21**      **Strengths, limitations and contaminated-soil applications of unconventional thermal technologies**

TECHNOLOGY	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATIONS
Molten salt	<ul style="list-style-type: none"> <li>Because salts are formed, no acid gases are produced.</li> <li>Technology designed for highly toxic inorganic or halogenated compounds.</li> </ul>	<ul style="list-style-type: none"> <li>Molten salts can be corrosive.</li> <li>Waste salt must be landfilled.</li> </ul>	<ul style="list-style-type: none"> <li>Process in experimental stage.</li> </ul>
High-temperature/ high-pressure steam	<ul style="list-style-type: none"> <li>Dioxins and furans not created as no oxygen is introduced in the process.</li> </ul>	<ul style="list-style-type: none"> <li>Treatment cost is US\$2/kg.</li> <li>Only liquid wastes can be treated.</li> <li>Technology still in pilot stage.</li> </ul>	<ul style="list-style-type: none"> <li>Process at pilot stage.</li> <li>Tested on PCB-contaminated liquids.</li> </ul>
Low temperature technology • Desorption	<ul style="list-style-type: none"> <li>Low fuel requirement.</li> <li>No products of combustion.</li> <li>Contaminants can be recovered.</li> </ul>	<ul style="list-style-type: none"> <li>Other waste is generated (carbon filters).</li> <li>High moisture content and high percentage of fines reduce process efficiency.</li> <li>Removes volatile compounds only.</li> </ul>	<ul style="list-style-type: none"> <li>Process at demonstration stage.</li> </ul>
Low temperature technology • AOSTRA-Taciuk process	<ul style="list-style-type: none"> <li>Uncontaminated oil can be recycled.</li> </ul>	<ul style="list-style-type: none"> <li>Hazardous wastes are not destroyed.</li> </ul>	<ul style="list-style-type: none"> <li>Technology demonstrated for recovery of oil in tar sands.</li> <li>Pilot-scale demonstration on hazardous wastes.</li> <li>Demonstrated on a pilot scale for soil and sediment at Superfund sites and as part of Great Lakes cleanup.</li> </ul>
Clay pretreatment	<ul style="list-style-type: none"> <li>Waste transformed into a useful product.</li> <li>Product can be sold to partially recover cost of treatment.</li> </ul>	<ul style="list-style-type: none"> <li>Generates other waste.</li> </ul>	<ul style="list-style-type: none"> <li>Technology demonstrated in Germany on sediment contaminated by heavy metals.</li> </ul>
Low temperature technology • Valorization of chlorinated residues	<ul style="list-style-type: none"> <li>HCl is recovered.</li> <li>Quenching of gas limits corrosion and maintenance.</li> <li>Treats chlorinated organic solvents in liquids, solids and gases.</li> </ul>	<ul style="list-style-type: none"> <li>Capital cost for a unit with a throughput of two tons per hour is US\$5 million.</li> </ul>	<ul style="list-style-type: none"> <li>Technology in operation in Europe for over 15 years.</li> <li>One unit operating in the U.S. and nine in Europe.</li> </ul>
Low temperature technology • Mercury roasting	<ul style="list-style-type: none"> <li>Mercury is recovered.</li> </ul>	<ul style="list-style-type: none"> <li>Solid residue must be disposed of in hazardous landfill.</li> </ul>	<ul style="list-style-type: none"> <li>Commercial plant in operation in Japan.</li> </ul>
Radio frequency heating	<ul style="list-style-type: none"> <li>In situ remediation of soil contaminated by volatile organics.</li> </ul>	<ul style="list-style-type: none"> <li>Large scale applications may be costly.</li> <li>Application below water table is more costly than above.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated at laboratory scale for several types of soils.</li> <li>Can be applied to clayey soils.</li> </ul>
In situ steam heating	<ul style="list-style-type: none"> <li>Good removal of volatile and particularly semivolatile organics.</li> <li>Treatment rate increases when volatilization is at ambient temperature.</li> </ul>	<ul style="list-style-type: none"> <li>Source of steam required.</li> <li>Removal not as effective in low permeability zones unless "detoxifier" system used.</li> <li>Drying of soil may increase sorption and hence inhibit removal of volatile compounds.</li> <li>Condensation may inhibit removal.</li> <li>"Detoxifier" system not applicable to coarse sand and difficult to monitor.</li> </ul>	<ul style="list-style-type: none"> <li>Application laboratory-demonstrated.</li> <li>Technology available from several vendors in Europe.</li> <li>Technology under demonstration at Superfund sites.</li> </ul>

Adapted from CH2M Engineering Ltd., 1991

Valorization of chlorinated residues technologies have been operating in Europe for over fifteen years. The technologies have been used to remove chlorinated organic solvents from liquids, solids or gases. These technologies are attractive because hydrochloric acid is recovered, but capital costs are quite high. (CH2M Hill Engineering, 1992).

A commercial mercury roasting unit is in operation in Japan for treatment of soil contaminated by mercury. Soil is placed in a furnace where mercury is volatilized for subsequent condensation and recovery. Solid residues must be landfilled.

In situ steam and radio frequency heating are attractive options for restoring soil contaminated by volatile organics but they have only been laboratory-tested on soil. Demonstration projects are currently under way at U.S. Superfund sites (Averett et al., 1990).

**4.6.5 Strengths and limitations for sediment treatment.** According to the USEPA, the suitability of high-temperature thermal processes for sediment treatment depends on volume of the material to be treated as well as its physical and chemical makeup, which can significantly affect treatment conditions, the following in particular:

- Extent of particle classification required.
- Amount of dewatering required and dewatering technology selected.
- Type of thermal treatment selected.
- Air pollution control system design.
- Treatment of residual ash prior to disposal (USEPA, 1991b).

As of 1990, incinerators had not yet been tested in the United States for sediment treatment. They have, however, been selected for a number of U.S. Superfund sites because destruction efficiencies are very high (>99 percent) for organic contaminants. As Table 4.22

Table 4.22 Anticipated performance of thermal technologies applied to sediment remediation

TECHNOLOGY	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABILITY	PERFORMANCE RATINGS**		
				EFFEC-TIVENESS	IMPLEMENT-ABILITY	COST
Radiant energy						
LARC	Conceptual	No	Proprietary	3	1	2
Ozonics	Conceptual	No	Proprietary	2	1	2
Photolysis	Conceptual	No	Emerging	2	1	2
Thermal energy						
Advanced electric reactor***	Pilot	No	Proprietary	4	2	1
Blast furnaces	Demonstrated	No	Available	3	2	1
Circulating bed combustor	Demonstrated	Yes	Available	4	3	2
EcoLogic*	Pilot	Pilot	Proprietary	4	3	2
Flame reactor process	Pilot	No	Proprietary	3	2	1
Fluidized-bed incineration***	Demonstrated	No	Available	4	2	1
High-temperature slag incineration***	Demonstrated	No	Proprietary	4	2	1
Industrial kilns	Demonstrated	No	Available	3	2	1
Infrared (Shirco) incineration***	Pilot	No	Proprietary	4	2	1
In situ vitrification (Battelle)	Pilot	Bench	Proprietary	4	2	1
Liquid injection incineration	Demonstrated	No	Available	3	1	1
Low-temperature thermal stripping	Demonstrated	No	Available	3	2	2
Lurgi pelletizing process	Pilot	Yes	Proprietary	3	1	1
Molten glass vitrification	Conceptual	No	Emerging	3	1	1
Molten salt incineration	Conceptual	No	Emerging	4	1	1
Multiple hearth incineration***	Demonstrated	No	Available	4	2	1
Plasma arc incineration	Pilot	No	Emerging	3	1	1
Pyretro incinerator	Pilot	No	Proprietary	3	1	1
Pyrolysis***	Demonstrated	No	Available	4	2	1
Pyrometallurgy	Demonstrated	No	Available	2	2	1
Pyroplasma process	Pilot	No	Proprietary	3	2	1
Radio frequency heating	Conceptual	No	Emerging	3	1	1
Roasting	Conceptual	No	Emerging	3	1	1
Rotary kiln incineration	Demonstrated	No	Available	4	2	2
Supercritical water oxidation***	Pilot	No	Proprietary	4	2	1
Taciuk	Pilot	Pilot	Proprietary	3	3	2
Vitrification***	Pilot	Bench	Proprietary	4	3	1
Wet air oxidation	Demonstrated	Bench	Proprietary	2	3	3

Notes

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

\*\*\* Technologies selected for demonstration projects at a later stage.

Adapted from Averett et al., 1990

shows, the low fuel value and high water content of sediment increases costs of using incineration technologies to treat sediment and limits their applicability.

Like other thermal processes, pyrolysis does not perform as well on matrices with high water contents. Hence a dewatering stage is required when treating sediment.

Low-temperature thermal process have demonstrated high removal efficiencies for a number of volatile organic compounds in soil. They have limited applications for sediment, however, because of its high water content. Sediment must be dewatered first, which considerably increases treatment costs.

**4.6.6 Technologies demonstrated for sediment treatment.** Table 4.23 lists thermal technologies demonstrated for sediment treatment. The table also lists name of the developer of the technology, place and scale of demonstration and contaminants treated.

**Incinerators.** As Table 4.23 indicates, rotary and infrared kilns have been used in Europe and the United States to treat contaminated sediment. Several plants in Europe are treat sediment commercially.

The Canadian Company Superburn Systems Ltd is in the process of treating 700 000 tons of soil and sediment from Sydney Tar Ponds, Nova Scotia using two revolving fluidized bed incinerators. The soil and sediment is contaminated by PAHs (an average 6900 ppm), zinc, lead, copper and aluminium Treatment time is estimated at seven years and cost at C\$50 million (Kendall, 1991).

**DAVES process.** Recycling Sciences International Inc. has developed a desorption and vapour extraction system (DAVES) that uses a low-temperature fluidized bed to remove organics and volatile inorganic compounds from soil, sediment and sludge. The process was tested on a pilot scale on sediment from Waukegan Harbour in Illinois. PCB concentrations of as much as 250 ppm in the material tested were cut to less than 2 ppm (USEPA, 1991c).

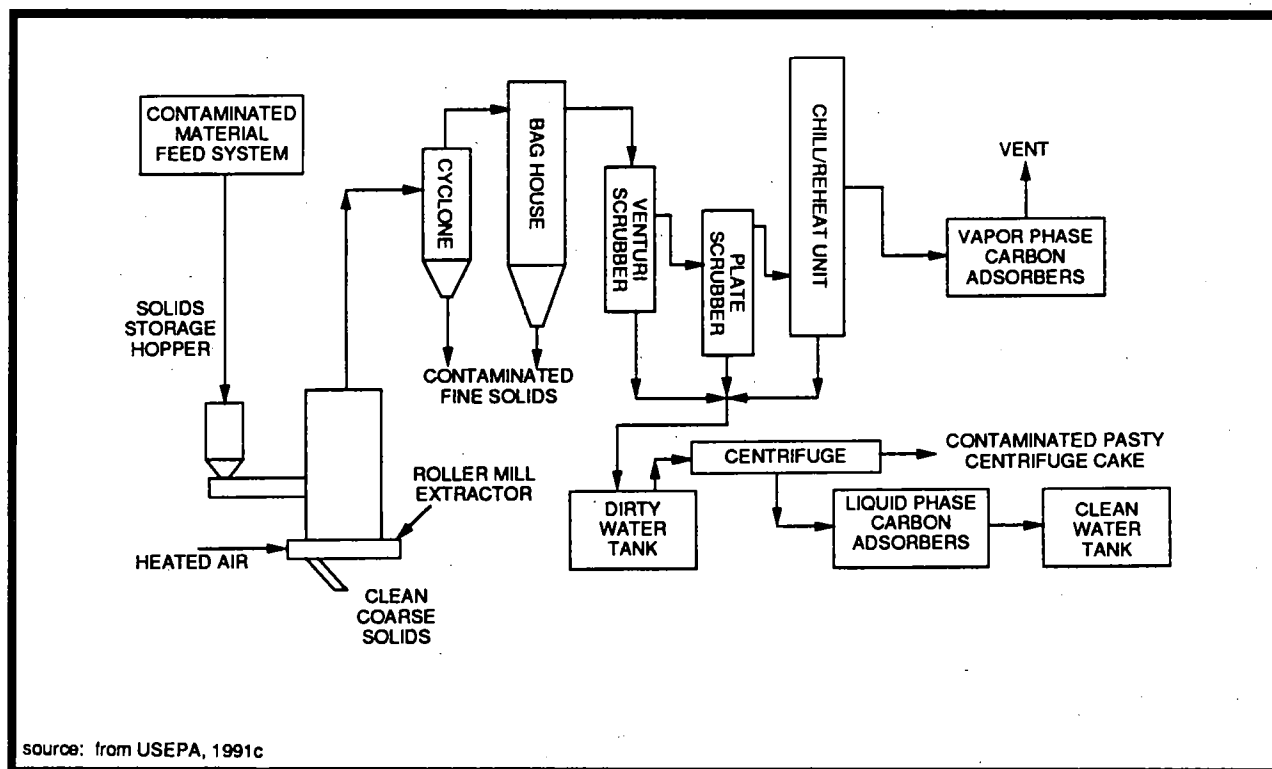
Figure 4.44 shows a schematic of the DAVES process.



Table 4.23 Thermal technologies demonstrated for sediment remediation

Technology	Developer	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Thermal destruction Rotary kiln	Several companies	U.S.	Grand Island, NE & Shreveport, LA	Commercial	Explosives	USEPA, 1991b
	Several companies	Holland	Not specified	Commercial	Organics	USEPA, 1991b
	Several companies	Germany	Not specified	Commercial	Organics	USEPA, 1991b
Infrared incineration	Shirco Infrared Systems Inc. (now ECOVA Corporation)	U.S.	Brandon, FL	Commercial	Metals, PCBs and other organics	USEPA, 1991b
	Ogden Environmental Services Inc.	U.S.	Swanson River, AK	Full	PCBs	Averett et al., 1990
Circulating bed incineration	Superburn Systems Ltd.	Canada	Sidney Tar Ponds, NS	Full	PAHs	
Wet air oxidation	Zimpro/Passavant Inc.	U.S.	Indiana Harbour, IN	Bench scale	PCBs	Averett et al., 1990
Thermal desorption • DAVES process  • LTTS process  • AOSTRA-Taciuk process	Recycling Sciences International Inc.	U.S.	Waukegan Harbour, IL	Pilot	PCBs	USEPA, 1991b
	US Army Toxics and Hazardous Materials Agency (USATHAMA)	U.S.	Wilmington, DE	Bench	PCBs and volatile and semivolatile organics	USEPA, 1991b
	SoilTech Inc.	U.S.	Waukegan, Superfund site	Pilot	PCBs	Averett et al., 1990
	UMATAC Industrial Process	Canada	Hamilton Harbour, Thunder Bay Harbour, ON	Bench	PCBs, HAPs and heavy metals	WTC, 1992b
Lurgi process	Lurgi Canada Ltd.	Germany	Hamburg harbour	Full	Organics and metals	WTC, 1992b

\* See Appendix C for addresses and telephone numbers of developers.



**Figure 4.44 Desorption and vapour extraction system (DAVES) process scheme**

Contaminated materials are fed into a co-current fluidized bed, where they are mixed with hot air (535°C to 760°C) from a gas-fired heater. Direct contact between the waste material and the hot air forces water and contaminants from the waste into the gas stream at a relatively low fluidized-bed temperature (about 175°C). The heated air, vaporized water and organics and entrained particles flow out of the dryer to a gas treatment system.

The gas treatment system removes solid particles, vaporized water and organic vapours from the air stream. A cyclone separator and baghouse remove most of the particulates in the gas stream from the dryer. Vapours from the cyclone separator are cooled in a venturi scrubber, counter-current washer and chiller section before they are treated in a vapour-phase carbon adsorption system.

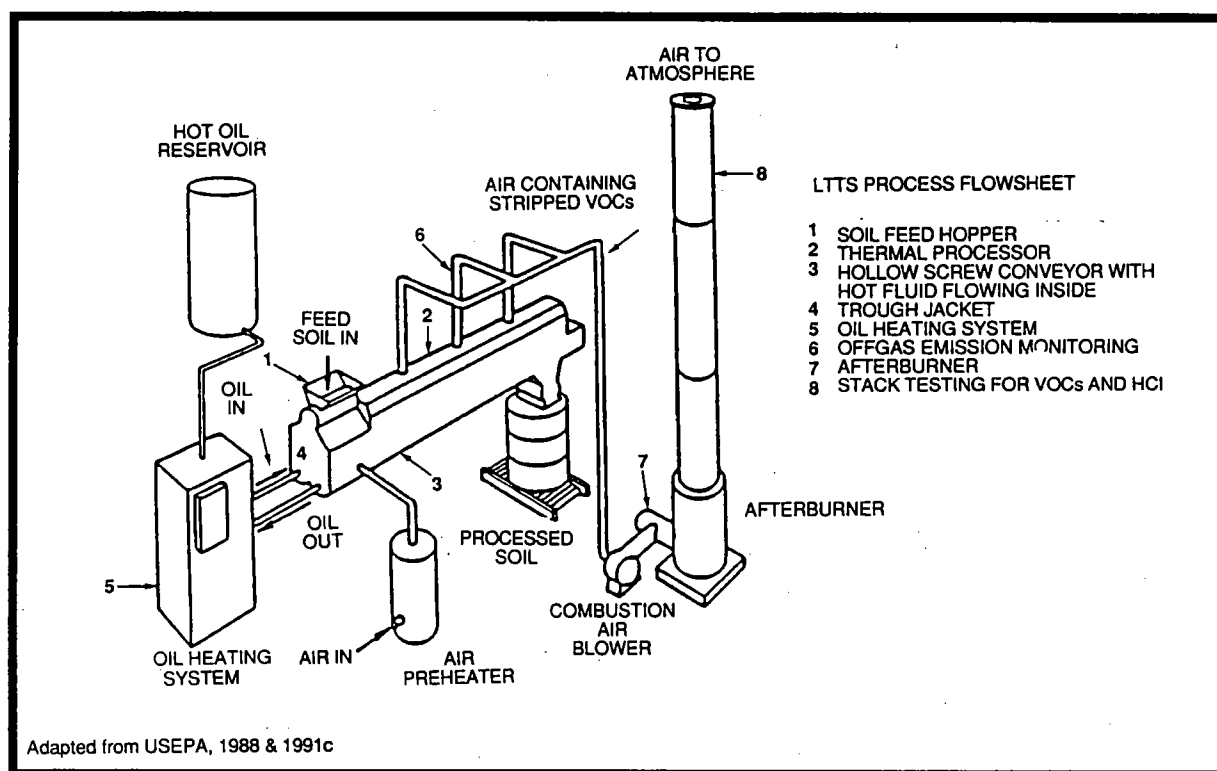
This technology can remove volatile and semivolatile organics, including PCBs, HAPs and PCPs, volatile inorganics (tetraethyl lead) and some pesticides from

soil, sediment and sludge. In general, the process treats waste containing less than 5 percent total organic contaminants and 30 to 90 percent solids. Nonvolatile inorganic contaminants (such as metals) are not treated but do not inhibit the process (USEPA, 1991c).

**LTTS process (low-temperature thermal stripping).** Low temperature thermal stripping processes physically remove volatile and semivolatile contaminants from soil, sediment, sludge and filter cakes. LTTS systems can be used alone to cleanup contaminated sites with less than ten percent total organics.

The LTTS process can be used to remove volatile organic substances such as HAPs; it is not generally used to treat inorganic contaminants and metals. The contaminated matrix is heated to between 95°C and 538°C to draw out water and volatile contaminants. This process does not require the very high temperatures incineration processes require.

Figure 4.45 shows a LTTS desorption process scheme.



**Figure 4.45 LTTS desorption process scheme**

Offgas is burned in an afterburner, condensed to reduce its volume or collected on a carbon adsorption system. For treatability test in the United States under the Great Lakes sediment cleanup program, only processes with air pollution control systems were considered. The LTTS process should be suitable for solids, water and oily waste. It is not designed to completely destroy contaminants, but treated sediment should be easier to dispose of.

**AOSTRA-Taciuk process.** A thermal desorption process was developed in the 1970s by Alberta Oil Sands Technology and Research Authority (AOSTRA) and UMATAC Industrial Processes. The process was originally designed to extract oil from bituminous sands in the Canadian west. When petroleum prices fell, the technology was applied to treatment of soil, sediment and other hazardous waste.

A pilot unit (throughput is 5 tons per hour) operated by UMATAC with is available for demonstration projects from Swan Hills in Calgary. Décontam Inc. of Montreal has the operating license for the AOSTRA-Taciuk technology in Eastern Canada. SoilTech, a U.S. firm, built and operates a commercial unit with a throughput of 5 to 20 tons per hour. This unit was used for demonstration and remediation projects with PCB-contaminated soil at Wide Beach Development site in New York and on PCB-contaminated soil/sediment at Waukegan Harbour in Illinois (USEPA, 1992g; USEPA, 1992h).

The AOSTRA-Teacake technology is similar to other low-temperature desorption technologies. Contaminated media are fed into a pyrolysis/combustion reactor called the AOSTRA-Taciuk Processor, the key to the process and its most innovative component (CH2M Hill Engineering Ltd., 1992).

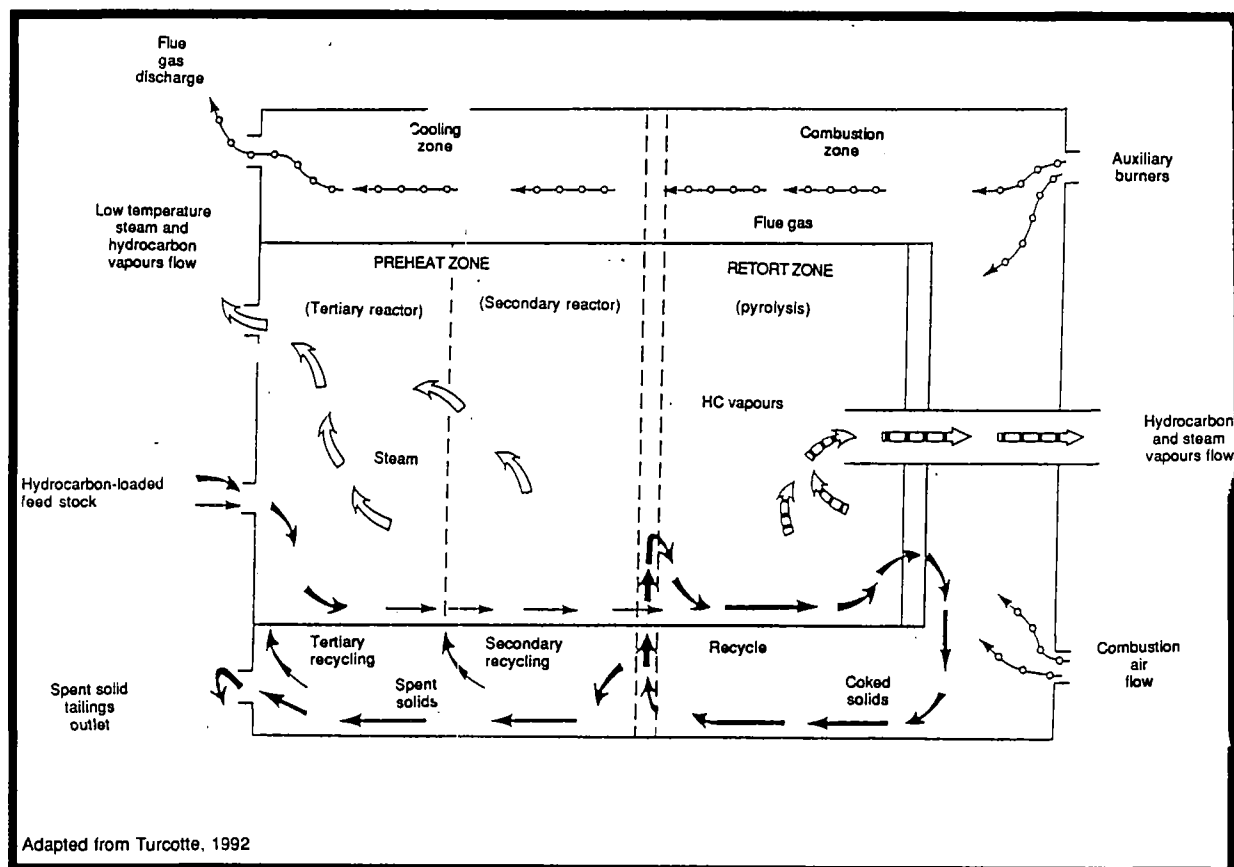


Figure 4.46 AOSTRA-Taciuk reactor schematic

As Figure 4.46 shows, the processor consists of a single horizontal rotating vessel with four compartments designed to recover and separate various product streams. Figure 4.47 shows other major process components.

The first compartment of the processor is the preheat zone. Here the contaminated feed is heated to 260°C. Water and low temperature volatiles such as light oils are volatilized here and then condensed externally.

The waste then moves to the second compartment, the reaction zone, where temperatures range from 370°C to 590°C. Here heavy oils and PCBs vaporize. To prevent hydrocarbon oxidation, anoxic (absence of oxygen) conditions are maintained in the preheat and reaction zones. The pyrolytic reactions produce a vapour stream and coke-coated particle residues. As Figure 4.47 shows, steam and residual hydrocarbon vapours are sent to the treatment plant's oil recovery system.

The coke-coated particles are transferred from the reaction zone to the combustion zone. Most of the coke is burned off in the combustion zone, where preheated combustion air is added. Heat from the combustion zone is recycled to fuel other parts of the process. Natural gas burners are also used to maintain operating temperatures between 540°C and 815°C. Inert hot solids are then recycled to the reaction zone, and excess solids are sent to the external compartment of the heat exchanger of the cooling zone where they are cooled by thermal transfer to the waste feed. The inert solids leave the processor and are further cooled by quenching before they are transported by conveyers or trucks to storage areas.

Heavy oils recovered at the base of the fractionating column can be returned to the reaction zone, used as supplementary fuel, sent to a hydrotreatment unit or sold as fuel.

Flue gases are treated by a series of cyclones to reduce concentrations of suspended solids, by precipitators, dedusters, baghouses or electrostatic precipitators, or scrubbers that remove particulates and sulphides produced by combustion of coke.

Water streams from the pyrolytic vapours recovery and separation system are steam desulphurized before passing to the wastewater treatment equipment.

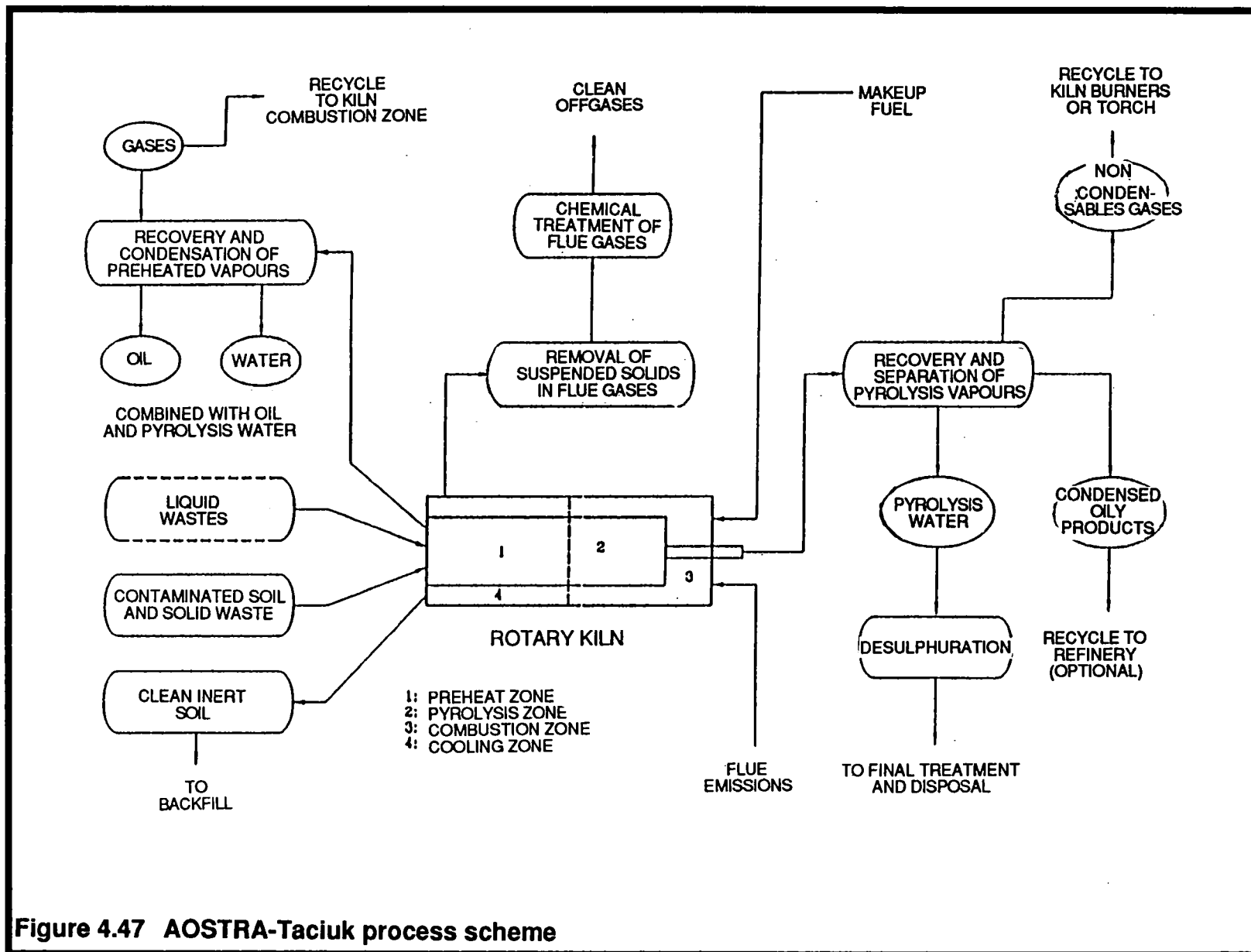


Figure 4.47 AOSTRA-Taciuk process scheme

Since tests of the AOSTRA-Taciuk process on soil from the Wide Beach site in New York and from Waukegan Harbour in Illinois were conclusive, the process was selected to treat all Waukegan Harbour sediment, which is highly contaminated by PCBs.

**Lurgi pelletizing process.** Lurgi Canada Ltd., entered in the SEDTEC technologies bank, is a subsidiary of the German-based firm Lurgi that has developed a process for dewatering contaminated harbour sediment in open-air beds. The dewatered material is then formed into small pellets that are incinerated to destroy organic contaminants. Residual solids are recovered and used as construction material or a substitute for gravel.

As Figure 4.48 shows, there are four main stages to this commercial process that converts sediment to vitrified pellets:

- Separation of sediment solid and clay fractions by sorters and hydrocyclones.
- Mechanical dewatering of the silt fraction by belt presses.
- Pelletizing of the silt fraction.
- Firing at temperatures between 1150°C and 1180°C with excess air to fix metals in a ceramic-like pellets that can be used as building material.

To prevent overheating during firing, carbon content of the sediment has to be reduced by adding a soft burned refractory clay, a filler (that is a material that reduces clay plasticity) commonly used in the ceramics industry.



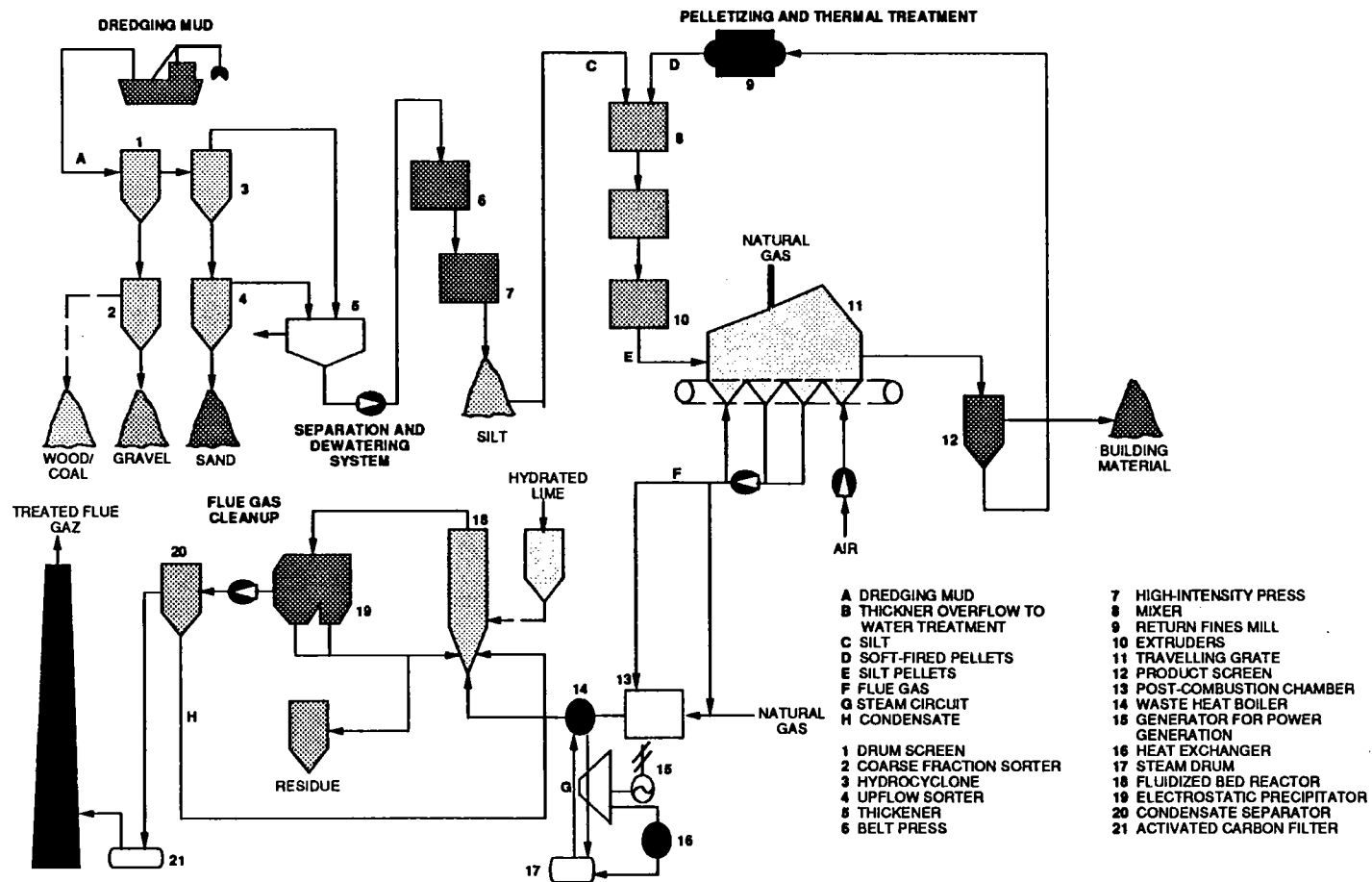
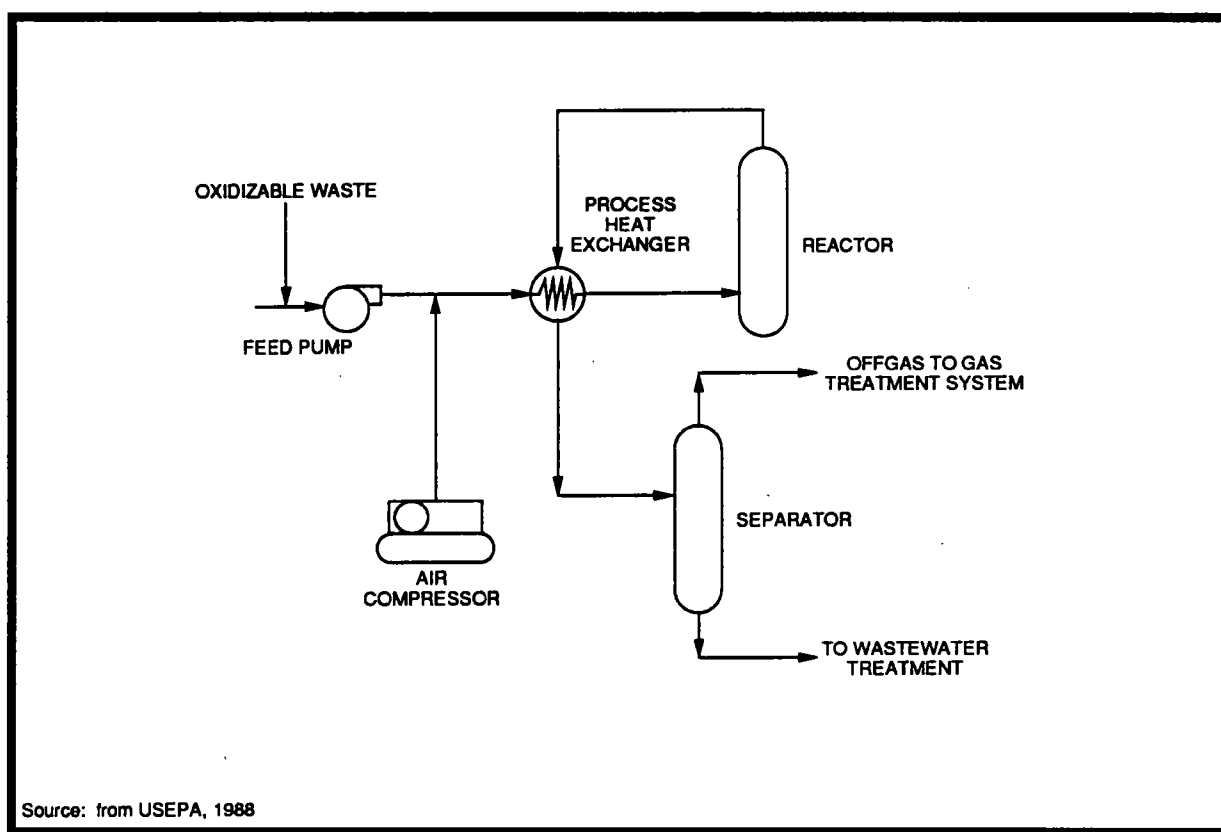


Figure 4.48 Lurgi process scheme

According to the vendor, tests on sediment from Hamburg Harbour in Germany demonstrated the following:

- Complete destruction of organic contaminants.
- Effective chemical fixation of metals.
- Production of an agglomerate of varied sizes and shapes suitable for building material.
- No volume increase in the product, unlike most other stabilization/solidification process.
- Effective treatment of air emissions and minimum volume of treatment residues to be disposed of.
- Treatment costs do not exceed costs of disposal in a hazardous landfill.

**Wet air oxidation.** Bench-scale tests by Zimpro/Passavant Inc. on Indiana Harbour sediment demonstrated a 52 percent destruction efficiency for PCBs. In addition, toxicity and leaching tests of treated solids demonstrated they were no longer hazardous waste. Cost of using this technology is approximately US\$25 per cubic yard (Averett et al., 1990).



**Figure 4.49 Zimpro Passavant wet air oxidation process scheme**

**4.6.7 Technologies under demonstration for sediment treatment.** As Table 4.24 shows, the USEPA and the USACE recommended for Great Lakes sediment remediation demonstration projects four of the twenty-eight thermal technologies they considered and evaluated: wet air oxidation, low-temperature thermal stripping, the AOSTRA-Taciuk pyrolysis process and the EcoLogic thermochemical process described in section 4.5 herein.

These thermal desorption processes were selected by the rating procedure shown in Table 4.22 because that can be implemented at lower cost and are more easily accepted by communities that are incineration processes; communities are reticent to accept incineration processes because of concerns about air emissions.

Table 4.24 Thermal technologies under demonstration for Great Lakes sediment remediation

Technology	Developer	Place of Demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Thermal desorption • ReTec process	Remediation Technologies Inc.	U.S.	Ashtabula River	Bench/pilot	PCBs and other organochlorines PAHs, oils and greases PCBs, PAHs, oils and grease PCBs	USEPA, 1992a
			Buffalo River	Bench/pilot		
			Grand Calumet River	Bench		
			Sheboygan Harbour	Bench		
Thermal desorption • AOSTRA-Taciuk	SoiTech Inc.	U.S.	Buffalo River	Bench	PAHs, oils and greases PCBs	USEPA, 1992a
			Indiana Harbour			
Incineration	Not specified	U.S.	Great Calumet River	Bench	PCBs, PAHs, oils and greases	USEPA, 1992a
Wet air oxidation	Zimpro/Passavant Inc.	U.S.	Sheboygan Harbour	Bench	PCBs	USEPA, 1992a
			Great Calumet River		PCBs, PAHs, oils and greases	

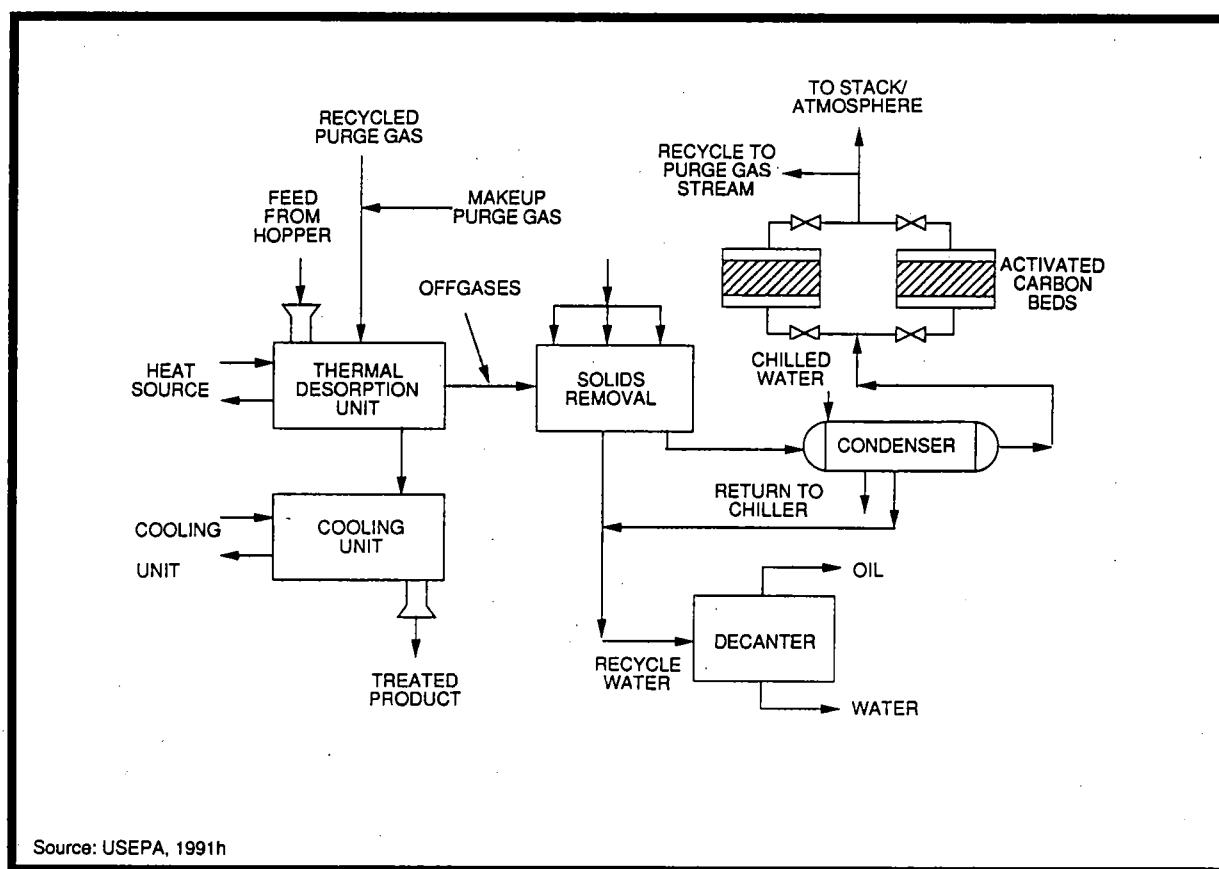
\* See Appendix C for addresses and telephone numbers of developers.

Other thermal technologies were selected for the second or their tiers of process options for U.S. Great Lakes sediment remediation projects because of the need to gain operational experience with thermal processes for contaminated sediment and to find out more about costs of their use. The technologies retained were rotary kiln, circulating bed combustor, advanced electric reactor, fluidized bed incineration, high temperature slagging incineration, infrared incineration and multiple hearth incineration (Averett et al., 1990).

The AOISTRA-Taciuk and wet air oxidation processes have already been described in the section on demonstrated technologies. The following paragraphs outline thermal technologies that have not yet been described.

**ReTeC desorption process.** Remediation Technologies Inc. (ReTeC) developed a high temperature thermal processor to treat solids and sludge contaminated with organic constituents. This process was selected by the USEPA and the USACE for bench-scale demonstration on sediment from the Ashtabula and Grand Calumet rivers and the Sheboygan Harbour (USEPA, 1992a).

As the process scheme in Figure 4.50 shows, the ReTeC process system consists of material feed equipment, a thermal processor, a particulate removal system, an indirect condensing system and activated carbon beds (USEPA, 1991h).



**Figure 4.50 ReTech high temperature thermal process scheme**

Waste is fed by two counter-rotational screw conveyors. A molten salt eutectic, consisting primarily of potassium nitrate, serves as the heat transfer media. This salt melt has heat transfer characteristics similar to those of oils and allows maximum processing temperatures of up to 455°C. The salt melt is noncombustible and poses no risk of explosion; its potential vapours are nontoxic. An electric or fuel oil/gas-fired heater is used to maintain the temperature of the transfer media. Treated product is cooled to less than 65°C.

The gas treatment system comprises a cyclone or quench tower for particulate removal, condensers for removal of organics, activated carbon beds to control volatile organic compounds and a droplet separator.

**X\*TRAX thermal desorption process.** As Table 4.24 indicates the X\*TRAX thermal desorption process is now being bench-scale tested on sediment from Thunder Bay Harbour. Developed by the U.S. firm Chemical Waste Management Inc., this technology extracts organic contaminants (volatiles, semivolatiles and PCBs) from soil, sludge and other matrices. The technology differs from incineration or pyrolysis in that chemical oxidation and reactions are not encouraged and no combustion byproducts are formed. The organic contaminants are removed as a condensed high BTU liquid, which must then be either destroyed in a permitted incinerator or used as supplemental fuel. Because of lower operating temperatures and gas flow rates, this process is less expensive than incineration (USEPA, 1991f).

Water and organic contaminants are volatilized in an indirectly heated rotary dryer. Nitrogen inert gas is used to prevent oxidation of the treated material and carry volatilized gases to the gas treatment system where organic vapours and dust particles are removed and recovered from the gas. The VOC gases are condensed and separated in the gas treatment unit (filters and carbon adsorbers) and the nitrogen is recycled back to the rotary kiln (USEPA, 1991f, Wastewater Technology Centre, 1992a).

**4.6.8 Technologies selected for sediment remediation projects.** Though incinerators have not been used to date to treat contaminated sediment on a regular basis, at least not in the United States, they have nevertheless been selected for remediation of several Superfund sites involving contaminated sediment because they are most effective options at the moment for destroying organic contaminants, even though they are very expensive (Averett et al., 1990).

A number of technologies were analyzed in developing a plan for treating New Bedford Harbour sediment, and incineration was selected to treat sediment from zones most heavily contaminated by PCBs.

As mentioned, a sediment remediation project is under way at Sydney Tar Ponds, Nova Scotia, in Canada. Two circulating bed incinerators built on site are being used to treat the sediment, which is highly contaminated by PAHs.

In 1990, thermal desorption was selected to restore two sites in the United States (American Thermostat in New York and Waukegan Harbour in Illinois.)

**4.6.9 Conclusions.** As the preceding sections show, high-temperature thermal technologies (incineration, vitrification and pyrolysis, for example) as well as low-temperature desorption processes have been demonstrated effective on most organic contaminants and for most matrices (soil, sludge and sediment).

Incineration technologies have been used to treat sediment in Europe, but they have not yet been used commercially in the United States even they have been considered for treatment of certain Superfund sites because of their high destruction/removal efficiencies. In Canada, circulating bed incinerators are being used to treat sediment at the Sydney Tar Ponds site in Nova Scotia.

Performance ratings of most thermal processes are generally low with sediment because of its high water content (which means a dewatering stage is required) and low heat value. Treatment costs are high, as a result, and this limits application of thermal technologies for sediment remediation, especially when large volumes of sediment must be remediated.

Since metals are not destroyed by thermal technologies, they generally turn up in the dust from the gas treatment systems and in the ash. In addition, with some thermal processes, certain metals in the ash are more mobile than they originally were because of changes in their oxidation state.



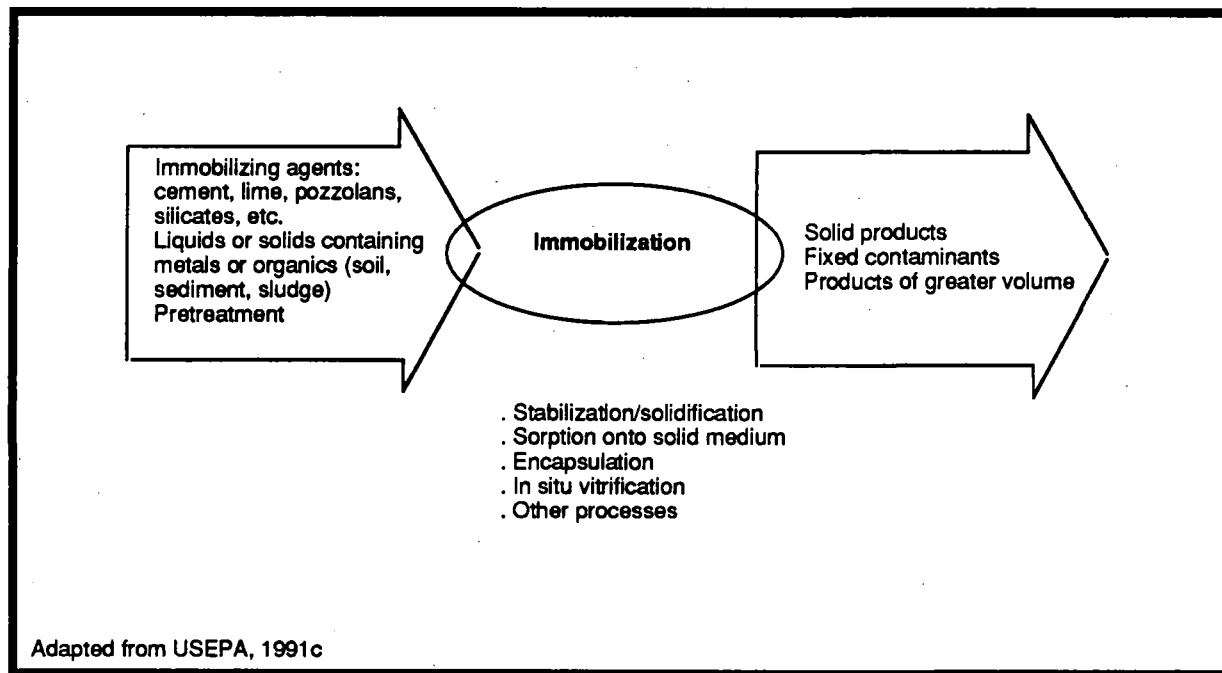
## 4.7            **Immobilization**

**4.7.1            Principle of treatment.** Immobilization technologies (solidification/stabilization) are generally designed to improve handling and physical characteristics of contaminated material, decrease surface area of the sediment mass across which transfer or loss of contaminants can occur, and/or limit solubility of contaminants by pH adjustment or sorption (USEPA, 1991b).

Solidification is a physical process, the conversion of a liquid or semi-solid to a solid by adding solidifying agents such as cement, silicates, pozzolans or other minerals. Solidification is considered effective for immobilizing metals as well as organics provided organics concentrations are low.

Stabilization is a chemical process that alters the chemical form of contaminants by association with a variety of chemical agents such as polymers. Stabilization is generally considered effective for immobilizing metals but not organics. In fact, organics may interfere with solidification/stabilization setting reactions (USEPA, 1991b).

Figure 4.51 shows immobilization inputs and products and technology variants.



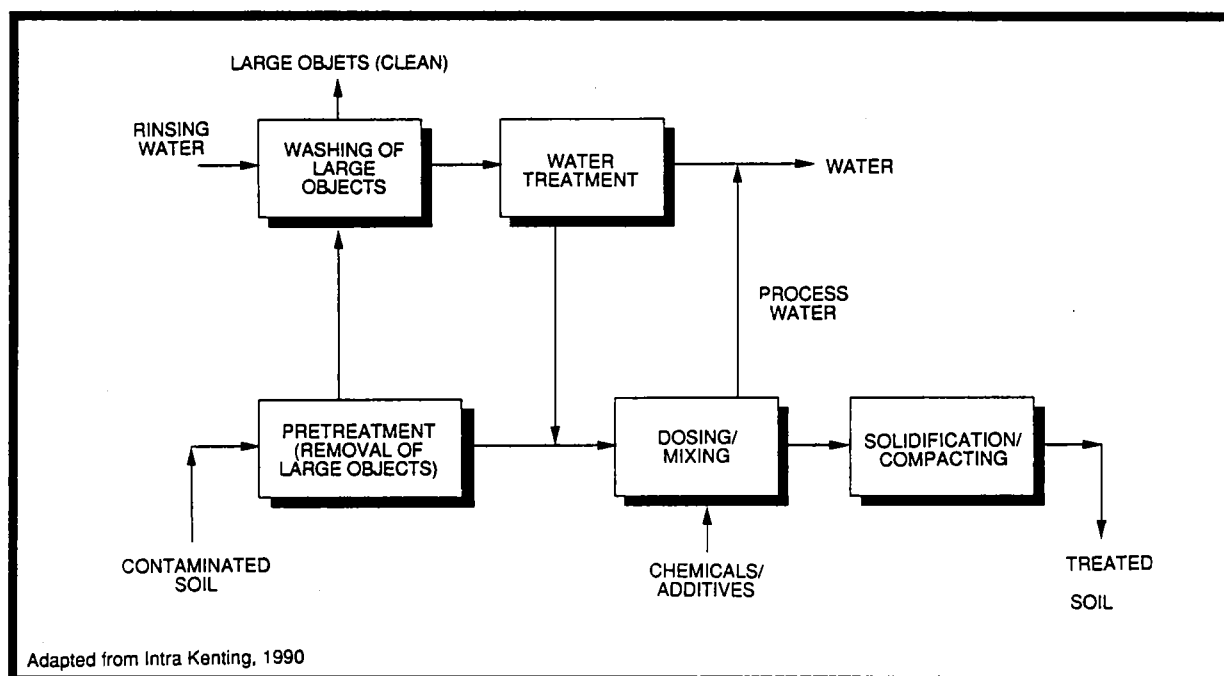
**Figure 4.51**                      **Immobilization inputs and products**

#### **4.7.2**                      **Technologies available**

**4.7.2.1**                      **Stabilization/solidification.** Figure 4.52 shows a stabilization/ solidification process scheme. As the figure shows, stabilization/solidification proceeds as follows:

- 1-        Pretreatment to remove large objects.
- 2-        Washing and removal or crushing of large objects and addition to the soil; if washing is used, a water treatment unit may be required.
- 3-        Mixing of contaminated soil with cementitious or pozzolanic chemicals or other additives and water.
4.        Pouring the mixture into moulds for solidification.

5. Disposal of treated material in landfills or other approved sites (Intra Kenting, 1990).



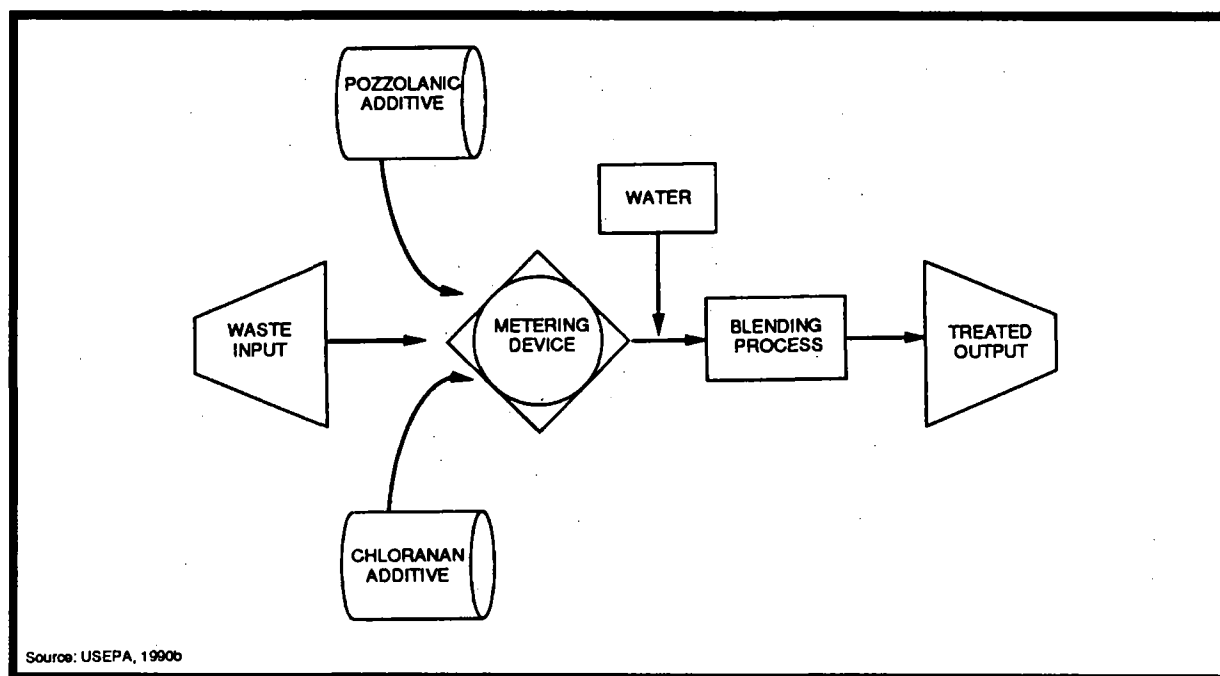
**Figure 4.52 Stabilization-solidification process scheme**

The sections that follow briefly describe stabilization/solidification technologies that use Portland cement, lime (with or without pozzolans), thermoplastics, organic polymers, silicates, modified clays, chloranans or patented products as well as sorption and in situ vitrification processes and other innovative soil-treatment processes still in the design stage.

**Portland cement-based processes.** Many stabilization/solidification processes incorporate Portland cement, water and other additives as binding agents for contaminated soil. Pozzolanic products such as fly ash may also be added to the cement to react with free calcium hydroxide and thus improve strength, handling characteristics and chemical resistance of the concrete-like product.

Cement processes reduce mobility of heavy metals; the elevated pH of the cement converts heavy metals to insoluble hydroxides or carbonates. Sorbents and other additives such as soluble silicates, clays, emulsifiers, carbon, zeolites, cellulosic sorbents and lime are often mixed with cement to improve treatment performance (Averett et al., 1990). The cement and other additives significantly increase the volume of treated soil, sometimes as much as 50% (Intera Kenting, 1990).

Figure 4.53 shows a schematic of a Portland cement-based stabilization/solidification process.

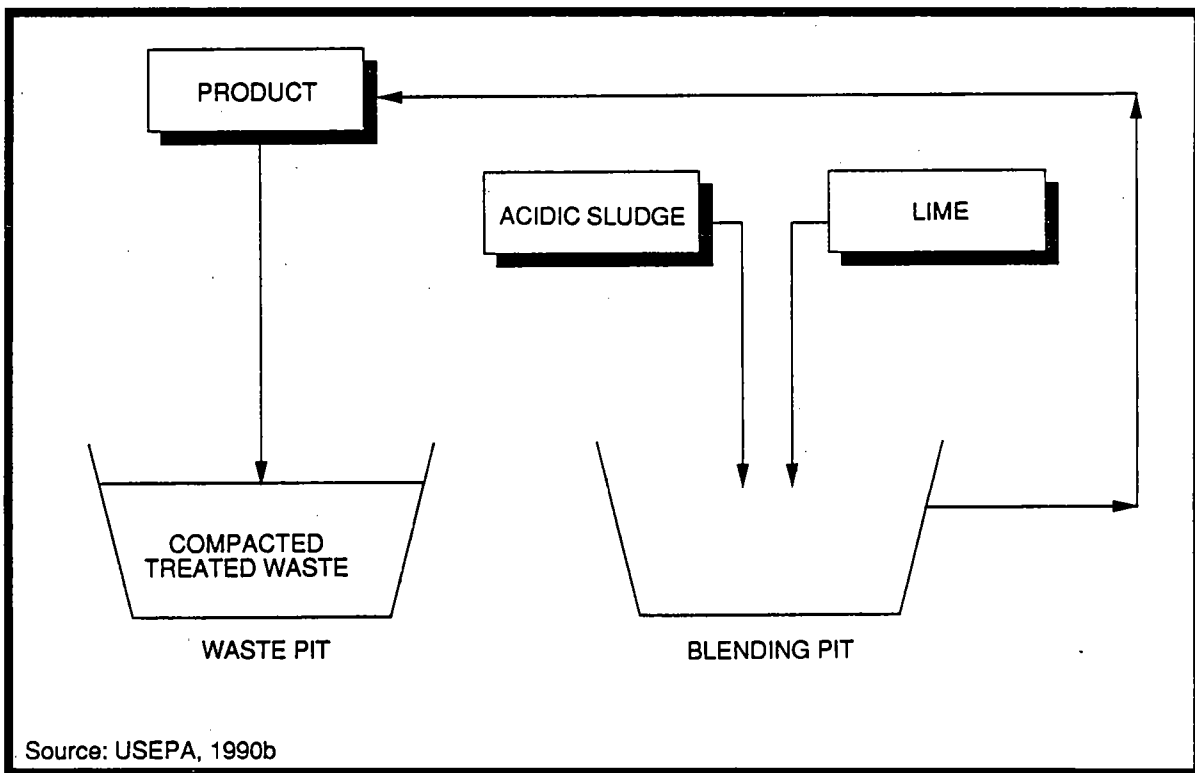


**Figure 4.53 Portland cement-based stabilization solidification process scheme**

This process is one of the more versatile and adaptable stabilization/solidification methods. In addition, the product is exceptionally strong and durable, and retains contaminated materials very effectively (Averett et al., 1990).

**Lime-based processes (with or without pozzolans).** With pozzolan-based processes, contaminated matrices set to a solid mass when mixed with hydrated lime. Pozzolans all contain silicic acid and frequently contain aluminum oxide. The pozzolanic material typically used for stabilization/solidification is bituminous coal fly ash or subbituminous coal fly ash. Pozzolan-based processes are less expensive than cement-based processes but they produce products that are less durable and leach more readily (Averett et al., 1990).

Figure 4.54 shows a schematic of a lime-based stabilization/solidification process.



**Figure 4.54 Lime-based stabilization solidification process scheme**

Lime can also be used in the form of quick lime ( $\text{CaO}$ ). The lime then reacts with water, generating significant heat and enlarging the surface area of the lime so wastes such as

oils are adsorbed on and microencapsulated in a calcium hydroxide. This process densifies the soil; the end-product is compact and but not solidified. (Intera Kenting, 1990).

**Thermoplastic microencapsulation.** Thermoplastic microencapsulation is a batch process that uses asphalt bitumen, paraffin or polyethylene injection into heated and dried waste to form a stable, solid waste matrix that is rigid but deformable. In this type of treatment, contaminants are physically incorporated into thermoplastic materials but not chemically bonded (Intera Kenting, 1990).

Wastes not applicable to treatment by this process include those with high water content and those containing strong oxidizers, anhydrous inorganic salts, tetraborates, iron and aluminum salts, xylene, toluene, grease or chelating and complexing agents such as cyanides and ammonium.

This process is attractive because it reduces volume of waste to be treated, decreases permeability and eliminates liquid from waste (which facilitates handling). However, the process has high energy requirements and demands specialized equipment and trained operators (Averett et al., 1990)

**Organic polymerization.** With these stabilization/solidification technologies, a monomer is added and mixed with the contaminated soil. A catalyst is then added to enhance the reaction that forms the polymer. The solid formed entraps particles in a spongy mass, but the polymer does not chemically react with the contaminated material. Water and liquid from the contaminated soil remain in the polymer after the reaction. The end-product therefore has to be dried or containerized prior to final disposal (Intera Kenting, 1990).

Urea formaldehyde is the most commonly used polymer; it can immobilize contaminants in a variety of wastes. Though this technology has been used primarily for

radioactive wastes, it has also been applied on a limited basis to immobilize organic chlorides, phenols, cyanides and arsenic (Averett et al., 1990).

Other organic polymers have been developed for waste solidification, among them polyesters and polyvinyl resins (Intera Kenting, 1990).

**Silicate-based processes.** These processes, which use siliceous material plus lime, cement, gypsum or other suitable setting agents, are currently the subject of intensive research and development. The siliceous material added to the waste may be fly ash, black furnace slag, kiln dust or other pozzolanic material. Soluble silicates like sodium silicate or potassium silicate may also be used. The technology entraps water, oils and other organics as well as inorganics (Intera Kenting, 1990).

Figure 4.55 shows a schematic of a silicate-based stabilization/solidification process.

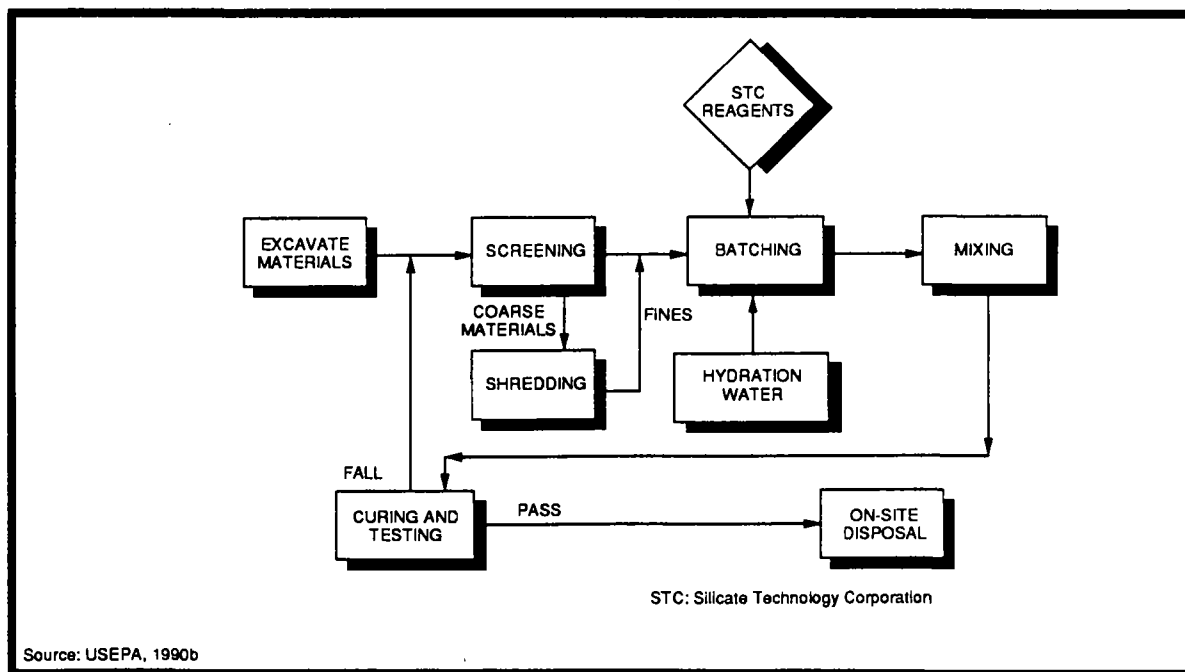


Figure 4.55 Silicate-based stabilization/solidification process scheme

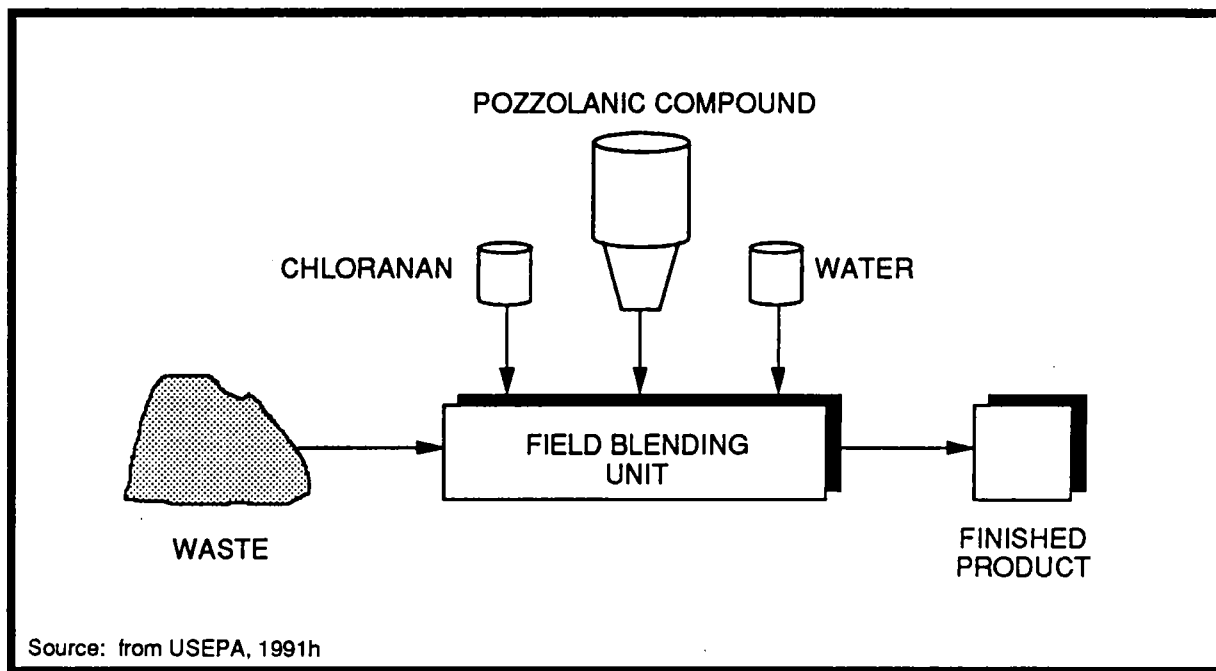
**Modified clays.** Organophilic or modified clays may be used to enhance stabilization of organic hazardous wastes. When modified clays are mixed with solidifying agents such as cement, kiln dust or fly ash, waste can be solidified into a stable mass with low leaching potential.

The clays used, mainly montmorillonite (in the form of bentonite) and attapulgite, 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 (Intera Kenting, 1990).

**Chloranan encapsulation.** Chloranan encapsulation involves injection of cement, water and an additive called chloranan into solids or sludge contaminated with organic compounds, heavy metals, oil and grease. Chloranan encapsulates organic contaminants to prevent their interference with the solidification process. Contaminants are immobilized in soil in a concrete-like matrix that is leach resistant. The chloranan process is available from New Environment Inc. in Hartford, Ohio (Averett et al., 1990) and Emtech Environmental Services Inc. (USEPA, 1991b).

Figure 4.56 shows a schematic of the Emtech Environmental Services Inc. chloranan encapsulation process.





**Figure 4.56 Chloranan encapsulation stabilization/solidification process scheme**

**Proprietary processes.** Many companies offer solidification/stabilization processes that use patented products: Soliditech Inc. (injection of URICHEM, a proprietary reagent, into a mixture of waste and pozzolanic fly ash, kiln dust or portland cement); Delaware Custom Material Inc., Silicate Technology Corporation (silicate-based process); Chemfix (a cement- or pozzolan-based process); Envirosafe (a fly ash and lime mixture); PQ Corporation (sodium silicate); Silica Bonding (Sil-B) (neutralization of sodium silicate by adding acid to form a silicic acid liquid; Wastech Inc. (proprietary cement-based binding agents) (Averett et al., 1990).

**4.7.2.2 Sorption.** Sorption processes involve adding a solid material that soaks up free liquid in soil or waste, yielding a product that is easier to handle. The process applies to organics as well as inorganics. Sorbents include fly ash, kiln dust, vermiculite and bentonite as well as synthetic materials such as activated carbon and certain resins.

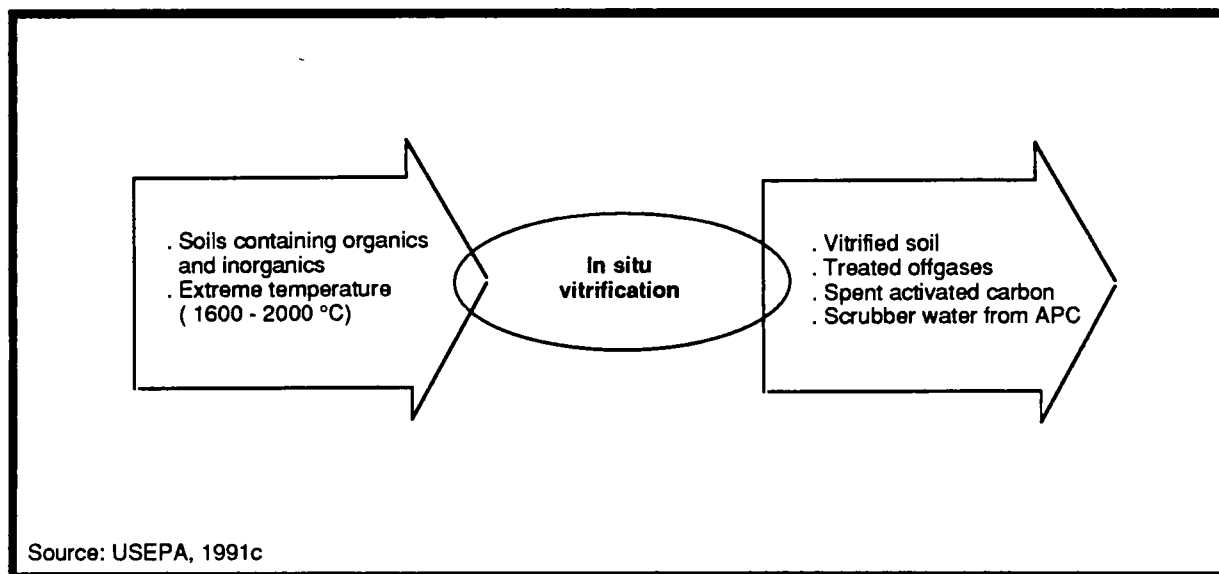
Sorbents that can be used to reduce liquid content of waste and limit its solubility are inexpensive and plentiful. They are often required in large amounts, however, and end-product disposal is sometimes a problem.

**4.7.2.3 Macroencapsulation.** Macroencapsulation technologies enclose waste by completely surrounding it with an impermeable coating (Intera Kenting, 1990). One macroencapsulation method involves placing the solidified/stabilized contaminated material in polyethylene or polyethylene-lined drums and welding or fusing the cover of the drum to form a container that completely isolates the waste from the surrounding environment (Averett et al., 1990; Intera Kenting, 1990).

Although macroencapsulation is one of the most effective solidification processes, it is clearly impractical when large volumes of waste or material must be treated, which is often the case with contaminated sediment (Averett et al., 1990).

**4.7.2.4 In situ vitrification.** Like off-site vitrification technologies, in situ vitrification processes use electrical power to melt contaminated soil and sludge into a stable glass and crystalline structure with very low leaching characteristics (USEPA, 1991c; USEPA, 1992b).

Figure 4.57 shows in situ vitrification inputs and products.

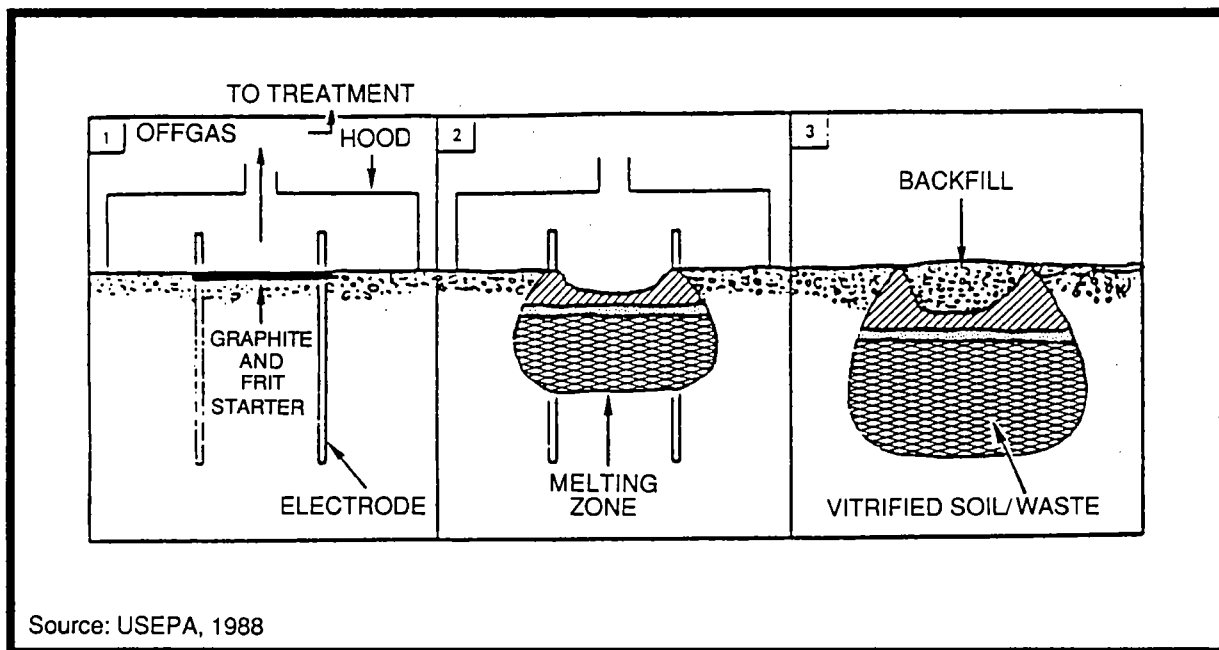


**Figure 4.57 In situ vitrification inputs and products**

Four electrodes are vertically inserted in a square arrangement in the contaminated soil to a depth of 5.40 m to 6.0 m. To start the vitrification process, graphite and glass frit are placed on the surface to complete the circuit between the electrodes. A current is run through the soil, heating it to 1600°C to 2000°C and causing it to melt. Organic contaminants are thus destroyed by pyrolysis. The pyrolyzed products migrate to the surface of the vitrified zone where they combust in the presence of oxygen. Inorganic contaminants are incorporated in the vitrified mass (Petitpas, 1990; USEPA, 1991c).

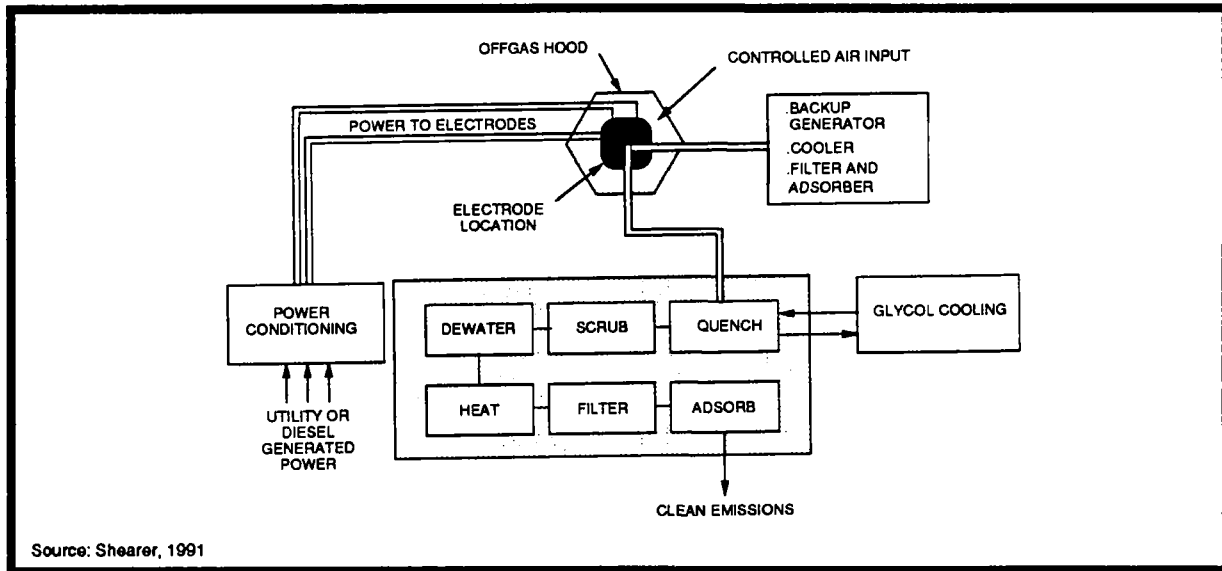
Combustion gases generated are drafted into a hood arranged over the processing area and drawn into an offgas treatment system before release into the atmosphere.

Figure 4.58 shows a cross section of an in situ vitrification process.



**Figure 4.58** Cross section of in situ vitrification process

As Figure 4.59 shows, the central components of the technology are an array of four molybdenum electrodes, electric power supply (three phases at 12 500 or 13 800 V), air pollution control equipment (quenching, scrubbing, mist elimination, humidity control, particulate filtration, and activated carbon adsorption) and a glycol cooling system to cool quenching/scrubber water (Shearer, 1991).



**Figure 4.59 In situ vitrification process scheme**

**4.7.2.5 Other processes.** *Ground freezing* is a stabilization/solidification process that uses freezing loops installed in the ground and a refrigeration system that pumps liquid through the loops. Freezing does not treat the waste, but it does decrease soil permeability. Immobilization is, of course, only temporary (Averett et al., 1990).

*Soil cooling* technologies lower soil temperature with cooling agents (dry ice, for example, that is, solid carbon dioxide) to reduce vapour phase and volatilization rate of volatile constituents. Long-term reliability requires repeated treatment, however.

Suppression of volatilization may be effective and required prior to in situ treatment to cut losses of volatile soil contaminants. Vapour phase volume can be diminished by compaction and water addition to modify soil structure and reduce air-filled pores in the soil (Averett et al., 1990).

**4.7.3 Applications.** Because heavy metal contaminants cannot be destroyed and because extraction of heavy metals from soil is a complex process, stabilization/solidification technologies, alone or in conjunction with other technologies, are often selected for soil remediation. Solidification/stabilization technologies can also be effective for some organics (Averett et al., 1990).

As Table 4.25 indicates, demonstrated or potential effectiveness of stabilization/solidification technologies on all inorganic soil and sludge contaminants is rated good to excellent. However, expert opinion is that the technologies will be only marginally to moderately effective on organic and reactive contaminants.

**4.7.4 Strengths, limitations and demonstrated applications of each technology.** Table 4.26 lists main strengths, limitations and applications or demonstrations of eight stabilization/solidification technologies:

- 1) Cement/pozzolan-based processes.
- 2) Lime-based processes.
- 3) Processes that use organically modified clay.
- 4) Thermoplastic encapsulation.
- 5) Macroencapsulation.
- 6) Organic polymerization.

Table 4.25 Effectiveness of immobilization technologies on contaminant groups for different matrices

CONTAMINANT GROUP	EFFECTIVENESS RATINGS*	
	STABILIZATION/ SOLIDIFICATION	IN SITU VITRIFICATION
	Soil/sludge	Soil/sludge
<b>Organics</b>		
Halogenated volatiles	1	1
Halogenated semivolatiles	1	1
Nonhalogenated volatiles	1	1
Nonhalogenated semivolatiles	1	1
PCBs	1	1
Pesticides (halogenated)	1	1
Dioxins/furans	1	1
Organic cyanide	1	1
Organic corrosives	1	1
<b>Inorganics</b>		
Volatile metals	2	1
Nonvolatile metals	2	1
Asbestos	2	1
Radioactive materials	2	2
Inorganic corrosives	2	1
Inorganic cyanides	2	1
<b>Reactives</b>		
Oxidizers	1	1
Reducers	1	1

\* EFFECTIVENESS RATINGS

2 Good to excellent. High probability the technology will be effective.

1 Marginal to moderate or potential. Exercise care in choosing the technology. Expert opinion is that the technology will be effective.

0 Ineffective. Expert opinion is that the technology cannot be used to treat this type of waste or contaminant.

X May have adverse effects.

Adapted from USEPA, 1990; 1991c

Table 4.26 Strengths, limitations and contaminated-soil and waste applications of immobilization technologies

TECHNOLOGY	STRENGTHS	LIMITATIONS	APPLICATIONS/ DEMONSTRATIONS
Solidification/ stabilization • Cement/Pozzolans	<ul style="list-style-type: none"> <li>Product is structurally secure.</li> <li>Product is less permeable than feed material.</li> <li>Product passes freeze/thaw test.</li> </ul>	<ul style="list-style-type: none"> <li>Poor results for organics and long-term stability unknown.</li> <li>Volume of waste can increase more than 100%.</li> <li>Calcium sulphate, borate and carbohydrates inhibit solidification.</li> <li>Acids react with carbonates and hydroxyls to weaken concrete.</li> <li>Pretreatment of waste required.</li> </ul>	<ul style="list-style-type: none"> <li>In situ treatments are emerging technologies.</li> <li>Demonstrated for treatment of excavated material (soil) and liquids contaminated with inorganics.</li> </ul>
Solidification/ stabilization • Lime	<ul style="list-style-type: none"> <li>Product does not harm the environment.</li> <li>Salts formed at neutral pH are insoluble after precipitation.</li> <li>Lime is inexpensive.</li> </ul>	<ul style="list-style-type: none"> <li>Sodium borate, calcium sulphate, potassium chromate and carbohydrates interfere with the reaction.</li> <li>High concentrations of oil and grease inhibit the reaction.</li> <li>Wastes must be sorted or shredded to uniform particle size.</li> <li>Quick lime is corrosive to skin.</li> <li>Hydrated lime, a very fine powder, is hard to handle.</li> </ul>	<ul style="list-style-type: none"> <li>Used in Germany since 1975.</li> <li>Demonstrated for metals.</li> </ul>
Solidification/ stabilization • Modified clays	<ul style="list-style-type: none"> <li>Organoclays can be custom-blended for optimum interaction with specific waste.</li> </ul>	<ul style="list-style-type: none"> <li>Laboratory-tested only.</li> </ul>	<ul style="list-style-type: none"> <li>Laboratory-tested only.</li> </ul>
Solidification/ stabilization • Thermoplastic encapsulation	<ul style="list-style-type: none"> <li>Solidified product has good structural properties and low permeability.</li> <li>The product may be usable in the construction industry.</li> </ul>	<ul style="list-style-type: none"> <li>Requires special mixing equipment.</li> <li>Waste must be compatible with the matrix.</li> </ul>	<ul style="list-style-type: none"> <li>Widely used in the nuclear industry and on PAH-contaminated soil.</li> </ul>
Solidification/ stabilization • Macroencapsulation	<ul style="list-style-type: none"> <li>Contaminants isolated from the environment.</li> <li>Product is structurally secure and impermeable.</li> </ul>	<ul style="list-style-type: none"> <li>Product must be landfilled.</li> <li>Binders are very expensive.</li> <li>"Jackets" require protection against photodegradation.</li> <li>VOC emission must be monitored during initial heating.</li> </ul>	<ul style="list-style-type: none"> <li>Tested at bench scale on organic, inorganic and highly toxic waste.</li> </ul>
Solidification/ stabilization • Organic polymerization	<ul style="list-style-type: none"> <li>Solidified product is very stable.</li> </ul>	<ul style="list-style-type: none"> <li>Product must be landfilled.</li> <li>Possibility of leaching if waste is encapsulated in the polymer.</li> </ul>	<ul style="list-style-type: none"> <li>Used for spills, in the nuclear industry, and for inorganic waste.</li> </ul>
Solidification/ stabilization • Silicates	<ul style="list-style-type: none"> <li>Product passes standard leaching tests.</li> <li>Wide variety of wastes can be treated.</li> </ul>	<ul style="list-style-type: none"> <li>Solidification rate is very slow.</li> <li>Pretreatment of waste by emulsifiers or surfactants may be required.</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrated at laboratory scale for several types of soil.</li> </ul>
Solidification/ stabilization • Ground freezing	<ul style="list-style-type: none"> <li>Chemicals not required.</li> <li>Reduced volume of soil requiring treatment, hence lower costs.</li> <li>Separation of contaminants from soil mass is possible.</li> </ul>	<ul style="list-style-type: none"> <li>Emissions of volatile organics.</li> <li>Capital and operating costs high compared to other treatment options.</li> <li>Not a long-term option.</li> </ul>	<ul style="list-style-type: none"> <li>Technology at bench-scale stage for metals (Cd, Zn, Cu, Ni) and volatile organics (chloroform, benzene, toluene, tetrachloro ethylene).</li> </ul>

Adapted from CH2M Engineering Ltd., 1991



- 7) Silicate-based processes.
- 8) Ground freezing.

Cement/pozzolan-based and lime-based processes are very well- understood technologies successfully used for many years to treat contaminated soil and liquids. Volume often increases when solidifying agents are added, however. In addition, these processes can be adversely affected by high concentrations of organics or by fine-grain material such as clay (Intera Kenting, 1990).

Technologies that use organically modified clays, macroencapsulation, silicates and ground freezing to immobilize contaminants in a stable matrix are still in the bench or laboratory stage of development for soil.

Thermoplastic encapsulation, macroencapsulation and organic polymerization processes have been frequently used on waste from the nuclear industry (CH2M Hill Engineering Ltd., 1992).

**4.7.5 Strengths and limitations for sediment treatment.** Solidification/stabilization technologies used for contaminated soil can also be applied to sediment or solid residues from sediment treatment processes. Stabilization/solidification processes can be performed in situ or immediately after excavation or following consolidation and dewatering in a disposal area. In confined disposal facilities, additives can be mixed with the partially dewatered dredged material using agricultural spreaders and tillers (Averett et al., 1990).

Stabilization/solidification processes are selected based on chemical and physical analyses of sediment to be treated. According to the USEPA (1991b), a number of tests are available for this purpose: Toxicity Characteristics Leaching Procedure (TCLP); leaching tests of the American National Standards Institute (ANSI); the Standard Batch Leachate Test (SBLT); and the usual

physical tests for determining bearing capacity, permeability, compressibility, moisture content and so forth of the material after treatment.

Research conducted since 1989 in the Netherlands for the Development Program Treatment Processes for Polluted Aquatic Sediment (DTTP) has demonstrated that chemical immobilization is not always effective for treating sediment. Leaching tests of treated material showed contaminant leachability did not always decrease and sometimes even increased. Current research, therefore, is focusing on thermal technologies (vitrification) that can immobilize heavy metals and organic contaminants in sediment (Dillen & Bruggeman, 1992).

As Table 4.27 shows, *thermoplastic encapsulation* has not yet been demonstrated for contaminated sediment. High energy costs and the high water content of sediment seriously limit application of this process to treat contaminated sediment unless the sediment is very well dewatered before treatment.

Because addition of organic substances is required, *organic polymerization* is not a very practical stabilization/solidification technology for contaminated sediment. Sorption processes can be applied to contaminated sediment in a manner similar to solidification stabilization processes. (Averett et al., 1990).

Though *in situ vitrification* can be applied to most soil types, there are two limiting factors: moisture content and amount of glass-forming material (silicas and aluminum oxides). When moisture content is high, the material to be treated must be dewatered first, increasing costs significantly. If there is insufficient glass-forming material, a fluxing material may be added to the soil (USEPA, 1991c).

Ground freezing or ground cooling stabilization/solidification processes are not suitable for contaminated sediment. Soil vapour pore volume reduction technology is still at the laboratory stage of development and has limited application to contaminated sediment (Averett et al., 1990).

Table 4.27 Anticipated performance of immobilization technologies applied to sediment remediation

TECHNOLOGY	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABILITY	PERFORMANCE RATINGS**		
				EFFECTIVENESS	IMPLEMENTABILITY	COST
Chlorinated encapsulation*	Demonstrated	No	Proprietary	3	2	2
Ground freezing	Conceptual	No	Emerging	2	1	2
In situ stabilization	Demonstrated	No	Available	2	3	2
Lime-based pozzolan	Demonstrated	Bench	Available	3	3	3
Macroencapsulation	Pilot	No	Proprietary	3	1	2
Organic polymerization	Demonstrated	No	Available	3	1	2
Portland cement-based	Demonstrated	Bench	Available	3	3	3
Proprietary processes	Demonstrated	Bench	Proprietary	3	3	3
Soil cooling	Conceptual	No	Emerging	1	1	2
Soil vapour pore volume reduction	Conceptual	No	Emerging	1	2	2
Sorption	Demonstrated	No	Emerging	3	2	3
Thermoplastic encapsulation	Pilot	No	Proprietary	3	1	1

Notes

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

**4.7.6 Technologies demonstrated for sediment treatment.** As Table 4.28 indicates, as of 1991 stabilization/solidification processes had been applied in the United States on a bench, pilot or full scale for treatment of contaminated sediment at five sites: Marathon Battery Co. site, Cold Spring, New York; the estuary of the Acushnet River, New Bedford, Massachusetts; the navigation channel at Indiana Harbour, Indiana; Buffalo River, New York; and the Halby Chemical site, Delaware.

Contaminants treated at these sites ranged from organics such as PCBs to metals such as cadmium, cobalt, nickel, lead, copper, chromium and arsenic (USEPA, 1991a; USEPA, 1991b).

*Stabilization/solidification* technologies have been laboratory-tested on contaminated sediment from Everett Bay, Washington, Indiana Harbour, Indiana, and New Bedford Harbour, Massachusetts. The tests demonstrated improved immobilization for most, but not all, heavy metals. Leachability of organic carbon in the Everett and Indiana Harbour sediment was not affected by stabilization/solidification. However, leachability of PCBs in New Bedford sediment was reduced by factors of 10 to 100. Estimated cost of stabilization/solidification for Indiana Harbour sediment was US\$55 per cubic yard (Averett et al., 1990).

A lime/pozzolan (fly ash) stabilization/solidification process was evaluated in the laboratory for treatment of sediment from Everett Bay and Indiana Harbour. Results of leachate testing for several heavy metals were mixed (Averett et al., 1990).

Stabilization/solidification processes have been used for full-scale sediment remediation projects in Japan (proprietary processes), in Belgium (Anvers), in Canada (Hamilton Harbour), and in the United States (Chesapeake Bay).

The Silicate Technology Corporation process has been tested on New Bedford Harbour sediment. The Chemfix process has been bench-scale tested on sediment from the

Table 4.28 Immobilization technologies demonstrated for sediment remediation

Technology	Developer*	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
• Not specified	Ebasco Services Inc.	U.S.	Cold Spring, NY	Bench Pilot	Heavy metals, Cd, Ni, Co	USEPA, 1991b
• Portland cement	Not specified	U.S.	Indiana Harbour, IN	Bench	PCBs and other organic contaminants and metals PCBs	USEPA, 1991b
	Not specified	U.S.	Everett Bay, WA	Laboratory		Averett et al. 1990
• Portland cement/ fly ash/lime, asphalt kiln dust	Not specified	U.S.	Buffalo River, NY	Bench	Organics	USEPA, 1991b
	Not specified	U.S.	Wilmington, DE	Bench	Heavy metals	USEPA, 1991b
	Atomic Energy of Canada Limited Research	Canada	Port Hope, ON	Bench	Heavy metals, organics, radioactive material	WTC, 1992a
• Portland cement/ hydrates, glycols, fly ash	Not specified	Canada	Lachine Canal, PQ	Laboratory	Metals & organics (PAHs, PCBs, HCB)	SLC, 1992b
• Ciment/pozzolan	Not specified	Canada	Lachine Canal, PQ	Laboratory	Metals and organics (PAHs, PCBs, HCB)	SLC, 1992b
• Ciment/pozzolan	Not specified	U.S.	Everett Bay, WA Indiana Harbour, IN	Laboratory	PCBs	Averett et al., 1990
• Silicates and other additives • Silicates	Silicate Technology Corporation	U.S.	New Bedford Harbour, MA	Bench	PCBs and heavy metals	Averett et al., 1990
	Not specified	Canada	Lachine Canal, PQ	Laboratory	Metals and organics (PAHs, PCBs, HCB)	SLC, 1992b
	Not specified	Canada	Lachine Canal, PQ	Laboratory	Metals and organics (PAHs, PCBs, HCB)	SLC, 1992b
• Patented processes	Chemfix Technology	U.S.	Marathon Battery Site	Bench	Heavy metals	Averett et al., 1990
• Fujibéton	c/o Pol-Consystems Ltd.	Japan	Waka River, BIWA Lake, West Takasago Harbour	Full	Heavy metals & organics	WTC, 1992a
• Krofchak	National Solidification Inc.	Canada	Hamilton Harbour, ON	Full	Heavy metals	WTC, 1992a
• Beak Aluminium	Beak Consultants Ltd.	Canada	Hamilton Harbour, ON	Bench	Heavy metals	Environment Canada, 1993
• Dufferin	Dufferin Construction Co. Inc.	Canada	Hamilton Harbour, ON	Bench	Heavy metals	WTC, 1992a
• Siallon	Siallon Technologies Inc.	Canada	Hamilton Harbour, ON	Bench	Hydrocarbons & metals	WTC, 1992a
• SILT	Silt N.V.	Canada	Hamilton Harbour, ON	Bench	Metals	WTC, 1992a
• TRIFIRMEX	Trident Engineering Associates Inc.	Europe	Anvers, Belgium	Full	Metals	WTC, 1992a
		U.S.	Indiana Harbour, IN Chesapeake Bay	Bench Full	Metals	WTC, 1992a Averett et al., 1990
• In situ vitrification	Geosafe Corporation	U.S.	New Bedford Harbour, MA	Bench	PCBs	USEPA, 1991b Averett et al., 1990

\* See Appendix C for addresses and telephone numbers of developers

Applications of solidification technologies are quite commonplace in Japan to physically consolidate sediment before building in aquatic environments (Averett et al., 1990).

Marathon Battery site. A number of small-scale tests of the Sil-B technology have been conducted on sediment from the Waka River in Japan.

In Canada, solidification/stabilization processes have been demonstrated on sediment from Port Hope and Hamilton Harbour in Ontario and on sediment from the Lachine Canal in Quebec.

As part of the Lachine Canal remediation project, the Restoration Technologies Division of the St. Lawrence Centre selected and laboratory-validated contaminated sediment treatment processes applicable for cleanup of the Lachine Canal. Six developers of chemical and/or physical immobilisation processes and one developer of a biodegradation/biofixation technology participated in the laboratory validation and submitted proposals for pilot-scale testing and for a comprehensive remediation project (St. Lawrence Centre, 1992b).

The laboratory tests demonstrated that the stabilization/solidification process based on liquid reagents composed of reactive hydrides, glycols, fly ash, copolymers and Portland cement seem the best options for treating sediment from the Lachine canal. This conclusion was based on physical and chemical performance (leachate testing) and geotechnical performance (compressibility, permeability and freeze/thawing tests). Laboratory test results showed the treated sediment was not very permeable, highly compressible, very alkaline, highly resistance to crumbling and not very leachable.

Four other immobilization technologies also gave satisfactory geotechnical performances and physical and chemical performances in the laboratory on sediment from the Lachine Canal: a technology that uses solidifying agents, hydration water, aluminosilicate plates; a technology that uses a mixture of silicate-based solid and liquid agents and other admixtures; a technology that uses cement and pozzolan-based solidification and sealing agents; and a technology that uses cement and patented solidifying agents). The sediment treated by the process that uses cement- and pozzolan-based solidification and impermeabilization agents showed geotechnical properties that could easily promote salting-out and biotransfer of contaminants.

Laboratory tests of the sixth immobilization process, which uses recycled materials such as calcite, phosphogypsum, lime, cement and fine ash, showed the treated material was unsuitable for disposal in the canal or in a sanitary landfill because contaminant concentrations

exceeded sediment decontamination criteria and leachate contaminant concentrations exceeded government of Quebec leachate standards under the *Regulation respecting solid waste*.

In situ vitrification was bench-scale tested on PCB-contaminated sediment from New Bedford Harbour, Massachusetts. Results showed PCBs in the offgas were below analytical detection limits, and metal leaching concentrations were below U.S. regulatory limits. Overall PCB mass balance indicated destruction of total PCBs exceeded 99.94 percent. Estimated cost ranges from US\$290 to US\$330 per ton of sediment (Averett et al., 1990).

**4.7.7 Technologies under demonstration for sediment treatment.** Of the twelve stabilization/solidification technologies they considered and evaluated, the USEPA and the USACE recommended six as options for sediment remediation demonstration projects in Great Lakes priority areas: chloranane encapsulation, in situ stabilization, pozzolan-based processes, lime-based processes, proprietary processes and sorption processes.

Table 4.29 lists sediment treatment demonstration projects using immobilization technologies. The table gives the demonstration site, the scale of demonstration and the contaminants treated.

Implementability ratings of immobilization processes are higher than those chemical or extraction processes because immobilization processes are easier to control. The possibility of in situ stabilization/solidification within a confined disposal facility is also an advantage. Costs of immobilization processes are generally less than US\$100 per cubic yard of sediment (Averett et al., 1990).

Soil freezing, macroencapsulation and thermoplastic microencapsulation were not considered viable options for treating sediment for the reasons outlined earlier.

**4.7.8 Technologies selected for sediment remediation projects.** Literature review did not indicate sites where immobilization technologies (other than in situ vitrification) have been selected for complete sediment remediation except in Japan, where stabilization/solidification technologies are used mainly for construction purposes.

Table 4.29 Demonstration projects using immobilization technologies for Great Lakes sediment remediation

Technology	Developer*	Place of demonstration		Scale of demonstration	Type of contamination	Reference
		Country	Site			
Stabilization/ solidification • Not specified	Siallon Technologies Inc.	Canada	Hamilton Harbour Thunder Bay Harbour	Bench	Chlorophenol PAHs	WTC, 1992 Environment Canada, 1993
Stabilization/ solidification • In situ	Not specified	U.S.	Sheboygan Harbour	Bench/pilot	PCBs	USEPA, 1992a
Stabilization/ solidification • Not specified	Not specified	U.S.	Buffalo River Great Calumet River	Bench/pilot	PAHs, oils & greases PCBs, PAHs, oils & greases	USEPA, 1992a
• Not specified	Ensotech	Canada	Welland Canal	Bench	PAHs	Environment Canada, 1993

\* See Appendix C for addresses and telephone numbers of developers.



In fact, given conclusive sediment treatment demonstration projects, the in situ vitrification process developed by Batelle is being considered for remediation of two U.S. sites--Sangamo/Crab Orchard National Wildlife Refuge in Illinois and Crystal Chemical in Texas, where soil and sediment are contaminated by PCBs and heavy metals such as lead, cadmium and arsenic. In 1992, demonstration projects at these two sites were still in the design stage (USEPA, 1991c).

**4.7.9 Conclusions.** As the preceding sections show, stabilization/ solidification technologies applied to contaminated soil are suitable for treating sediment or solid residues from sediment decontamination technologies. Sediment can be treated in situ, or immediately after dredging, or in confined disposal facilities, after consolidation and dewatering.

Demonstrated or potential effectiveness of stabilization/solidification technologies on all inorganic soil and sludge contaminants is good to excellent. However, expert opinion is that the technologies will be only marginally to moderately effective on organic and reactive contaminants.

To date, test results for sediment seem contradictory. Demonstration projects in the Netherlands showed chemical immobilization technologies are not always effective for treating sediment. Leaching tests of treated material showed contaminant leachability does not always decrease and sometimes even increases.

In addition, tests on sediment in the United States showed many but not all heavy metals were immobilized. Six processes are nevertheless now being used for Great Lakes sediment remediation demonstration projects, mainly because of their ability to treat sediment in confined disposal facilities.

Laboratory tests on sediment from the Lachine Canal showed a number of stabilization/solidification processes are suitable for treating sediment from the canal; this conclusion was based on physical and chemical performance (leaching tests) and geotechnical performance (compressibility, hydraulic conductivity and freeze/thawing tests).

As in the Netherlands, demonstration projects conducted in the United States indicate that in situ vitrification is a very efficient and promising immobilization technology for treating contaminated sediment.

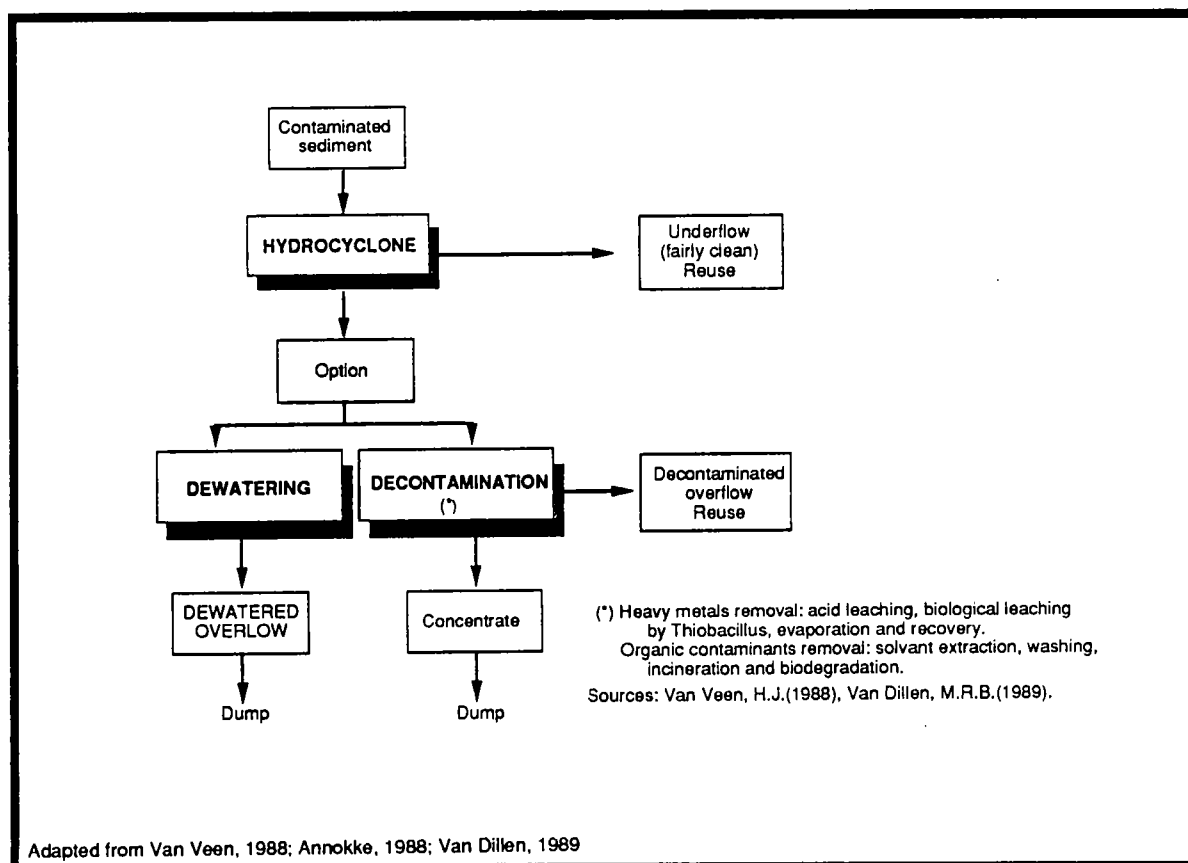
#### 4.8 Treatment trains

Sites are often contaminated by organics as well as inorganics, yet most technologies for treating contaminated sediment cannot simultaneously treat heavy metals and organics. The trend today, as a result, in research and demonstration projects dealing with treatment of contaminated soil and sediment is towards development of integrated treatment trains that can address all problems at a site. In addition, most contaminated-sediment treatment technologies require one or more pretreatments and must be coupled with effluent treatment technologies (see section 5 herein).

Treatment trains should be considered not only to address specific contamination problems but also for complementarity. Sediment contaminated with metals and PCBs, for example, might first be dewatered in preparation for a metal extraction process. The treated sediment could then be incinerated to destroy PCBs. With this treatment train, incineration costs are lower because sediment water content has been reduced, and treatment of incineration offgas is simpler because of the metals removal prior to incineration (USEPA, 1991b).

The Dutch tested a treatment train approach on sediment contaminated with PAHs. Results showed hydrocyclone overflow could be biologically treated in aerated basins and hydrocyclone underflow could be treated by solvent extraction with triethylamine (TEA) or by biodegradation (if the contaminants are not too strongly sorbed to sediment particles). If unpolluted, treated sediment could also be reused without further treatment (USEPA, 1991b).

Figure 4.60 shows a schematic of a treatment train used in the Netherlands on contaminated sediment.



**Figure 4.60 Scheme of treatment train used in Holland**

Table 4.30 completes Figure 4.60, listing treatment technologies currently the subject of research and demonstration projects in the Netherlands for treatment of sediment which has first been separated by hydrocyclones and dewatered. The table indicates sediment fraction (total, light or heavy) and contaminants each technology treats. Other technologies not listed in the table (solvent extraction, froth flotation, electromagnetic separation and incineration) are also used in the Netherlands to treat sediment (Dillen & Bruggeman, 1992).

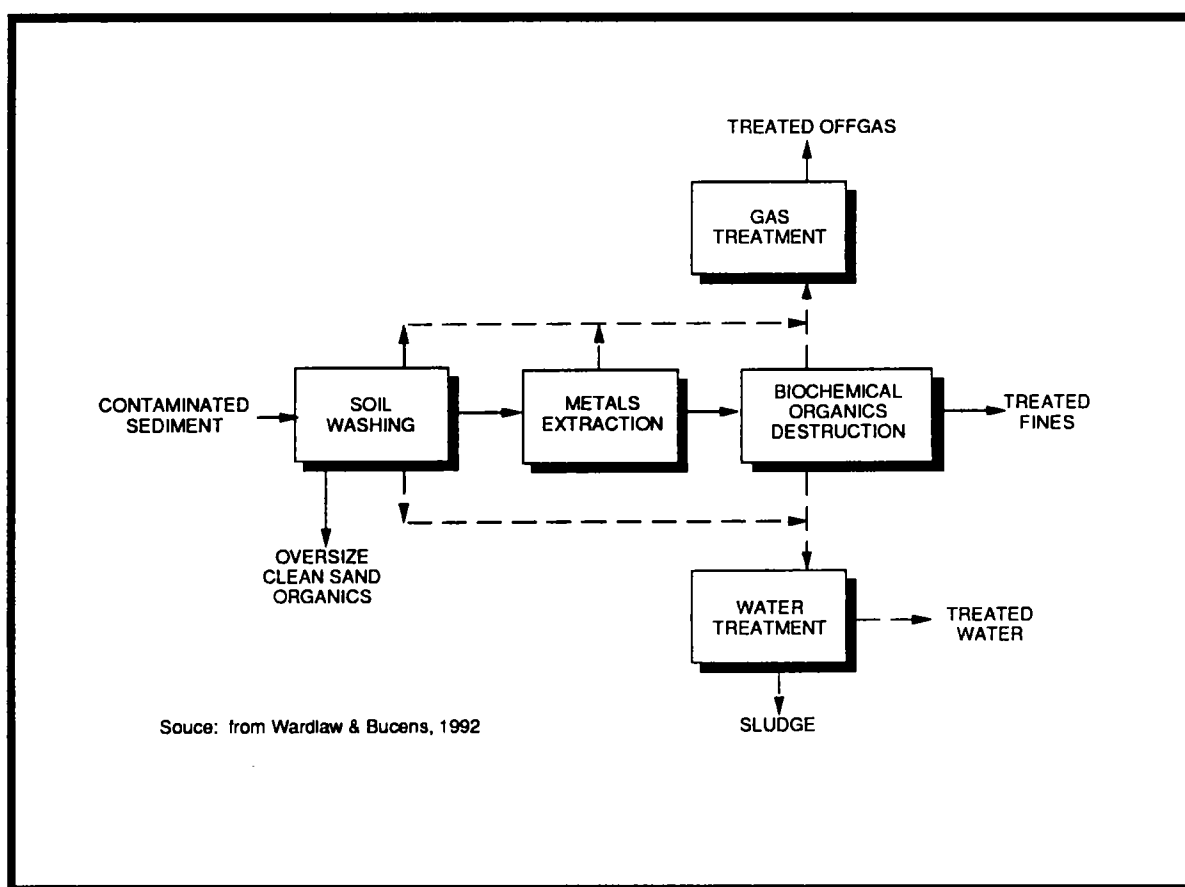
Table 4.30 Sediment remediation technologies under demonstration in the Netherlands

TECHNOLOGY	FRACTION			CONTAMINANT
	Total	Light	Heavy	
<b>Biological treatment</b>				
Landfarming	x			PAHs, oils
Aeration basin		x		PAHs, oils
Bioreactor	x		x	PAHs, oils
<b>Chemical treatment</b>				
Extraction with acid	x	x	x	Heavy metals
Extraction with complexing agents		x	x	Heavy metals
Oxidation with hydrogen peroxide	x			PAHs, oils
<b>Physical and chemical treatment</b>				
Flotation			x	Organic micropollutants, heavy metals
Gravitation separation			x	Organic micropollutants, heavy metals

Adapted from Dillen and Bruggeman (1992)

As mentioned, a treatment train approach was also tested in Canada in the summer of 1992 on sediment from the Toronto Harbour. The treatment unit was designed and built by SNC-Lavalin to treat harbour sediment of variable grade contaminated by heavy metals and organics. Now operated by the Toronto Harbour Commission, the unit uses a treatment train of three core technologies within a large temporary structure coupled with a physical and chemical water treatment unit and an offgas treatment system (scrubber, activated carbon filter and biofilter).

Figure 4.61 shows a schematic of this treatment train.



**Figure 4.61 Toronto Harbour Commission facility treatment train schematic**

As the figure shows, the treatment train uses the three following technologies in sequence: soil washing (Bergmann), metal extraction (Metanetix process) and biotreatment (SNC-Lavalin bioreactor). These three processes have already been described. Test results have not yet been reported as this guide goes to press (Wardlaw and Bucens, 1992).

## 4.9            Containment

Containment technologies are designed to prevent release into the environment of hazardous compounds in contaminated matrices and their uptake by living organisms, including human beings. Contamination can result from direct contact with contaminated waste, volatilization, or leaching into surface water and groundwater.

Contaminants in sediment at the bottom of a waterway are liable to resuspension or return to solution as a result of natural (wind, waves, tides and floods, for example) or anthropogenic (dredging, shipping and so forth) phenomena. When sediment is dredged and disposed of upland, risks of contaminating the surrounding environment are the same as with contaminated soil.

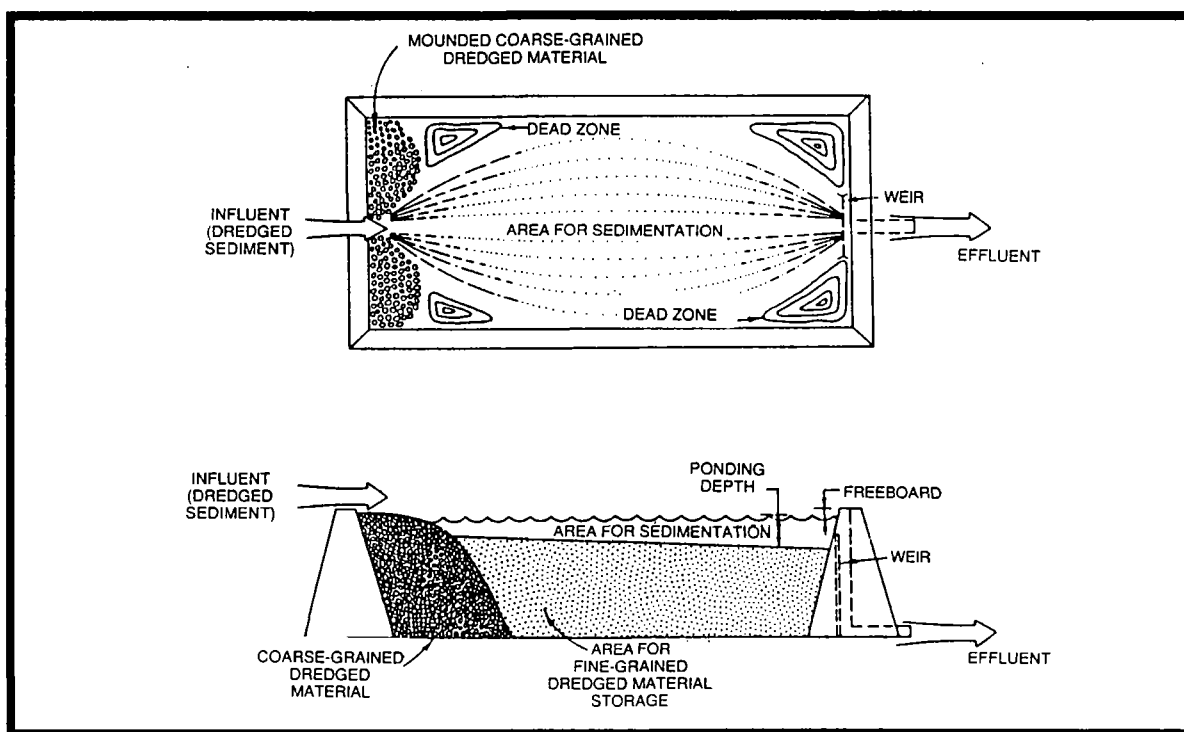
In the sections that follow, shoreline and upland technologies for containment of contaminated sediment are briefly described.

**4.9.1            Principle of treatment.** Shoreline or upland sediment containment technologies are basically designed to encapsulate contaminated sediment in watertight enclosures to prevent volatilization of contaminants to the air, and contamination of surface water and groundwater by precipitation and leachate in contact with the sediment. Containment technologies also prevent plant, animal and human contact with contaminants.

## 4.9.2 Technologies available

**4.9.2.1 Upland confined disposal facility (CDF).** Upland CDFs are simply diked settling basins above the water table. Generally they are built close to the worksite.

Figure 4.62 shows a schematic of the concept.



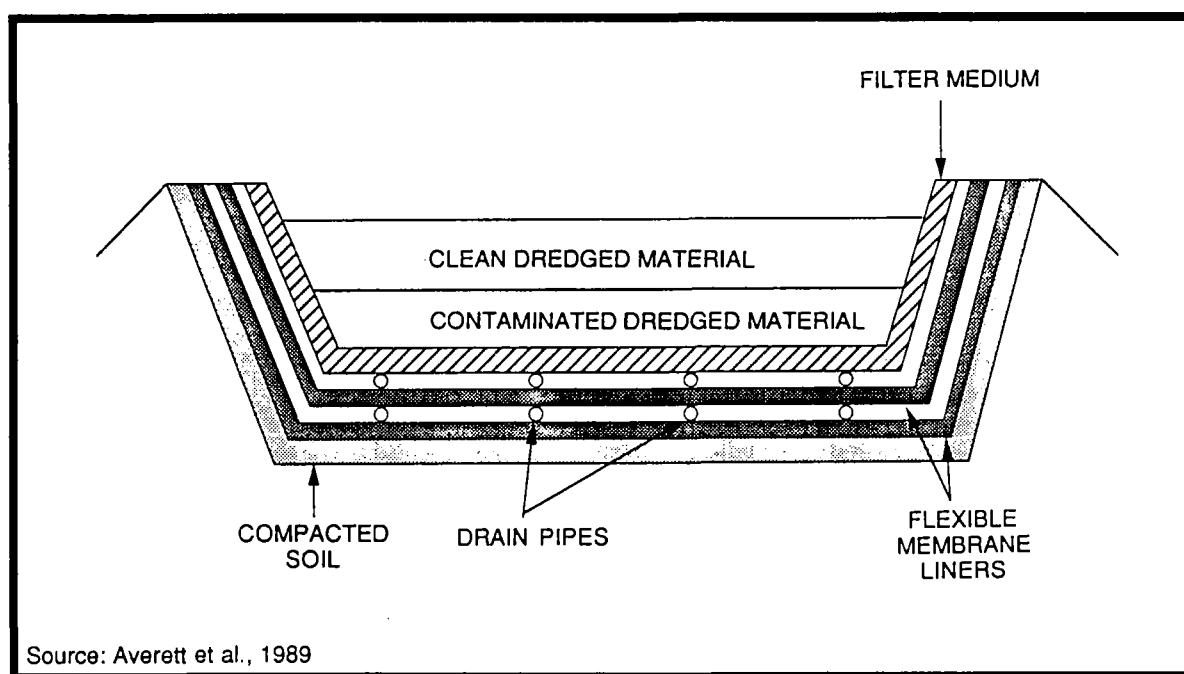
Source : USACE (1987)

**Figure 4.62 Schematic of upland confined disposal facility**

The most widely used disposal option for contaminated sediment in North America and in Europe is the CDF. Originally designed to retain suspended solids in material removed with hydraulic dredges until acceptable suspended solids concentrations for discharge elsewhere were obtained, CDFs are still used for disposal of about half the sediment dredged from the Great Lakes. Since CDFs are designed to retain as high a percentage of fine-grained sediment particles as practicable, and since most sediment contaminants are attached to solid fines, CDFs are reasonably efficient for containment of contaminants (Averett et al., 1990).

In addition, since CDFs have been in use for many years now, a variety of environmental controls are available to minimize contaminant losses, among them effluent and leachate treatment technologies, impermeable bottom and dike liners, groundwater pumping, surface drainage and capping with a cement mixture, bentonite, high-density polyethylene membranes and/or layers of clay and topsoil.

Figure 4.63 shows a cross section of a CDF specially designed for contaminated sediment. The sediment is contained by membranes and capping, and the facility is equipped with a runoff and leachate collection system.



**Figure 4.63 Cross section of confined disposal facility specially designed for contaminated sediment**

CDF storage capacity can range from a hundred thousand cubic metres to more than a million cubic metres. To dispose of highly contaminated sediment from Rotterdam Harbour, the Dutch government authorized construction of a watertight CDF with a two millimetre thick high-density membrane and a capacity of 1.2 million cubic metres. This facility covers twenty-nine hectares and is surrounded by a dike 3.3 metres high. Groundwater and leachate quality is monitored constantly. According to the certificate of authorization issued in 1985, a plan for treatment of contaminated sediment temporarily stored in the facility must be submitted after ten years of operation.



**4.9.2.2 Sanitary landfill.** Slightly contaminated sediment and process residues can be disposed of in sanitary landfills, where it can be buried or used as capping material, depending on residual contamination level. Because of its high water content, sediment must be dewatered first and leaching tests must confirm leachate meets standards of the Quebec Regulation respecting solid waste.

**4.9.2.3 Hazardous landfill.** Contaminated sediment can be disposed of in a hazardous landfill authorized to receive contaminated soil. The only hazardous landfill site in Quebec authorized to receive contaminated soil is in Ville LaSalle; the site is operated by Cintec Environnement Inc.

At this site, contaminated soil is placed in a cell with two geosynthetic liners separated by a drainage layer of sand. The facility can contain up to 300 000 cubic metres of soil contaminated by organics and inorganics. Leachate is treated with a physical and chemical process before release into sewers. Since water content of soil placed in the facility must not exceed 40 percent, sediment must be dewatered first.

**4.9.3 Strengths and limitations of containment technologies.** Strengths and limitations of containment technologies compared to treatment technologies have already been briefly discussed in Chapter 2, which deals with cleanup scenarios.

**4.9.4 Conclusions.** Until there are conclusive demonstrations of effective and economical technologies for treating large volumes of sediment, in-water, shoreline and upland containment technologies will remain popular options for contaminated sediment cleanup scenarios. The most striking example of this is in the Netherlands. Although there has been remarkable progress in recent years in biological, chemical, thermal, immobilization, and physical and chemical extraction technologies for treating sediment, containment remains the solution of choice in the Netherlands because of the large volumes of sediment that must be treated every year and the exorbitant costs of treatment technologies.

#### 4.10 Summary of technologies under demonstration for remediation of Great Lakes sediment

Figure 4.64 lists all biological, extraction, chemical, thermal, immobilization and containment technologies evaluated by the U.S. government for effectiveness, cost and implementability for remediation of Great Lakes sediment. See Chapter 3 of this guide for more information on evaluation and selection criteria considered by the USEPA and the USACE.

In Figure 4.64, treatment technologies are classified according to anticipated cost and current stage of development. Anticipated effectiveness is also indicated. Technologies selected for Great Lakes sediment remediation demonstration projects are listed in bold.

Technologies selected for demonstration projects on the *Canadian* side, as already mentioned, are as follows, listed by technology type:

- Biological
  - Dearborn process
  - Institute of Gas Technology process
  - SNC-Lavalin bioreactor
- Extraction
  - Altech washing unit
  - Beak extraction unit
  - Bergmann washing unit
  - Tallon extraction unit
  - BioGenesis washing unit
  - Cognis extraction unit
  - Metanetix unit
  - EcoLogic process
- Thermal
  - AOSTRA-Taciuk process
  - X\*TRAX process

- Chemical

- Immobilization
  - Ensotech process
  - Siallon process

COST US \$/cy	IMPLEMENTABILITY RATING (*)			
	1 - CONCEPTUAL/EMERGING	2 - BENCH	3 - PILOT	4 - COMMERCIAL
1 200 \$ or more	Integrated vapor and steam stripping (2)** Liquid injection incineration (3) Lurgi pelletizing process (3) Molten glass vitrification (3) Molten salt incineration (4) Plasma arc incinerator (3) Pyrotron incinerator (3) Radio frequency heating (3) Roasting (3) Thermoplastic microencapsulation (3)	<b>Advanced electric reactor (4)***</b> Blast furnace (3) Electroacoustic (2) Flame reactor (3) Fluidized bed incineration (4) <b>High-temperature slag incineration (4)</b> Industrial kiln (3) <b>Infrared incineration (4)</b> <b>In situ vitrification (4)</b> <b>Multiple hearth incineration (4)</b> <b>Pyrolysis (4)</b> Pyrometallurgy (2) Pyroplasma pyrolysis (3) Sollex (keresene) (3) <b>Supercritical water oxidation (4)</b>	<b>Vitrification (4)</b>	
2 100 \$ to 200 \$	Aurex washing (3) CF Systems-CO <sub>2</sub> (3) Chemical hydrolysis (2) CREP soil washing (2) Ground freezing (2) Harbauer semibatch soil washing (3) Hamon soil washing (3) Heidamij mobile soil washing (3) In situ vacuum and steam extraction (2) LARC extraction (3) Macroencapsulation (3) O.H. Materials (3) Organic polymerization (3) Oxidation of inorganics (2) Ozonics (2) Photolysis (2) Reduction of metals (2) Reduction of organics (1) Steam stripping (2) Thionation (1)	<b>Acid leaching (3)</b> Anaerobic digestion (2) BioTrol soil washing (2) Chelation (3) <b>CF Systems-Propane (3)</b> <b>Chloranene encapsulation (3)</b> Composting (2) EPA Mobile soil washing unit (2) <b>Low energy extraction (3)</b> <b>Low-temperature thermal stripping (3)</b> Mechanical aeration/extraction (2) MTA Remedial Res. soil washing (2) <b>Nucleophilic substitution (4)</b> <b>Oxidation of organics (3)</b> <b>Rotary kiln incineration (4)</b> Soil pore volume reduction (1) Surfactants (3)	<b>AOSTRA-Tactuk process (3)</b> <b>BEST extraction (4)</b> <b>Circulating bed combustor (4)</b> <b>EcoLogic (4)</b> <b>In situ stabilization (2)</b>	
3 20 \$ to 100 \$	<b>Bioreactors (3)</b> Enzymes (2)	<b>Sorption (3)</b>	<b>Aerobic bioreclamation (3)</b> <b>Anaerobic bioreclamation (3)</b> <b>Lime-based pozzolans (3)</b> <b>Portland cement-based solidification (3)</b> <b>Proprietary processes (3)</b> <b>Wet air oxidation (2)</b>	
4 20 \$ or less				

Notes : \* Performance rating (2) (see table 3.3).

\*\* Effectiveness rating (see table 3.3)

\*\*\*Processes shown in bold have been selected for Great Lakes cleanup demonstration projects.

Source : Adapted from Averett et al., 1990.

**Figure 4.64 Classification of 79 sediment treatment technologies evaluated and selected for testing by USEPA and USACE for Great Lakes**

## **5. EFFLUENT AND LEACHATE TREATMENT**

### **5.1 Objectives**

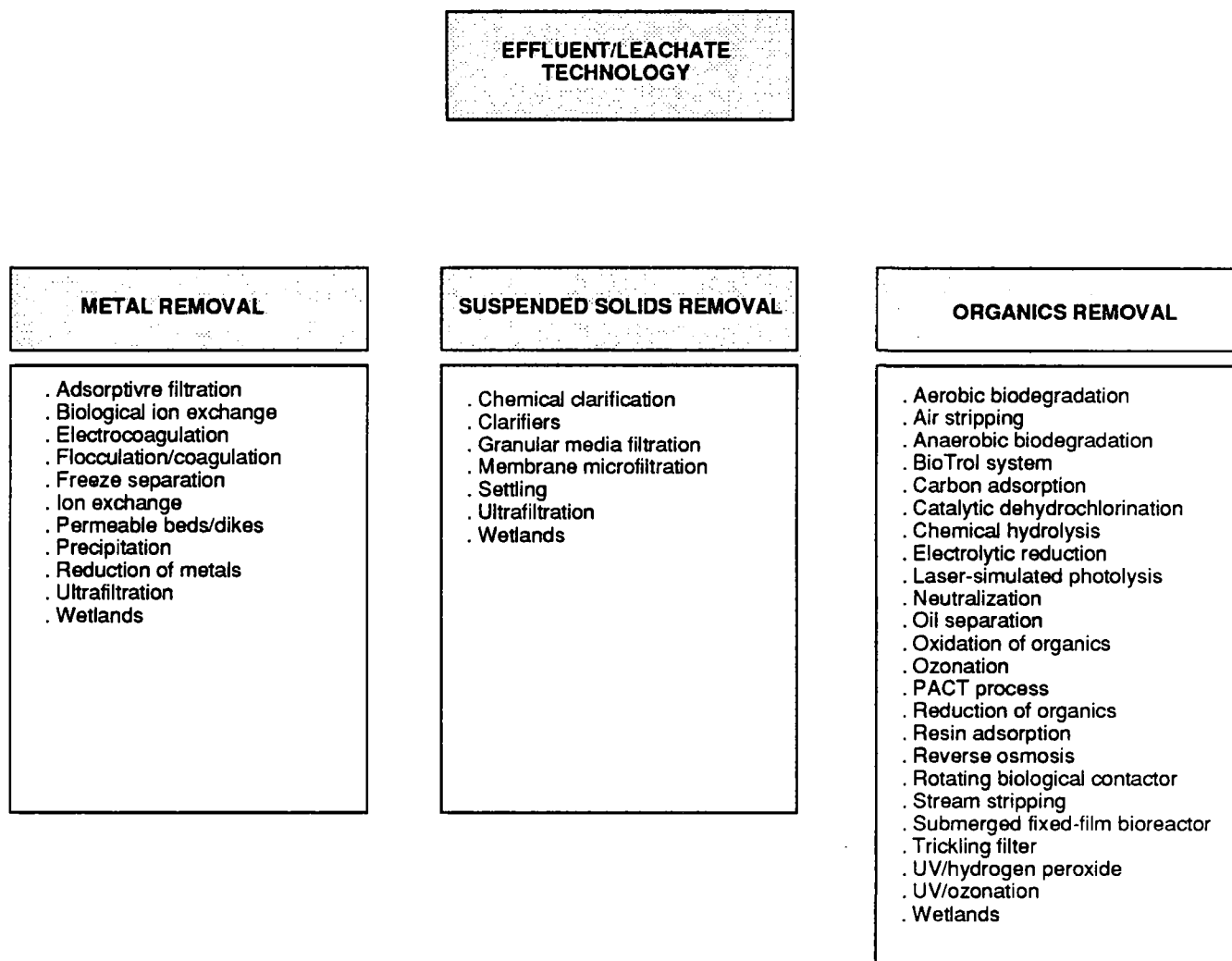
Most soil remediation projects require wastewater treatment units to decontaminate process effluents or runoff. Such units are even more important for contaminated sediment remediation projects. Because the high water content of sediment at the extraction site, effluents or leachates must be treated, especially when hydraulic dredges are used. It is important, therefore, to ensure that effluent or leachate treatment technologies selected meet the following objectives:

- a) Effluent or leachate quality that complies with applicable regulatory water quality standards and criteria.
- b) No contamination of other environments and other environmental media.
- c) Compatibility with removal, treatment, or disposal options.
- d) Acceptable capital and operating costs (Averett et al., 1990).

To meet these objectives with dredging projects, a treatment train approach is generally required because of the variability of effluent or leachate from sediment pretreatment, treatment or disposal processes: in any one effluent or leachate stream, for example, flow, contaminant concentrations and type of contamination (organic and inorganic, conventional as well as potentially toxic contaminants) can vary considerably. Commonly used industrial wastewater treatment processes are, however, generally effective for dredging project effluents and leachates (Averett et al., 1990).

### **5.2 Effluent and leachate treatment processes**

As indicated in Figure 5.1, effluent or leachate treatment technologies considered by the USEPA and the USACE for Great Lakes sediment cleanup projects divide into three categories: metals removal, suspended solids removal and organic treatment.



Source : Averett *et al.* 1990.

**Figure 5.1** *Effluent/leachate process options considered for Great Lakes sediment cleanup*

Most of these technologies concentrate contaminants such as heavy metals and organics in another medium, generally sludge, which is then treated or disposed of. Conventional contaminants which may also be a concern (nutrients, ammonia, oils and greases, and oxygen-demanding material) for dredging projects are removed by most processes that remove dissolved organics.

**5.2.1 Metals removal.** Most technologies that can be used to remove metals from dredged sediment are commonly used for industrial wastewater treatment. Of the technologies listed in Figure 5.1, only a few (biological ion exchange, electrocoagulation, adsorptive filtration, ultrafiltration and natural or artificial wetlands) are relatively new concepts currently being demonstrated for metals removal.

**5.2.2 Suspended solids removal.** Since most contaminants released during dredging and sediment treatment operations are associated with suspended solids, suspended solids removal technologies are important not only because they reduce turbidity but also because they remove the particles to which most of the contaminants are attached. Metals and organic contaminants dissolved in the water must be removed by other types of treatment.

**5.2.3 Organic treatment.** Organic contaminants in effluents or leachates from contaminated sediment may be treated biological, chemically or physically. Applicability and effectiveness of the options listed in Figure 5.1 depend on contaminant concentrations and flow rates.

### 5.3 Applications and limitations of effluent and leachate treatment processes

Flocculation using polymers and inorganic flocculants has been demonstrated effective for *removal of* metals associated with particulate matter in dredging effluents. These technologies have not yet been demonstrated in the field for removal of dissolved metals however. Ion exchange and precipitation are probably two of the more efficient metals removal processes, but they must generally be designed for specific metals and usually require major investments in operational control for efficient operation.

Many of the technologies listed in Figure 5.1 for *suspended solids removal* have already be applied to USACE dredging projects: settling, clarification with prior addition of flocculants, chemical clarification using polyelectrolytes, granular media filtration and sand-filled weirs. Settling has been used for dredging projects as well as for dewatering of dredged sediment and for supernatant suspended solids control for many years.

The rest of the solids removal technologies--membrane microfiltration, wetlands and ultrafiltration have been used successfully to treat municipal and industrial wastewater.

According to Averett et al., (1990), mechanical biological processes for *organic treatment* should not be considered for dredging projects because of the low organic matter content of sediment and the fluctuating flows and extremes of temperature of effluents from sediment pretreatment and treatment processes. However, biological processes such as nitrification, nutrient catabolism and photosynthesis can be used to degrade nutrients, oxygen-demanding materials and other organics in confined disposal facilities for dredged material.



According to Averett et al. as well, air and steam stripping can be used for volatile organic contaminants, but these are generally not a problem in contaminated sediment.

#### 5.4 **Processes recommended for cleanup of the Great Lakes**

**5.4.1 Process evaluation and selection criteria.** Selection and evaluation criteria used by the USEPA and the USACE in recommending effluent treatments for Great Lakes sediment remediation projects are the same as those used to evaluate and select sediment pretreatment and treatment technologies; these are described in Chapter 3 of this guide (tables 3.3 and 3.4).

As Table 5.1 indicates, in addition to general process information (state of development, sediment application experience and availability of equipment in the United States), the USACE and the USEPA also rated each process from 1 to 4 for each of the following three performance factors: effectiveness in removing contaminants and meeting remediation goals; demonstrated application for soil and/or contaminated sediment; and anticipated unit cost of treatment.

**5.4.2 Processes recommended.** Figure 5.2 divides effluent treatment options by treatment type and lists in bold the processes recommended for demonstration projects in five Great Lakes "Areas of Concern" based on the ratings shown in Table 5.1.

Table 5.1 Anticipated performance of effluent treatment technologies

TECHNOLOGY	STATE OF DEVELOPMENT	APPLIED TO SEDIMENT	AVAILABILITY	PERFORMANCE RATINGS		
				EFFEC-TIVENESS	IMPLEMENT-ABILITY	COST
Suspended solids removal						
Chemical clarification*	Demonstrated	Yes	Available	3	4	4
Clarifiers	Demonstrated	No	Available	3	2	3
Granular media filtration	Demonstrated	Yes	Available	3	3	3
Membrane microfiltration	Demonstrated	No	Available	4	3	2
Settling (CDF)	Demonstrated	Yes	Available	3	4	4
Ultrafiltration	Demonstrated	No	Available	4	2	2
Wetlands	Demonstrated	Yes	Available	4	3	3
Metals removal						
Adsorption filtration	Conceptual	No	Emerging	3	2	3
Biological ion exchange	Conceptual	No	Emerging	3	2	3
Electrocoagulation	Conceptual	No	Emerging	3	2	3
Flocculation/coagulation	Demonstrated	Yes	Available	3	4	4
Freeze separation	Conceptual	No	Emerging	2	2	2
Ion exchange	Demonstrated	No	Available	4	3	3
Permeable treatment beds/dikes	Demonstrated	Yes	Available	3	3	3
Precipitation	Demonstrated	No	Available	4	3	3
Reduction of metals	Demonstrated	No	Available	3	2	3
Ultrafiltration	Conceptual	No	Emerging	3	2	2
Wetlands	Demonstrated	Yes	Available	3	3	3
Organic treatment						
Aerobic biodegradation	Demonstrated	No	Available	2	2	3
Air stripping	Demonstrated	No	Available	2	2	3
Anaerobic biodegradation	Demonstrated	No	Available	2	2	3
BioTrol aqueous treatment system	Pilot	No	Proprietary	2	2	3
Carbon adsorption	Demonstrated	Yes	Available	4	3	3
Catalytic dehydrochlorination	Demonstrated	No	Available	2	2	2
Chemical hydrolysis	Demonstrated	No	Available	2	2	2
Electrolytic reduction	Conceptual	No	Emerging	2	2	2
Laser simulated photolysis	Conceptual	No	Emerging	2	2	2
Neutralization	Demonstrated	No	Available	2	2	3
Oil separation	Demonstrated	No	Available	2	4	4
Oxidation of organics	Demonstrated	Yes	Available	3	2	3
Ozonation	Demonstrated	No	Available	3	2	3
PACT process	Demonstrated	No	Available	3	2	2
Reduction of organics	Conceptual	No	Emerging	2	1	2
Resin adsorption	Demonstrated	No	Available	3	2	3
Reverse osmosis	Demonstrated	No	Available	4	2	1
Rotating biological contactor	Demonstrated	No	Available	2	2	3
Steam stripping	Demonstrated	No	Available	3	2	2
Submerged fixed-film bioreactor	Conceptual	No	Emerging	2	2	3
Trickling filter	Demonstrated	No	Available	2	2	3
UV/hydrogen peroxide	Demonstrated	Yes	Available	3	2	3
UV/ozonation	Demonstrated	No	Available	3	2	3
Wetlands	Demonstrated	No	Available	3	3	3

**Notes**

\* Technologies shown in bold have been recommended by the USACE and the USEPA for Great Lakes sediment remediation demonstration projects.

\*\* See Table 3.3 for information on performance ratings.

Adapted from Averett et al., 1990

In Figure 5.2, recommended effluent treatment technologies are classified according to stage of development (emerging or conceptual, bench-scale demonstration, pilot-scale demonstration or commercial) and treatment cost (one of four cost categories used in evaluating Great Lakes projects). Anticipated or demonstrated effectiveness, as assessed by Averett et al., is also indicated.

Of the eleven metals removal technologies considered, five have effectiveness, implementability and cost ratings acceptable for contaminated sediment effluent or leachate treatment demonstration projects and were recommended by the USEPA and the USACE: flocculation/coagulation, ion exchange, permeable treatment beds or dikes, precipitation and wetlands (Averett et al., 1990).

Of the seven technologies considered for *suspended solids removal* all except clarifiers and ultrafiltration have acceptable effectiveness, implementability and cost for contaminated sediment remediation projects and were recommended by the USEPA and the USACE. Clarifiers and ultrafiltration were not recommended because of their low implementability ratings (see Table 5.1).

For *organic treatment*, ultraviolet oxidation and ozonation have been well demonstrated on a wide range of organic contaminants. According to Averett et al. (1990), the most promising processes for treating organics in effluent and leachate are carbon adsorption, oxidation, oil separation, the PACT process (activated carbon), resin adsorption, steam stripping and wetlands. Of the twenty-four technologies considered for organic treatment, eight were recommended because of their effectiveness, implementability on sediment and cost: carbon adsorption, resin adsorption, oxidation, ozonation, oil separation, wetlands, UV/ozone and UV/hydrogen peroxide. Reverse osmosis, steam stripping and PACT were screened out because of high costs.

COST \$/cy	IMPLEMENTABILITY RATING			
	1* EMERGING OR CONCEPTUAL	2 BENCH	3 PILOT	4 COMMERCIAL
1 \$200 or more		• reverse osmosis (4)**		
2 \$100 to \$200	• reduction of organics(2)	• catalytic dehydrochlorination(2) • chemical hydrolysis(2) • PACT process(3) • laser simulated photolysis(2) • electrolytic reduction(2) • freeze separation • steam stripping(3) • ultrafiltration(4)	• membrane microfiltration(4)***	
3 \$20 to \$100		• resin adsorption(3) • aerobic biodegradation(2) • anaerobic biodegradation(2) • submerged fixed-film bioreactor(2) • clarifiers(3) • rotating biological contractor(2) • biological ion exchange(3) • electrocoagulation(3) • adsorptive filtration(3) • trickling filter(2) • neutralisation (2) • Oxidation of organics(3) • Ozonation(3) • reduction of metals(3) • air stripping(2) • biotrol soil washing(2) • UV/ozonation (3) • UV/hydrogen peroxide(3)	• carbon adsorption(4) • ion exchange(4) • granular media filtration(3) • permeable beds/dikes(3) • precipitation (4) • wetlands(3)	
4 \$20 or less				• settling (3) • chemical clarification(3) • flocculation/coagulation (3) • oil separation(2)

Notes:

\* : Performance rating (see Table 3.3)

\*\* : Effectiveness rating (see Table 3.3)

\*\*\* : Processes shown in bold have been selected for Great Lakes cleanup demonstration projects.

Adapted from Averett et al., 1990

**Figure 5.2 Classification of 41 effluent treatment technologies considered and selected for Great Lakes sediment cleanup demonstration projects**

## 6. GENERAL CRITERIA FOR TREATMENT TECHNOLOGY SELECTION

As the preceding sections on technologies for pretreatment, sediment treatment and effluent treatment show, there is no universally applicable technology that can treat a wide range of organic and inorganic contaminants regardless of the matrix to be treated and the physical and environmental characteristics of the contaminated site. Most thermal, biological, extraction, chemical and immobilization technologies have specific environmental, technical and economic strengths and limitations depending on matrices and contaminants to be treated.

Environmental, technical and economic aspects must all, therefore, be considered when evaluating and selecting treatment technologies, so all concerned--project proponents, contractors, government agencies, environment protection groups and the public--can better identify and evaluate what is at stake in selecting a particular technology to treat contaminated sediment.

The preceding chapters highlighted strengths and limitations (technical and economic ones in particular) of a variety of technologies. It is important at this stage to get a wider screening perspective by considering **technical, economic and environmental aspects of all work planned** (environmental aspects include protection of public health and social considerations).

### 6.1 Proposed screening criteria for sediment treatment technologies

Table 6.1 lists suggested technical, economic and environmental criteria for evaluating and selecting technologies for a contaminated sediment treatment train (dredging, pretreatment, treatment properly speaking, effluent treatment and process residue disposal).

The list has been made as exhaustive as possible, but it must nevertheless be revised and adapted in light of site-specific features and new developments in contaminated treatment technologies (which are changing at a rapid rate at the moment).

**Table 6.1 Selection criteria for contaminated sediment treatment trains**

FACTORS	CRITERIA
TECHNICAL	<ul style="list-style-type: none"> <li>• Nature and degree of contamination</li> <li>• Physical characteristics of the sediment</li> <li>• Stage of development of the technology</li> <li>• Technology efficiency and effectiveness</li> <li>• Simplicity of operation and maintenance</li> <li>• Reliability of treatment processes</li> <li>• Availability of equipment and simplicity of implementation</li> <li>• Throughput</li> <li>• Completion time</li> <li>• Flexibility</li> <li>• Compatibility with excavation, pretreatment and effluent treatment technologies</li> <li>• Amount of land available for treatment units</li> <li>• Experience and training of operators</li> </ul>
ENVIRONMENTAL	<ul style="list-style-type: none"> <li>• Environmental performance</li> <li>• Potential environmental and human health impacts</li> <li>• Potential impacts of related activities (dredging, transport and storage)</li> <li>• Compliance with regulations and policies of all levels of government</li> <li>• Community acceptance</li> <li>• Certificates of authorization issued for the technology</li> <li>• Long-term effectiveness</li> <li>• Short-term effectiveness</li> <li>• Reduction of toxicity, mobility and volume of contaminants</li> <li>• Gas, liquid or solid process waste streams</li> <li>• Health risks for workers and public</li> <li>• Proximity to sensitive areas (biological and human environments)</li> <li>• Risks of accidental spills</li> <li>• Environmental monitoring and control program</li> <li>• Reliability history of the technology</li> </ul>
ECONOMIC	<ul style="list-style-type: none"> <li>• Costs of dredging, transport and storage</li> <li>• Costs of pretreatment and effluent treatment</li> <li>• Costs of sediment treatment</li> <li>• Costs of disposal of process residues</li> <li>• Costs of studies to obtain government permits</li> <li>• Costs of chemical analyses and of quality assurance and quality control programs</li> <li>• Costs of starting up and shutting down operations</li> <li>• Costs to guarantee a safe worksite</li> <li>• Maintenance costs</li> </ul>

## **6.2 Review of principles, strengths and limitations of each treatment technology type**

The preceding sections described principles and main technical and economic strengths and limitations of each type of technology (biological, chemical, extraction, thermal, immobilization and containment) for treating contaminated media. Table 6.2 summarizes this information to facilitate comparison of strengths, limitations, secondary impacts and treatment costs of the six technology types.

## **6.3 Potential environmental and health impacts of treatment technologies**

The City of Toronto's Environmental Protection Office, with the help of the Ontario Ministry of the Environment and Health and Welfare Canada, evaluated potential environmental and health impacts of soil treatment technologies, focusing on technologies developed and used in North America (Kendall et al., 1991).

Kendall et al. used fifteen criteria to evaluate potential environmental and health impacts suggested by a technology review. The fifteen criteria are listed and defined in Table 6.3.

The criteria address environmental and health concerns and associated technology performance by examining contaminant destruction and removal efficiencies, treatment completion times and process emissions. Long-term effectiveness is indicated by residue mobility and toxicity.

Other hazards evaluated include fire and explosion hazard and those associated with transportation of heavy equipment and hazardous materials, and worker and community exposure.

Amount of noise, odours, dust and visual disturbance caused by operation of a technology is covered under community disturbance.

**Table 6.2 Review of principles, strengths and limitations of each treatment technology type**

TYPE OF PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	COSTS (US\$)
<b>Biological processes</b>  <b>Principle</b>  Use microorganisms (bacteria or fungi) or enzymes to break down PCBs, pesticides and other organic contaminants into innocuous or less toxic compounds (CO <sub>2</sub> , CH <sub>4</sub> or inorganic salts).	Can be applied to sediment provided use of microorganisms is appropriate for type of contamination.  Used commercially to treat soil, liquid effluents and groundwater.	Efficiency limited by bioavailability of contaminants and presence of metals.  To date, biodegradation of sediment has been tested only on a bench scale.  Temperature is often a limiting factor.  Large land areas and long treatment times generally required.  Reliability cannot be guaranteed because optimum conditions must be maintained at all times.  Costs difficult to estimate.	Emissions of volatile organics.  Incomplete degradation of hazardous substances.  Leachate.	\$130-270/cy
<b>Extraction</b>  <b>Principle</b>  Remove contaminants from a medium by dissolving them in a fluid which is then treated.	Can remove organic contaminants as well as heavy metals but rarely both simultaneously.  Generally removes contaminants from the solvent so the solvent can be reused in the process.  Widely used for soil decontamination.  Attractive technologies for sediment because they concentrate contaminants in small volumes of material.	Most processes require multiple extraction cycles to achieve high efficiencies.  Posttreatment processes required to treat or dispose of concentrated effluents.  Feasibility for treating sediment difficult to evaluate for lack of full-scale demonstration projects, problems regenerating solvent and possible toxicity of solvent residuals.  Not very efficient for matrices with high percentages of clay and silt.	Emissions of volatile organics.  Wastewater discharge.  Residue disposal.	> \$100/cy



**Table 6.2 Review of principles, strengths and limitations of sediment remediation technologies (continued)**

TYPE OF PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	COST (US\$)
<p><b>Chemical processes</b></p> <p>Principle:</p> <p>Use chelating or bond-breaking agents, acids or bases, chlorine displacement, oxidation or reduction to destroy, detoxify or remove contaminants in contaminated media.</p>	<p>Widely applied in the chemical industry to treat a limited number of compounds present mainly in water.</p> <p>Alters the form of the material to render it less toxic or changes its solubility, stability, separation potential or other properties to make it easier to handle or to dispose of it.</p>	<p>Few of these technologies have been used to treat organics and heavy metals in sediment.</p> <p>Difficult to identify the chemical reaction capable of treating very specific contaminants in sediment.</p> <p>Reaction that treats one contaminant may increase the mobility of others.</p> <p>Costs difficult to estimate.</p>	<p>Emissions of volatile organics.</p> <p>Wastewater discharge.</p> <p>Residue disposal.</p>	<p>&gt; \$100/cy</p>
<p><b>High-temperature thermal processes</b></p> <p>Principle:</p> <p>Heat soil and sediment to temperatures several hundreds or thousands of degrees above ambient temperature.</p>	<p>Generally the most effective but also the most costly option for destroying organics.</p> <p>Destruction efficiency exceeds 99%.</p> <p>Not yet applied to sediment in the U.S. but selected for a number of U.S. Superfund sites.</p> <p>These technologies can be used for soil, sediment, sludge, liquids or gas.</p>	<p>Does not destroy any but the most volatile metals, such as mercury and lead which volatilize at high temperatures. These metals must be collected and treated before offgas is released to the atmosphere.</p> <p>Changes the oxidation state of some metals in sediment, sometimes making the metals more mobile in the ash than they were initially in the sediment.</p> <p>Incinerator emissions from processing sediment high in fines may be high in particulates; particle size must be reduced before incineration.</p> <p>Applicability often limited by the length of time it takes to obtain government permits and the marked community reticence about incineration projects.</p>	<p>Air emissions.</p> <p>Byproduct disposal.</p>	<p>Very high \$200-\$1300/cy</p>

**Table 6.2 Review of principles, strengths and limitations of sediment remediation technologies (continued)**

TYPE OF PROCESS	APPLICATIONS	LIMITATIONS	SECONDARY IMPACTS	COST (US\$)
<b>Low-temperature thermal processes</b>  Principle:  Heat material to several hundreds of degrees to extract volatile compounds, which are then collected and passed to a gas treatment system. Low-temperature thermal processes function with or without oxidizing agents or in the presence of hydrogen or other reducing agents.	Highly effective and possibilities for application to sediment.	Expensive, especially if water content of sediment is high.	Air emissions.  Byproduct disposal.	Less than incineration
<b>Immobilization</b>  Principle:  Limit contaminant mobility by decreasing surface area of sediment mass across which transfer of contaminants can occur, and limit solubility of contaminants by pH adjustment or sorption.	Improves handling and physical properties of materials.  Solidification (physical process) and stabilization (chemical process) are often selected for remediation of soil contaminated by heavy metals since heavy metals cannot be destroyed.  Solidification is an effective treatment for organic contamination.	Not effective in stabilizing organic contaminants.  Organics can interfere with solidification/stabilization reactions.	Emissions of organic volatiles.  Leachate and long-term physical stability of end products.	<\$100/cy
<b>Containment</b>  Principle:  Encapsulate contaminants with capping material or in watertight enclosures to prevent release of contaminants into the environment.	Containment is often selected as a solution for two reasons: it is inexpensive; there are no treatment centres or treatment technologies that can do the job.  Most common solutions are in-situ or off-site level bottom capping, contained aquatic disposal or upland confined disposal facilities.	Generally limited to slightly or only moderately contaminated sediment.	Long-term stability.	Costs of capping and CDFs are low (\$10 to \$20/cy). Cost of hazardous landfill disposal is high (>200 US\$/cy)

Adapted from Averett et al, 1990; USEPA, 1990a, 1991a, 1991b

Table 6.3 City of Toronto environmental and health impacts criteria

CRITERIA	
Destruction efficiency	Most technologies separate contaminants from soil; few technologies actually destroy contaminants or make them less toxic.
Removal efficiency	This criterion refers to percentage of contaminants removed by the technology.
Completion time	Completion time affects costs as well as duration of worker and community exposure.
Process emissions	This criterion refers to the technology's ability to mitigate, reduce or destroy contaminants in air emissions and wastewater or solid residues.
Residue mobility	No single technology can remove all contamination from a site. Residue mobility is a measure of the tendency of remaining contaminants to move in the environment.  This criterion considers toxicity and bioavailability of residual contaminants.
Residue toxicity	Treatments that require flammable or explosive materials or high pressures and temperatures can pose fire and explosion hazards.
Fire/explosion hazards	Transportation of heavy equipment can be a source of disruption and risks for workers and community.
Transportation of heavy equipment	Amount and nature of hazardous materials transported on site is important in assessing risks for workers and community.
Transportation of hazardous materials	Volatile compounds may be released during excavation of contaminated soil, and treatment processes can generate waste streams--air, water and solids--that are hazardous for workers and community.
Worker/community exposure	Noise, odour and dust generated by treatment can disturb the community. Operations may also have a visual impact.
Community disturbance	Risk levels differ with stage of development of a technology (conceptual, bench, pilot or commercial).
Stage of development	Cost of treatment.
Cost	Case histories of sites successfully treated by the technology can confirm performance claims made by technology developers.
Independent technology evaluations	This criterion refers to types of waste and contaminants the technology can effectively remove or destroy.
Waste applicability	

Adapted from Kendall et al., 1991

CRITERION TECHNOLOGY															
	Destruction efficiency	Removal efficiency	Completion time	Process emissions	Residue toxicity	Residue mobility	Fire/explosion hazards	Transport of heavy equipment	Transport of hazardous materials	Worker/community exposure	Community disturbance	Stage of development	Costs	Independent technology evaluations	Waste applicability
In situ vacuum extraction	●	●	●	●	●	●	○	○	●	●	○	○	○	○	●
In situ air/steam stripping	●	●	●	●	●	●	○	●	●	●	○	●	●	○	●
Radio frequency treatment	●	●	●	●	●	●	●	●	●	●	○	●	○	●	●
Electroremediation	N/A	●	○	●	●	●	○	○	○	○	○	●	●	●	●
In situ solidification	●	●	○	○	●	●	○	●	○	●	○	○	○	○	●
On-site solidification	●	●	○	●	●	●	○	●	●	●	○	○	●	○	●
Landfarming	●	●	●	●	○	●	○	○	●	●	●	●	○	●	●
In situ bioremediation	●	●	●	○	○	●	○	○	○	○	○	○	●	●	●
On-site bioremediation	●	●	●	○	○	○	○	●	○	○	○	○	●	●	●
Infrared incineration	○	○	●	●	●	●	●	●	●	●	●	○	●	○	○
In situ vitrification	○	○	●	●	○	○	●	●	○	●	●	●	●	●	○
Encapsulation	●	●	○	○	●	●	○	●	○	○	○	○	●	●	○
Excavation and off-site disposal	●	●	○	●	●	●	○	●	●	●	●	○	●	●	○
Dechlorination	○	○	○	○	●	●	○	○	●	●	●	●	●	○	●
On-site soil washing	●	○	○	●	●	●	○	○	●	●	●	○	○	○	○
In situ soil washing	●	●	●	●	●	●	○	●	○	○	○	●	-	●	●
Solvent extraction	●	●	●	○	●	●	●	○	●	●	●	○	○	○	○
Low temperature thermal desorption	●	○	○	●	●	●	●	●	●	●	●	○	○	●	●

#### LEGEND

- High concern
- Moderate concern
- Low concern
- Not a concern

N/A Not applicable

- Not available

Adapted from Kendal et al., 1991

**FIGURE 6.1** Matrix of potential environmental and health concerns related to soil remediation technologies.

The remaining criteria are cost, stage of development of the technology, number of independent evaluations of the technology's effectiveness (that is, number of demonstration projects) and applicability of the technology to different wastes.

Figure 6.1 shows the results of the Kendall et al. (1991) evaluation of eighteen technologies (physical, chemical, biological and thermal). As the chart shows, four levels of concerns were used to rate severity of potential environmental and health impacts of each technology: not a concern, low concern, moderate concern and high concern.

Main results of the evaluation are summarized below.

**Destruction efficiency.** Destruction efficiency was rated not a concern with high-temperature thermal technologies (incineration and vitrification). These technologies almost completely destroy contaminants.

Destruction efficiency was rated a high concern with all extraction, washing, desorption, radio-frequency treatment and immobilization (solidification, encapsulation, excavation and off-site disposal) technologies. These technologies only remove or desorb contaminants in treated matrices; contaminants must then be treated or immobilized in the matrices.

**Removal efficiency.** Contaminant removal efficiency of infrared incineration was rated not a concern. Removal and destruction efficiency of this technology is 99.9 percent.

Contaminant removal efficiencies of immobilization (solidification, encapsulation and off-site disposal) and on-site treatment (air/steam stripping and soil flushing) technologies were rated high concerns.

**Completion time.** Completion times of in situ electroacoustic technologies, on-site solidification, extraction and off-site disposal are generally rapid and were rated not a concern.

Completion times of technologies with low throughputs in tons per day (radio frequency treatment) as well as technologies that require relatively long treatment times (biotechnologies and soil flushing) and those whose completion times are difficult to estimate (in situ vacuum extraction) were rated high concerns.

**Process emissions.** Process emissions from in situ solidification technologies, in situ or on-site bioremediation, encapsulation, dechlorination and solvent extraction were rated low concerns.

Process emissions were rated a high concern for the following technologies: on-site solidification technologies (emissions of organics and volatiles); infrared incineration (emissions of particles, and ash and water management); on-site washing (emissions associated with treated fines, chelating agents or surfactants in water, and emissions of volatile organic compounds); and thermal desorption (soil excavation known to possibly cause loss by volatilization of 60 to 90 percent of volatile contaminants).

**Residue mobility.** Residue mobility was rated a concern with all technologies apart from in situ vitrification (long-term stability of the vitrified mass).

Residue mobility was rated a high concern with in situ electroacoustic technologies (partial desorption and mobility of residual inorganics and increased mobility of volatile and semivolatile organic compounds), solidification (cannot immobilize certain metals and organics and does not eliminate long-term risks of contaminant mobility), infrared incineration (mobility of metals in ash), on- or off-site containment (contaminants not treated or fixed) and washing (desorption but not removal of contaminants).

**Residue toxicity.** Residue toxicity was rated a low concern with on-site bioremediation and on-site vitrification.

Residue toxicity was rated a high concern with electroacoustic technologies (toxicity and bioavailability of partially desorbed residual inorganics), solidification (toxic to some soil bacteria; possible toxicity of contaminants in the leachate; contaminant toxicity unaffected), infrared incineration (toxic ash), encapsulation or off-site disposal (contaminant toxicity unaffected) and washing (toxic fines, bioavailability of contaminants in wastewater, and chelating agents and surfactants can damage the environment).

**Fire/explosion hazards.** Fire/explosion hazards were rated not a concern for technologies which do not use toxic or flammable substances (solidification, biotechnologies, encapsulation and off-site disposal, and soil washing).

Fire/explosion hazards were rated a high concern for infrared incineration (fuel oil used as an additive), vitrification (combustible materials in the subsurface), solvent extraction (solvents are flammable) and thermal desorption (risk of explosion in presence of oxygen).

**Transportation of heavy equipment.** Transportation of heavy equipment was rated not a concern for vacuum extraction, electroacoustic treatment, landfarming, in situ bioremediation, dechlorination, on-site washing and solvent extraction. These technologies do not require any special heavy equipment or more than one trailer to transport process equipment.

Transportation of heavy equipment was rated a high concern for infrared incineration because a number of trailers are required to transport incineration equipment and frontend loaders are required to transport soil and ash.

**Transportation of hazardous materials.** In situ solidification and encapsulation technologies do not require transportation of hazardous materials. Transportation of hazardous materials was therefore rated not a concern for these technologies.

Transportation of hazardous materials was rated a high concern with excavation and off-site disposal technologies and solvent extraction because they require, respectively, transport of untreated contaminated soil and transport of flammable solvents, liquid nitrogen or other hazardous chemicals.

**Worker/community exposure.** This impact was rated a low concern with the following technologies: electroacoustic treatment, in situ bioremediation, on-site bioremediation, encapsulation and soil flushing.

Worker/community exposure was rated a high concern with on-site solidification, infrared incineration, in situ vitrification and low temperature thermal desorption for one or more of the following reasons: exposure associated with excavation of contaminated soil, mixing, long-term leaching of unfixed or desorbed contaminants, air emissions, handling of contaminated soil and ash, and fire hazards.

**Community disturbance.** This impact was rated a low concern for technologies that generate few or no emissions and little noise or dust and that do not require excavation of soil because treatment is in situ (vacuum extraction, air/steam stripping, electroacoustic treatment, solidification, bioremediation and soil flushing).

Community disturbance was rated a high concern for technologies that require excavation of contaminated soil with associated disturbances (noise, dust, odours and visual impacts) as well as technologies that generate air emissions, which are generally viewed as unacceptable by the public (excavation and off-site disposal, solvent extraction and infrared incineration).



**Stage of development.** Stage of development was rated not a concern for technologies which have been successfully used for remediation or have been demonstrated at a number of sites: in situ vacuum extraction, on-site solidification, in situ bioremediation, infrared incineration, on-site soil washing and solvent extraction.

Stage of development was rated a high concern for soil flushing because the technology has only been tested on a pilot scale, and this at only one or two sites in the United States and Europe.

**Cost.** Cost was rated not a concern for vacuum extraction: cost ranges from US\$11 per ton to US\$55 per ton for vacuum extraction.

Technologies for which cost was rated a high concern that could significantly limit use of the technology for remediation are as follows: in situ bioremediation (US\$320 per ton), on-site bioremediation (US\$170 to US\$500 per ton), in situ vitrification (US\$275 to US\$385 per ton), excavation and off-site disposal (real costs cannot be estimated because permanence and long-term viability of the solution cannot be guaranteed) and dechlorination (US\$200 to US\$600 per ton).

**Independent technology evaluations/case histories.** Independent technology evaluations were rated not a concern for technologies that have been demonstrated at a number of sites under the supervision of environmental protection agencies (such as the USEPA) and for which reports of test results are available for consultation (in situ vacuum extraction, in situ and on-site solidification, infrared incineration and solvent extraction).

Independent technology evaluations were rated a high concern for technologies for which test results were not available as of publication of the study or for which the only performance data are vendor's claims (radio-frequency treatment, electroacoustic treatment, on site bioremediation, soil flushing and low-temperature thermal desorption).

**Waste applicability.** Although treatability tests are always necessary to demonstrate effectiveness for a given matrix, waste applicability was rated not a concern for in situ vitrification since this technology can treat high concentrations of metals as well as radioactive substances, organics and volatiles.

Waste applicability was rated a high concern for technologies that treat only nonpolar halogenated organics or only soluble or loosely adsorbed contaminants (dechlorination and soil flushing).

As Kendall et al. (1991) specify, the ratings given in Figure 6.1 reflect potential hazards only. Real risks depend largely on site-specific conditions: nature of contamination and matrices to be treated, hydrologic conditions, proximity to residential areas, time and resources available and proposed land use. In other words, it is not possible to select the best technology for a given site based on the information in Figure 6.1 alone.

For a realistic comparison of technologies, an in-depth site- and matrix-specific risk assessment is required. In addition, risk assessments must be regularly updated given the current rapid development of technologies.

#### **6.4 Anticipated costs for sediment remediation**

In the preceding sections, costs of using technologies to treat soil and sediment were given when available in the literature.

Many of the cost estimates come from demonstration or remediation projects that treated soil, however. Cost estimates for treating sediment come mainly from vendors' claims or were extrapolated from bench- or pilot-scale demonstrations.

A great deal of caution is in order when extrapolating costs from any project. Costs for a particular activity, even one that is well known, can be very different in different contexts. Table 6.4, for example, compares costs of capital dredging, maintenance dredging and dredging of contaminated sediment based on Dutch experience.

**Table 6.4 Dutch cost comparison of three types of dredging projects**

	CAPITAL DREDGING	MAINTENANCE DREDGING	DREDGING CONTAMINATED SEDIMENT
Type of material	Rock	Silt/sand	Silt
Total cost in US\$/m <sup>3</sup>	50	5	125*
Total cost in US\$ to dredge a 10-cm layer from an area 140 m x 100 m	70 000	7 000	175 000
Total cost in US\$ to dredge an area of 140 m x 100 m with 30-cm tolerance (normal maintenance project)	-	20 000	500 000

Note

\* Treatment costs included.

Adapted from Van Oostrum, 1992

As the table shows, type of material and total cost per cubic metre of sediment vary considerably depending on the type of dredging. Table 6.5 shows main differences between maintenance dredging and dredging for sediment remediation; these differences explain the discrepancy in unit cost, respectively US\$5 per cubic metre and US\$125 per cubic metre. In fact, objectives, dredging specification, design profile, restrictions on sediment resuspension in the water column, predredging site investigations, and performance requirements (precision, quality control and so forth) are very different with the two types of dredging.

Other factors that must be considered in selecting treatment technologies for sediment cleanup projects are that hundreds of thousands or millions of cubic metres of sediment must generally be treated and that sediment contamination levels are usually lower than soil contamination levels. In addition, since aquatic organisms are in direct contact with sediment and certain contaminants bioaccumulate in the food chain, decontamination objectives (residual contaminant levels) are more stringent for sediment than for soil.

These factors are significant not only in the cost of remediation projects but also the selection of sediment treatment technologies. Technologies for treating sediment must have higher destruction and removal rates than those that treat soil, and multiple treatment cycles may be required to meet sediment remediation objectives.

For a number of years to come, until sufficiently accurate data from full-scale sediment remediation demonstration projects are available, site-specific treatability studies will be required to estimate with any accuracy the real costs of treating contaminated sediment.

Besides, treatment costs given in the literature generally do not reflect all costs of remediation. This is why, before selecting what appears to be the least costly technology or technologies, it is important to make sure that all cost elements have been covered (see Table 6.6 for elements considered in USEPA-supervised treatability studies for U.S. Superfund projects) (USEPA, 1992e).

Likewise, it is important to make sure that treatability tests and demonstration projects at any given site are planned to provide all costs at all stages of a sediment remediation

**Table 6.5 Main differences between maintenance dredging and dredging contaminated sediment**

MAINTENANCE DREDGING	DREDGING CONTAMINATED SEDIMENT (cleanup)
<p><b>Objective</b></p> <ul style="list-style-type: none"> <li>• Maintain safe draft</li> </ul> <p><b>Dredging specification</b></p> <ul style="list-style-type: none"> <li>• Create a flat bottom within tolerances</li> </ul> <p><b>Design profile</b></p> <ul style="list-style-type: none"> <li>• Flat</li> </ul> <p><b>Resuspension and transport of sediment in the water column</b></p> <ul style="list-style-type: none"> <li>• Not a concern</li> </ul> <p><b>Predredging site investigations</b></p> <ul style="list-style-type: none"> <li>• Technical feasibility of dredging operations and volume estimates</li> </ul> <p><b>General characteristics</b></p> <ul style="list-style-type: none"> <li>• Large scale</li> <li>• Standard equipment</li> <li>• Inexpensive per cubic metre</li> <li>• Goal is high productivity</li> <li>• Large tolerances (20 to 50 cm)</li> <li>• Simple monitoring</li> </ul>	<ul style="list-style-type: none"> <li>• Completely remove contaminated sediment</li> </ul> <ul style="list-style-type: none"> <li>• Minimize total volume of material dredged (contaminated sediment only)</li> </ul> <ul style="list-style-type: none"> <li>• Irregular (determined by profile of contaminated layer)</li> </ul> <ul style="list-style-type: none"> <li>• Minimize resuspension (no overflow, no spills; install siltscreen)</li> </ul> <ul style="list-style-type: none"> <li>• Technical and environmental feasibility of dredging operations, nature of contamination, dimensions of contaminated area, sediment treatability and volume estimates</li> </ul> <ul style="list-style-type: none"> <li>• Small scale</li> <li>• Specialized high-tech equipment</li> <li>• Expensive per cubic metre</li> <li>• High degree of dredging accuracy required</li> <li>• Small tolerances (5 to 10 cm)</li> <li>• Expert monitoring</li> <li>• Quality control</li> </ul>

Adapted from Van Oostrum, 1992

**Table 6.6 Cost elements considered for Superfund (U.S.) treatability studies**

Item no.	Description
1	Site preparation
2	Permitting and regulatory requirements
3	Capital equipment
4	Startup
5	Labour
6	Consumables & supplies
7	Utilities
8	Effluent treatment and disposal
9	Residuals/waste shipping and handling
10	Analytical services
11	Maintenance & modifications
12	Demobilization

Adapted from USEPA, 1989a

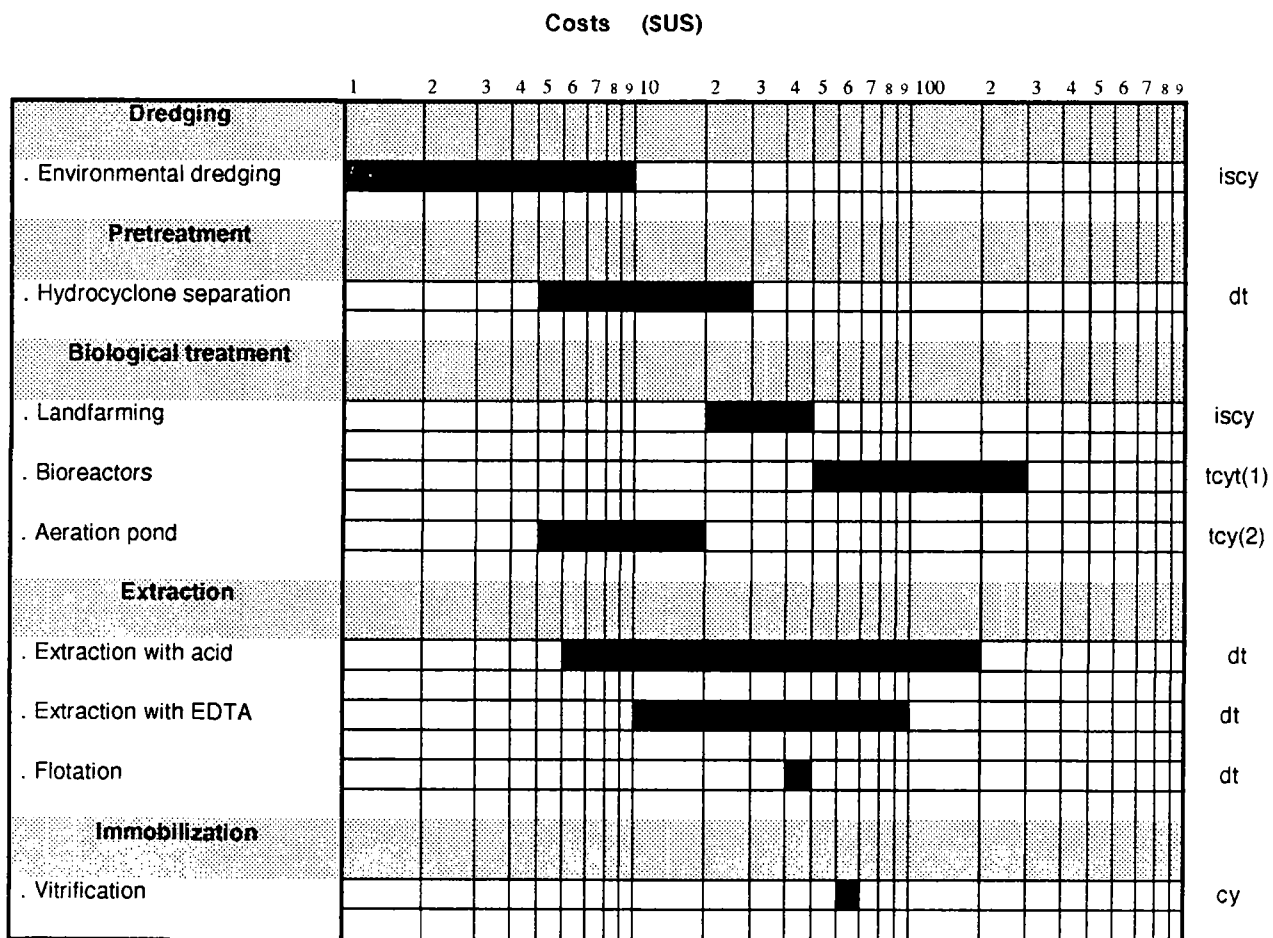
project (dredging, transportation, pretreatment, sediment treatment, effluent treatment and residue disposal).

The Dutch government has nevertheless had substantial experience treating contaminated sediment since 1986, and despite the reservations outlined above treatment costs can be estimated. Figure 6.2 compares cost of components of sediment treatment projects. As the figure shows, costs can range from US\$5 to US\$300 per cubic yard or US\$6 to US\$200 per dry ton depending on type of treatment selected (biological, extraction or immobilization).

If costs are compared using volume of in situ sediment treated, treatment costs (biological, extraction and immobilization) range from US\$30 to US\$120 per cubic metre. Costs for dredging and hydrocyclone separation before treatment range respectively from US\$2 to US\$15 and from US\$2 to US\$120 per cubic metre of in situ sediment (Van Dillen and Bruggeman, 1992).

Figure 6.3 shows anticipated costs (in US\$ per cubic yard) of each type of treatment discussed in the guide based on cost estimates of projects under consideration in the U.S. and Canada. The figure also shows cost range of dredging, transport, pretreatment and effluent treatment activities. As the figure indicates, costs of components of a sediment treatment project can vary considerably depending on volume of sediment to be treated and technology selected.

The values in these figures serve as indicators only and are to be interpreted with a great deal of caution since most are based on projects that have not been carried out. In addition, costs can be expected to decrease substantially with further development of treatment technologies and experience with real sediment remediation projects.



Notes :

cy : cubic yard

iscy : in situ cubic yard

tcy(1) : treated cubic yard (50% dry material)

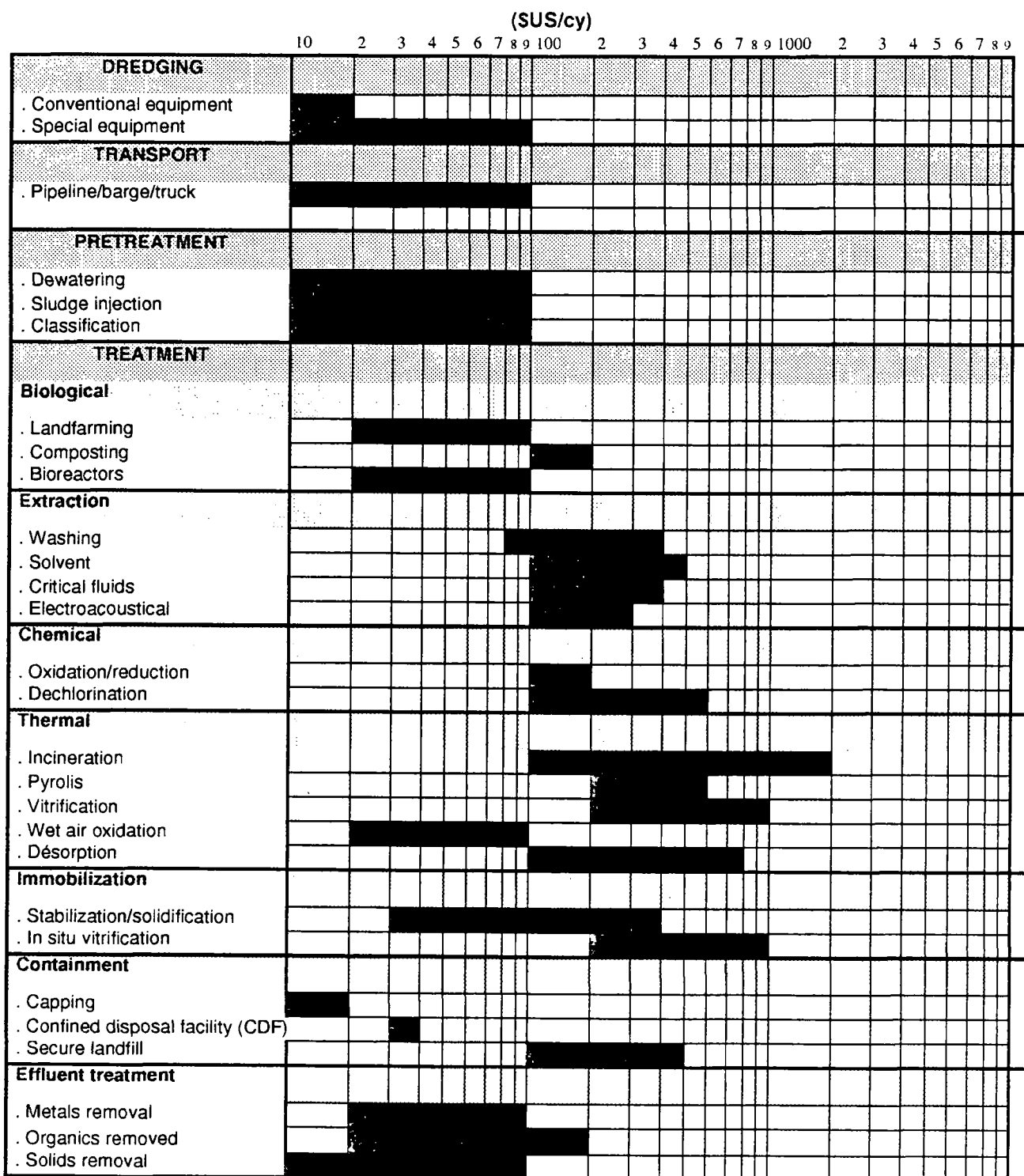
tcy(2) : treated cubic yard (10% dry material)

dt : dry tonne

Source : Adapted from Van Dilen & Bruggeman, 1992

**Figure 6.2 Cost comparison of sediment treatment project components based on Dutch experience**





**Figure 6.3 Cost comparison of sediment treatment project components based on U.S. and Canadian experience**

## 7. CONCLUSIONS AND RECOMMENDATIONS

The Technology Development Branch of the St. Lawrence Centre has published this *Screening Guide for Contaminated Sediment Treatment Technologies* to assist promoters of sediment dredging and remediation projects by describing the latest developments in contaminated sediment treatment technologies and scenarios. The guide is also meant to encourage development of innovative technologies for contaminated sediment remediation, and to this end, among others, includes descriptions of strengths and limitations of technologies demonstrated or under demonstration to pretreat or treat sediment and to treat effluent from sediment treatment or disposal operations.

Though the goal was an exhaustive review of the latest technological developments, process improvements may turn technologies that now seem unpromising for treatment of contaminated sediment into attractive options; or demonstration projects, treatability studies or experience with real sediment treatment projects may show certain apparently promising technologies to be less suitable than expected.

Accordingly, before selecting a scenario or a technology for a given site, site conditions must be compared with those where the scenario or technology was demonstrated; factors to be considered include nature and scope of contamination, type of sediment and environmental and socioeconomic conditions.

Despite these reservations, this guide to sediment treatment technologies and scenarios prompts the conclusions and recommendations outlined below.

### 7.1 Management of dredged material

As in most industrialized countries, the management of dredged material and the contaminated sediment at the bottoms of our waterways pose ever increasing technological, economic and environmental challenges for developers, contractors and governments.

To make matters worse, sediment--uncontaminated as well as contaminated--must regularly be dredged to keep shipping channels safe and ensure the prosperity of Canadian industrial and commercial enterprises that depend on harbour infrastructures for supplies and for delivery of their products.

However, the highly contaminated sediment in our waterways and the lack of environmentally sound dredges and of centres authorized to treat or dispose of sediment has complicated maintenance dredging and harbour facility expansion activities. In addition, project proponents and dredging companies are often unprepared to deal with these problems.

In the past, the only considerations when designing, assessing and carrying out projects were economic and technical. Nowadays, projects are subject to increasingly more stringent and constantly changing environment protection regulations. In addition, developers and bidders must now consider environmental and social aspects of a project to obtain authorization certificates and sometimes have to face public consultation procedures that call their entire plans into question.

### **Recommendations**

1. Governments should continue efforts to make available to dredging project proponents regional centres or sites authorized to treat or dispose of contaminated sediment as well as sediment deemed uncontaminated.
2. Governments should continue to educate all concerned by updating or publishing laymen's guides to sound environmental practice for sediment sampling and analysis, and for dredging, treatment, disposal or beneficial use of dredged material.
3. Contaminated sediment dredging and remediation projects should systematically be subject to environmental control and monitoring so real project impacts can be measured and project design and execution can be constantly improved not only to minimize negative environmental impacts but also to environmentally enhance project sites with wildlife and sociorecreational facilities.

## **7.2 Management of contaminated sediment**

The presence of contaminated sediment is a source of concern for the public as well as for government departments responsible for industrial and economic development and government departments responsible for protecting the environment and land resources. Whereas the former departments are concerned about checks on development of productive activities, the latter must assess socioeconomic and environmental impacts of action as well as no action and must be sure their decisions are sound in the long term given site uses and resources, and presence or absence of point or nonpoint sources of pollution.

### **Recommendation**

1. Given the environmental and socioeconomic issues at stake, every situation must be studied thoroughly on a case-by-case basis before a decision is made to treat contaminated sediment. The study must include consideration of the following factors: presence of active sources of pollution, nature and scope of contamination, risks of contaminant resuspension or return to solution as a result of natural (spring and fall flooding, storms and violent winds) or anthropogenic (dredging, commercial shipping and recreational navigation) phenomena, and presence of sensitive resources or uses at or close to the site to be restored.

## **7.3 Treatment technologies**

As this guide clearly indicates, although research and development efforts date back only a few years, remarkable progress has already been made in technologies for pretreatment, treatment and safe disposal of contaminated sediment.

**Pretreatment.** Of the twenty-six pretreatment technologies considered by the USEPA and the USACE for Great Lakes sediment remediation projects, some have been used in dredging projects for a number of years to dewater sediment by promoting settling of suspended solids: settling ponds, CDFs and slurry injection of chemicals or nutrients (to accelerate settling and enhance biodegradation of organics in settling ponds or CDFs).

Some innovative technologies (hydrocyclone separation, centrifugation) have been the subject of European sediment treatment research and development projects for a number of years. These projects have demonstrated the technologies are effective in dewatering sediment prior to treatment and in separating contaminated sediment fractions (fines) from coarse fractions (sand), which are generally uncontaminated. These technologies considerably reduce volume of sediment to be treated; this means treatment costs are lower and sediment is easier to handle at all process stages. These technologies are currently under demonstration in the United States and Canada.

**Sediment treatment.** Twenty-three of the seventy-nine sediment treatment technologies (biological, physical and chemical extraction, chemical, thermal and immobilization) considered in the early 1990s to cleanup sediment in the Great Lakes were recommended by the USACE and the USEPA. Some of these technologies are under demonstration in the U.S. (Assessment and Remediation of Contaminated Sediment (ARCS) program) and in Canada (Great Lakes Action Plan (GLAP) because they are expected to perform well technically, economically and environmentally.

The treatment technology data banks developed by the Burlington Wastewater Treatment Centre (SEDTEC, discussed in this guide) and by the USEPA (VISITT) list more than one hundred technology developers that claim to be able to treat contaminated sediment. As this guide shows, however, few technologies have actually been validated by bench-, pilot-, or full-scale demonstration projects in North America.

The guide also indicates however that demonstration projects under way in Europe, the United States and Canada have already identified efficient biological, physical and chemical,

and thermal technologies for treating contaminated sediment; these technologies are available in Canada for sediment treatment demonstration projects.

According to the Dutch government, although physical and chemical extraction, and biological technologies tested proved effective in removing or destroying sediment contaminants, it will take another two to ten years of research to develop efficient and competitive technologies.

In the meantime, many sediment treatment projects use common containment technologies for sediment disposal: capping with clean material, contained aquatic disposal, partially submerged contained aquatic disposal facilities enhanced for wildlife, shoreline containment (harbour expansion and upgrading projects), upland confined disposal facilities (CDFs) built specially for contaminated sediment, or hazardous or special landfills.

**Effluent and leachate treatment.** Liquid effluents from handling, pretreatment and treatment of contaminated sediment as well as CDF runoff or leachate contaminated by heavy metals and organics can be treated by a wide variety of technologies proven successful in decontaminating industrial and municipal wastewater.

Of the forty-two technologies considered by the USEPA and the USACE for effluent and leachate treatment, the eighteen most suitable for removing metals, organics and suspended solids from sediment were selected for Great Lakes sediment remediation demonstration projects.

Thanks to financial participation in demonstration projects of governments and technology developers and vendors, new and promising technologies are emerging all over the world. These developments, which will probably increase in coming years, should bring constant improvements in technologies, making them more effective, versatile and economical.

### **Recommendations**

1. Given the rapid development of treatment technologies, governments must continue to publish and update documents on treatment technologies to help project proponents select effective technologies suitable for the projects for which they are responsible.
2. Because the nature of the sediment and contaminants to be treated is site-specific, treatability studies using typical sediment from the site to be treated must remain a requirement to demonstrate effectiveness of technologies selected, identify amount and quality of process byproducts and provide a more accurate estimate of treatment costs.

#### **7.4 Potential environmental and health impacts of treatment technologies**

Chapter six of this guide uses fifteen evaluation criteria to describe potential environmental and human health impacts of twenty treatment technologies. The technology comparison is based on a study conducted in Ontario (Kendall et al., 1991). As the chapter shows, technology suitability depends largely on site-specific conditions: nature of contamination and matrices to be treated, hydrologic conditions, proximity to residential areas, availability of time and resources and proposed land use. Some technologies will be appropriate under one set of conditions but not under another.

The technology comparison also shows "best" and "worst" technologies cannot be identified simply by adding up performance ratings for each criteria. Instead, choices must be based on in-depth comparative risk assessment involving detailed characterization of the site to be restored.

The choice of in situ versus on-site or off-site technologies will also be dictated by specific site and contaminant characteristics. Though in situ methods which do not require

excavation of matrixes to be treated are generally preferable as far as environmental and human health impacts are concerned, contaminant destruction and removal efficiencies of these technologies are low, treatment effectiveness is hard to control and evaluate, and treatment time is relatively long. In addition, with some technologies, untreated contaminants may with time desorb, migrate off site and become bioavailable (Kendall et al., 1991).

### **Recommendations**

1. To adequately assess potential environmental and health impacts of treatment technologies, treatability tests or demonstration projects under real conditions using pilot units on typical matrices from the site to be treated are recommended. In addition, intensive environmental monitoring and control should be required at all stages of treatment (excavation, pretreatment, treatment and effluent and emissions treatment) and of disposal of byproducts and process residues to provide a more accurate assessment of treatment efficiency and real environmental and human health impacts.
2. Studies to quantify environmental and human health risks of the presence of contaminated sediment at the bottoms of waterways should be undertaken simultaneously.
3. Development of innovative and promising technologies should continue to be financially supported and given technical and administrative assistance by all levels of government.
4. A concerted effort by governments, legislators, researchers, vendors and development project proponents is essential to development of innovative and promising technologies.
5. Governments should continue to publish guides and procedures to ensure effective monitoring of remediation work and treatment technologies and to minimize impacts on the environment and on the health of workers and community members.



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**APPENDIX A**

**TECHNOLOGY DEVELOPMENT FUNDING PROGRAMS**

## Technology development funding programs

NAME OF PROGRAM	ABBREVIATION	PROGRAM ADMINISTRATOR(S)	ELIGIBLE PROJECTS	WHO CAN APPLY	PROGRAM ENDS (SIZE OF FUND)	HOW TO APPLY	CONTACTS
Technology Development Program	TDP	SLC	<p>Projects dealing with treatment technologies for •</p> <p>Se di me nt</p> <ul style="list-style-type: none"> <li>• Soil</li> <li>• Hazardous waste</li> <li>• Industrial waste</li> </ul>	<ul style="list-style-type: none"> <li>• Industries</li> <li>• Private firms</li> <li>• Municipalities</li> <li>• Research centres</li> <li>• Universities</li> </ul>	31/3/98	Unsolicited proposals	EC, SLC, Yvan Valiquette Montreal (514) 283-3557 EC, SLC, René Rochon Montreal (514) 283-0676 EC, SLC, Gérard Girouard Montreal (514) 283-6536
Environmental Innovation Program	EIP	SSC	<p>Projects which support the following objectives</p> <ul style="list-style-type: none"> <li>• Clean air, water and land</li> <li>• Sustainable use of renewable resources</li> <li>• Protection of special species and spaces</li> <li>• Preservation of the integrity of Northern Canada</li> <li>• Environmentally responsible decision-making</li> <li>• Minimization of impacts of environmental emergencies</li> </ul>	<ul style="list-style-type: none"> <li>• Industries</li> <li>• Universities</li> <li>• Native groups</li> <li>• Nongovernment organizations</li> <li>• Individuals</li> </ul>	Not specified	Unsolicited proposal to SSC	SSC, Gérard Straus Hull (819) 956-1770 Joseph Caramango Montreal (514) 283-2137
Environmental Technology Commercialization Program (Technology for Environmental Solutions Initiative, Green Plan)	ETCP	ISTC EC NRCC(IRAP)	<ul style="list-style-type: none"> <li>• Projects that involve a leading-edge area of environmental technology</li> <li>• Pilot or technology demonstration projects or preliminary studies for such projects</li> </ul>	<ul style="list-style-type: none"> <li>• For-profit corporations and partnerships with head offices in Canada</li> <li>• Associations (businesses, universities or research centres)</li> </ul>	31/3/97	Preliminary and official applications	ISTC, Emile Beauchamps Montreal (514) 973-5000 EC, SLC, Yvan Valiquette Montreal (514) 283-3557 NRCC, IRAP office Montreal (514) 283-8231
Program for Development and Demonstration of Site Remediation Technology	DESRT	EC MENVIQ	<p>Projects dealing with new technologies for handling soil and/or sediment</p> <ul style="list-style-type: none"> <li>• Soil characterization</li> <li>• Assessment</li> <li>• Cleanup</li> <li>• Conformity control</li> </ul>	<ul style="list-style-type: none"> <li>• Private firms</li> <li>• Universities</li> <li>• Municipalities</li> <li>• Industries</li> </ul>	31/3/95 \$50 million Canada \$12.5 million Quebec	Unsolicited proposal or bid	EC, DESRT, David Hutchison Hull (819) 953-5228 EC, SLC, Gérard Girouard Montreal (514) 283-9274 MENVIQ, Michel Goulet Quebec City (418) 643-8161

## LEGEND

SLC	St. Lawrence Centre
SSC	Supply and Services Canada
EC	Environment Canada
ISTC	Industry, Science and Technology Canada
NRCC	National Research Council of Canada
IRAP	Industrial Research Assistance Program
MENVIQ	Quebec Department of the Environment (ministère de l'Environnement du Québec)

## Technology development funding programs (continued)

NAME OF PROGRAM	ABBREVIATION	PROGRAM ADMINISTRATOR	ELIGIBLE PROJECTS	WHO CAN APPLY	PROGRAM ENDS	HOW TO APPLY	CONTACTS
Environmental Research and Technological Development Fund	ERTDF	MENVIQ	Projects dealing with the following: <ul style="list-style-type: none"> <li>• Waste and residue management (reduction, recycling, recycle, reuse, enhancement and safe disposal)</li> <li>• Cleanup and restoration (water, air and soil)</li> <li>• Sustainable development</li> </ul>	<ul style="list-style-type: none"> <li>• Research centres</li> <li>• Private firms</li> <li>• Community groups</li> </ul>	31/3/94	<ul style="list-style-type: none"> <li>• Unsolicited proposal</li> </ul>	MENVIQ, Yvon Gosselin Montreal (514) 643-9262 MENVIQ, Michel Goulet Quebec City (418) 643-8161

LEGEND

SLC	St. Lawrence Centre
SSC	Supply and Services Canada
EC	Environment Canada
ISTC	Industry, Science and Technology Canada
NRCC	National Research Council of Canada
IRAP	Industrial Research Assistance Program
MENVIQ	Quebec Department of the Environment (ministère de l'Environnement du Québec)

**APPENDIX B**

**CONSTITUENTS OF USEPA CONTAMINANT GROUPS**

## CONSTITUENTS OF USEPA CONTAMINANT GROUPS

## HALOGENATED VOLATILES

Bromodichloromethane  
 Bromoform  
 Bromomethane  
 Carbon tetrachloride  
 Chlorodibromomethane  
 Chlorobenzene  
 Chloroethane  
 Chloroform  
 Chloromethane  
 Chloropropane  
 Dibromomethane  
 Cis, 1,3-dichloropropene  
 1,1-Dichloroethane  
 1,2-Dichloroethane  
 1,1-Dichloroethene  
 1,2-Dichloroethene  
 1,2-Dichloropropane  
 Fluorotrichloromethane  
 Methylene chloride  
 1,1,2,2-tetrachloroethane  
 Tetrachloroethene  
 1,1,1-Trichloroethane  
 1,1,2-Trichloroethane  
 1,2-Trans-dichloroethene  
 Trans-1,3-dichloropropene  
 1,1,2-trichloro-1,2,2-trifluoroethane  
 Trichloroethene  
 Vinyl Chloride  
 Total chlorinated hydrocarbons  
 Hexachloroethane  
 Dichloromethane

## HALOGENATED SEMIVOLATILES

2-chlorophenol  
 2,4-dichlorophenol  
 Hexachlorocyclopentadiene  
 p-chloro-m-cresol  
 Pentachlorophenol  
 Tetrachlorophenol  
 2,4,5-trichlorophenol  
 2,4,6-trichlorophenol  
 Bis-(2-chloroethoxy)methane  
 Bis(2-chloroethyl) ether  
 Bis(2-chloroisopropyl) ether  
 4-bromophenyl phenyl ether  
 4-chloroaniline  
 2-chloronaphthalene  
 4-chlorophenyl phenylether  
 1,2-dichlorobenzene  
 1,3-dichlorobenzene  
 1,4-dichlorobenzene  
 3,3-dichlorobenzidine  
 Hexachlorbenzene  
 Hexachlorobutadiene  
 1,2,4-trichlorobenzene  
 Bis(2-chloroethoxy)phthalate

Bis(2-chloroethoxy) ether  
 1,2-bis(2-chloroethoxy)ethane

## NONHALOGENATED VOLATILES

Acetone  
 Acrolein  
 Acrylonitrile  
 Benzene  
 2-Butanone  
 Carbon disulphide  
 Cyclohexanone  
 Ethyl acetate  
 Ethyl ether  
 Ethyl benzene  
 2-hexanone  
 Isobutanol  
 Methanol  
 Methyl isobutyl ketone  
 4-methyl-2-pentanone  
 n-butyl alcohol  
 Styrene  
 Toluene  
 Trimethyl benzene  
 Vinyl acetate  
 Xylenes

## NONHALOGENATED SEMIVOLATILES

Benzoic acid  
 Cresols  
 2,4-dimethylphenol  
 2,4-dinitrophenol  
 2-methylphenol  
 4-methylphenol  
 2-nitrophenol  
 4-nitrophenol  
 Phenol  
 Acenaphthene  
 Acenaphthylene  
 Anthracene  
 Benzdine  
 Benzo(a)anthracene  
 Benzo(b)fluoranthene  
 Benzo(k)fluoranthene  
 Benzo(a)pyrene  
 Benzo(ghi)perylene  
 Benzyl alcohol  
 Bis(2-ethylexyl)phthalate  
 Butyl benzyl phthalate  
 Chrysene  
 Dibenzo(a,h)anthracene  
 Dibenzofuran  
 Diethyl phthalate  
 Dimethyl phthalate  
 Di-n-butyl phthalate  
 4,6-dinitro-2-methylphenol  
 2,4-dinitrotoluene  
 2,6-dinitrotoluene

**NONHALOGENATED  
SEMIVOLATILES (continued)**

Di-n-octyl phthalate  
1,2-diphenylhydrazine  
Fluoranthene  
Fluorene  
Indeno(1,2,3-cd)pyrene  
Isophorone  
2-methylnaphthalene  
Naphthalene  
2-nitroaniline  
3-nitroaniline  
4-nitroaniline  
Nitrobenzene  
n-nitrosodimethylamine  
n-nitrosodi-n-propylamine  
n-nitrosodiphenylamine  
Phenanthrene  
Pyrene  
Pyridine  
2-methylnaphthalene  
Bis phthalate  
Phenyl naphthalene

**PESTICIDES**

Aldrin  
Bhc-alpha  
Bhc-beta  
Bhc-delta  
Bhc-gamma  
Chlordane  
4,4'-DDD  
4,4'-DDE  
4,4'-DDT  
Dieldrin  
Endosulfan I  
Endosulfan II  
Endosulfan sulphate  
Endrin  
Endrin aldehyde  
Ethion  
Ethyl parathion  
Heptachlor  
Heptachlor epoxide  
Malathion  
Methylparathion  
Parathion  
Toxaphene

**VOLATILE METALS**

Arsenic  
Bismuth  
Lead  
Mercury  
Tin  
Selenium

**OTHER CATEGORIES**

Asbestos

**INORGANIC CORROSIVES**

Hydrochloric acid  
Nitric acid  
Hydrofluoric acid  
Sulphuric acid  
Sodium hydroxide  
Calcium hydroxide  
Calcium carbonate  
Potassium carbonate

**PCBs**

PCB (Aroclor)-1016  
PCB (Aroclor)-1221  
PCB (Aroclor)-1232  
PCB (Aroclor)-1242  
PCB (Aroclor)-1248  
PCB (Aroclor)-1254  
PCB (Aroclor)-1260  
PCB NOS (not otherwise specified)

**ORGANIC CORROSIVES**

Acetic acid  
Acetyl chloride  
Aniline  
Aromatic Sulphonic acids  
Cresylic acid  
Formic acid

**NONMETAL TOXIC ELEMENTS**

Fluorine  
Bismuth

**NONVOLATILE METALS**

Aluminum  
Antimony  
Barium  
Beryllium  
Bismuth  
Cadmium  
Calcium  
Chromium  
Copper  
Cobalt  
Iron  
Magnesium  
Manganese  
Nickel  
Potassium  
Selenium  
Sodium  
Vanadium  
Zinc

**RADIOACTIVES**

Radioactive isotopes of iodine, barium, uranium  
Radium  
Gamma radioactivity  
Alpha radioactivity  
Beta radioactivity

**ORGANIC CYANIDES**

Organonitriles

**INORGANIC CYANIDES**

Cyanide  
Metallic cyanides (e.g., ferricyanide, sodium cyanide)

**OXIDIZERS**

Chlorates  
Chromates

**REDUCERS**

Sulphides  
Phosphides  
Hydrazine

**APPENDIX C**

**ADDRESSES OF VENDORS AND DEVELOPERS OF  
SOIL AND SEDIMENT TREATMENT TECHNOLOGIES**

**ADDRESSES OF VENDORS AND DEVELOPERS OF  
SOIL AND SEDIMENT TREATMENT TECHNOLOGIES**

(Sources: Intera Kenting, 1990, USEPA, 1990b; USEPA, 1991c;  
USEPA, 1991h; Wastewater Technology Centre, 1992a)

**PRETREATMENT**

S.A. Extract  
Head Office  
Zi de la Gare BP 62  
44980 Sainte-Luce-sur-Loire  
France

Cintec Environnement Inc.  
2401 Lapierre  
Lasalle, Quebec  
Canada H8N 1B7  
P. Guérin (514) 364-6860

J.Y. Barbier  
Tel. 40 25 66 00

Derrick Environmental Services Corp.  
590 Duke Road  
Buffalo, New York  
USA 14225

S. Valine  
Tel. (716) 683-9010

Silt N.V.  
Tijdokstraat, 28  
Zeebrugge  
Belgium B-8380

K. van Craenenbroeck  
Tel. 32 50 546144

**BIOLOGICAL**

Netherlands Organization for Applied  
Scientific Research (TNO)  
TNO/MT  
Postbus 342  
3800 AH, Apeldoorn  
The Netherlands

G.J. Annokke  
Tel. 080-601212

Encore Environmental  
344 West Henderson Road  
Columbus, Ohio  
USA 43214

Tel. (416) 279-2222



Development Programme Treatment Processes for  
Polluted Aquatic Sediments (DTPP)

P.O. Box 17, Maerlane 16

8200 AA Leleystack

The Netherlands

Tel. 31 3200 70456/70533

Dearborn Environmental Consulting Group

3451 Erindale Station Road

P.O. Box 3060, Station A

Mississauga, Ontario

Canada L5A 3T5

Alan Seech

Tel. (416) 279-2222

HAECON N.V.

Deinsesteenweg 110

Ghent, Drogen

Belgium B-9031

B. Malherbe

Tel. 32 91 265094

Institute of Gas Technology

3424 South State Street

Chicago, Illinois

USA 60616

V.J. Srivastava

Tel. (312) 567-5282

SNC-Lavalin

2 Place Félix-Martin

Montreal, Quebec

Canada H2Z 1Z3

F. Dionne

Tel. (514) 866-1000

Ecova Corporation

3820 159th Avenue NE

Redmond, Washington

USA 98052

Arnon Sugar

Tel. (206) 883-1900

Roy F. Weston

Weston May

West Chester, Pennsylvania

USA 19380

R.T. Williams

Tel. (215) 363-0774

TNO/MT

Postbus 342

3800 Ah Appeldoorn

The Netherlands

G.J. Annokke

Tel. 055-493940

Remediation Technologies, Inc.  
Damonhill Square  
9 Pond Lane  
Concord, Massachusetts  
USA 01742

H.K. Schmidt  
Tel (508) 371-1422

## EXTRACTION

CF Systems Corporation  
3D Gill Street  
Woburn, Massachusetts  
USA 01801

Chris Shallice  
Tel. (617) 937-0800

Dehydro-Tech Corporation  
6 Great Meadow Lane  
East Hanover, New Jersey  
USA 07936

T.C. Holcombe  
Tel. (201) 887-2182

Resources Conservation Corporation  
3630 Cornus Lane  
Ellicott City, Maryland  
USA 21043

Lanny Weimer  
Tel. (301) 596-6066

Art International Inc.  
273 Franklin Road  
Randolph, New Jersey  
USA 07869

W. Steiner  
Tel. (201) 361-8840

Public Works and Water Management of the  
Netherlands  
Rijkswaterstaat  
Central Dredging Division  
P.O. Box 2280  
2280 HV Rijswijk  
The Netherlands

Bergman USA Inc.  
72-11 West Stratford Road  
Stratford Springs, Connecticut  
USA 06076-0535

R.P. Traver  
Tel. (203) 684-6844

Altech Consulting Ltd.  
225 Sheppard Avenue West  
Willowdale, Ontario  
Canada M2N 1N2

A.R. Keen  
Tel. (416) 226-0148

Toronto Harbours Commission  
60 Harbour Street  
Toronto, Ontario  
Canada M5J 1B7

Dennis Lang  
Tel. (416) 863-4830

Beak Consulting Ltd.  
42 Arrow Road  
Guelph, Ontario  
Canada M1K 1S6

D. Major  
Tel. (519) 763-2325

DeVoe Environmental Laboratories  
1130 Valdavia Way  
Palm Springs, California  
USA 92262

I. DeVoe  
Tel. (619) 778-6000

BioVersal USA Inc.  
10626 Beechnut Court  
Fairfax, Virginia  
USA 22039

C.L. Wilde  
Tel. (703) 250-3442

Recycling Sciences International Inc.  
30 South Wacker Drive, Suite 1420  
Chicago, Illinois  
USA 60606

A. Novelli  
Tel. (312) 559-0122

Ecotechniek BV  
Beneluxlaan 9  
P.O. Box 8447  
Utrecht, RK  
The Netherlands 3503

Tel. 31 30 957922

COGNIS Inc.  
2330 Circadian Way  
Santa Rosa, California  
USA 95407

J. Mielenz  
Tel. (707) 576-6223

Tallon Metal Technologies Inc.  
110 Leacock Road  
Pointe-Claire, Quebec  
Canada H9R 1H1

B. Holbein/D.Hall  
Tel. (514) 694-0080

## SOIL WASHING

Harmon Environmental Services Inc.  
1530 Alabama Street  
Auburn, Alabama  
USA 36830

William C. Webster  
Tel. (205) 821-9253

IT Corporation  
312 Directors Drive  
Knoxville, Tennessee  
USA 37923

R.D. Fox  
Tel. (615) 690-3211

Roy F. Weston Inc.  
P.O. Box 177  
Ohmsett Facility-Waterfront  
Highway 36  
Leonardo, New Jersey  
USA 07737

James Nash  
Tel. (201) 906-3464

## SOLVENT EXTRACTION

Sanexen International  
3027 Harvester Road, Unit 204  
Burlington, Ontario  
Canada L7N 3G2

Mark Cvar  
Tel. (416) 681-3366

BP Oil Company  
200 Public Square  
Cleveland, Ohio  
USA 44114-2375

John Laskowski  
Tel. (216) 586-3968

USEPA  
Risk Reduction Engineering Laboratory  
26 West Martin Luther King Drive  
Cincinnati, Ohio  
USA 45628

Ed Bates  
Tel. (513) 569-7774

Excalibur Enterprises Inc.  
13661 E. Marina Drive, #112  
Aurora, Colorado  
USA 80014

G. Downey  
Tel. (303) 752-4363

BioTrol Inc.  
210 Carnegie Centre, Suite 101  
Princeton, New Jersey  
USA 08540

P. Sheehan  
Tel. (609) 951-0314

Batelle Memorial Institute  
505 King Avenue  
Columbus, Ohio  
USA 43201

S. Chauhan  
Tel. (614) 424-4812

Soil Cleaning Company of America Inc.  
753 Peralta Avenue  
San Leandro, California  
USA 95477

V. Rothlisberger  
Tel. (415) 568-1234

Ecova Corporation  
3820 159th Avenue NE  
Redmond, Washington  
USA 98052

A. Bourquin  
Tel. (206) 883-1900

USEPA  
Risk Reduction Engineering Laboratory  
Woodridge Avenue  
Edison, New Jersey  
USA 08837-3679

R. Traver  
Tel. (201) 321-6677

Heijmans Milieutechniek BV  
Graafsebaan 13  
NL-5240 BB Rosmalen

Tel. 31 0 4192-89358

NBM Bodemsanering BV  
Zonweg 33  
P.O. Box 16032  
NL-2500 BA Den Haag

Tel. 31 0 70-3814331

Heidemij Restosoffendiensten BV  
Afdeling Milieutechniek  
Sluisweg  
P.O. Box 660  
NL-5140 AR Waalwijk

Tel. 31 0 4160-44080

## CHEMICAL

Eli EcoLogic International Inc.  
143 Dennis Street  
Rockwood, Ontario  
Canada N0B 2K0

J Nash/D. Hallet  
Tel. (519) 856-9591

Galson Remediation Corporation  
6627 Joy Road  
East Syracuse, New York  
USA 13057

Robert L. Peterson  
Tel. (315) 436-5160

USEPA 15-210  
Emergency Response Division  
401 M Street, SW  
Washington DC  
USA 20460

David Lopez  
Tel. (202) 382-2471

## THERMAL

### Rotary kiln incinerators

Weston Services Inc.  
Weston May  
West Chester, Pennsylvania  
USA 19380

John W. Noland  
Tel. (215) 430-3103

ENSCO Environmental Services Inc.  
First Tennessee Bank Building  
Franklin, Tennessee  
USA 37064

Tel. (615) 794-1351

IT Corporation  
321 Directors Drive  
Knoxville, Tennessee  
USA 37923

Tel. (615) 690-3211

Vesta Technology Corp.  
1670, West McNab Road  
Ft. Laderdale, Florida  
USA 33309

Tel. (305) 978-1300

### **Circulating bed incinerators**

Ogden Environmental Services Inc.  
10955 John Jay Hopkins Drive  
San Diego, California  
USA 92121

C.M. Hashiguschi  
Tel. (619) 455-3045

Superburn Systems Ltd.  
#201-2034 West 12th Avenue  
Vancouver, British Coloumbia  
Canada V6J 2G2

B. Putt  
Tel. (604) 732-7592

### **Infrared incineration**

OH Materials Canada Ltd.  
2180 Speers Road  
Oakville, Ontario  
Canada L6J 6L5

Tel. (416) 847-1700

ECOVA Corporation  
12790 Merit Drive  
Dallas, Texas  
USA 75251

Tel. (214) 404-7540

Westinghouse/Haztech  
5280 Panola Industrial Blvd.  
Decatur, Georgia  
USA 30035

Tel. (404) 981-9332

### **Oxygen-enriched incineration**

American Combustion Technologies  
4476 Park Drive, Suite 100  
??2985 Gateway Drive, Suite 100  
Norcross, Georgia  
USA 30079

G. Gitman  
Tel. (404) 564-4180

**Heat soaking furnace**

PPM Canada Ltd.  
1 Yonge Street, Suite 801  
Toronto, Ontario  
Canada M5E 1E5

Tel. (416) 364-1919

**Plasma arc incinerator**

Westinghouse  
P.O. Box 286  
Madison, Pennsylvania  
USA 15663

Tel. (412) 722-5714

Retech Inc.  
100 Henry Station Road  
Ukiah, California  
USA 95482

Tel. (707) 462-6522

Von Roll Inc.  
Environmental Engineering Division  
3080 Nothwoods Circle, Suite 200  
Norcross, Georgia  
USA 30071

Tel. (404) 729-0500

**Others**

SoilTech Inc.  
94 Inverness Terrace East, Suite 100  
Englewood, Colorado  
USA 80112

Tel. (303) 790-1410

Cintec Environment Inc.  
2401 Lapierre  
Lassalle, Quebec  
Canada H8N 1B7

Pierre Turcotte  
Tel. (514) 364-6860



US Army Toxic and Hazardous Materials  
Agency  
Aberdeen Proving Ground, Maryland  
USA 21010-5401

D. Averett  
Tel. (601) 634-3949

Chemical Waste Management Inc.  
3001 Butterfield Road  
Oak Brook, Illinois  
USA 60521

T. Birggs  
Tel. (708) 218-1500

Zimpro Passavant Environmental Systems  
310 West Military Road  
Rochschild, Washington  
USA 54474

W.M. Copa  
Tel. (715) 359-7211

Recycling Sciences International  
30 South Wacker Drive  
Chicago, Illinois  
USA 60606

W.C. Meenan  
Tel. (312) 559-0122

UMATAC Industrial Process  
210-2880 Glenmore Trail, SE  
Calgary, Alberta  
Canada T2C 2E7

R.M. Ritcey  
Tel. (403) 279-8080

Lurgi Canada Ltd.  
100 Adelaide Street West  
Toronto, Ontario  
Canada M5H 1S3

R.F. Day  
Tel. (416) 366-5611

ECOVA Corporation (Shirco)  
3820 159th Avenue, NE  
Redmond, Washington  
USA 98052

J. Cioffi  
Tel. (206) 883-1900

Remediation Technologies Inc.  
9 Pond Lane  
Concord, Massachusetts  
USA 01742

M. McCabe  
Tel. (508) 371-1422

**IMMOBILIZATION**

Pol-Con Systems Ltd.  
300-3665 Kingsway  
Vancouver, British Columbia  
Canada V5R 5W2

D. Jones  
Tel. (604) 436-3440

Emtech Environmental Services Inc.  
305 Arthur Street  
Forth Worth, Texas  
USA 76107

L. Cadona  
Tel. (817) 332-5481

Chemfix Technologies Inc.  
3858 North Causeway 2500  
Metaire, California  
USA 70002

W. Bua  
Tel. (504) 831-3600

Wastech Inc.  
114 Tulsa Road  
P.O. Box 4638  
Oak Ridge, Tennessee  
USA 37831

K. Peacock  
Tel. (615) 483-6515

Batelle Nothwest  
P.O. Box 999  
Richland, Washington  
USA 99352

W.F. Bonnes  
Tel. (509) 376-3340

Atomic Energy of Canada Limited Research  
Chalk River Laboratories  
Chalk River, Ontario  
Canada K0J 1J0

D.H. Charlesworth  
Tel. (613) 584-3311

Beak Consultants Ltd.  
14 Abacus Road  
Brampton, Ontario  
Canada L6T 5B7

D. Wilson  
Tel. (416) 794-2325

Dufferin Construction Company Inc.  
505 North Service Road East  
Oakville, Ontario  
Canada L6H 1A5

D. Ostrader  
Tel. (416) 842-2741

Siallon Technologies Inc.  
16755 Von Karman Ave.  
Irvine, California  
USA 92714-9998

T. McDowell  
Tel. (714) 833-3232

Trident Engineering Associates Inc.  
2010 Industrial Drive  
Annapolis, Maryland  
USA 21401

E.B. Marquard  
Tel. (410) 224-3550

Chemical Waste Management  
3001 Butterfield Road  
Oak Brook, Illinois  
USA 60521

R. Fitzpatrick  
Tel. (708) 218-1678

Geosafe Corporation  
2000 Logston Avenue  
Richland, Washington  
USA 99352

Tel. (509) 375-3268

International Solidification Inc.  
256 Bronte Road  
Oakville, Ontario  
Canada L6L 3C6

D. Krofchak  
Tel. (416) 825-0003

#### **Portland cement-based solidification/stabilization**

HAZCON Engineering Inc.  
P.O. Box 1247  
Brookshire, Texas  
USA 77423

R. Funderburk  
Tel. (800) 227-6534

Canadian Waste Management Corp.  
#205-2003 McKnight Blvd. NE  
Calgary, Alberta  
Canada T2E 6L2

W. Rama  
Tel. (403) 291-5082

Soliditech Inc.  
6901 Corporate Drive, Suite 215  
Houston, Texas  
USA 77036

C. Brassow  
Tel. (713) 778-1800

**Lime-based solidification/ stabilization**

Separation and Recovery Systems Inc.  
Irvine, California  
USA 92714

J. Franco  
Tel.

**Solidification/stabilization with silicates**

Silicate Technology Corporation  
Scottsdale Technology Centre  
7655 East Gilging Road, Suite B2  
Scottsdale, Arizona  
USA 85260

G. Maupin  
Tel. (602) 948-7100

Chemfix Technologies Inc.  
Suite 620, Metairie Centre  
2424 Edenborn Avenue  
Metairie, Louisiana  
USA 70001

P.N. Baldwin  
Tel. (504) 831-3600

Siallon Technologies Inc.  
P.O. Box 3324  
1659 Industrial Road  
Cambridge, Ontario  
Canada N3H 4T3

W. Moncrieff  
Tel. (519) 653-1442

**Miscellaneous  
solidification/stabilization**

CECOS International Inc.  
2321 Kenmore Avenue  
Buffalo, New York  
USA 14207

Wastech Inc.  
P.O. Box 4368  
114 Tulsa Road  
Oak Ridge, Tennessee  
USA 37830

E.B. Peacock  
Tel. (615) 483-6515

International Waste Technologies  
150 North Main Street, Suite 910  
Wichita, Kansas  
USA 67202

J.P. Newton  
Tel. (316) 269-2660

Stablex Canada Inc.  
760 Industrial Blvd.  
Blainville, Quebec  
Canada J7C 3U4

S. Demeule  
Tel. (514) 871-1176

SILT N.V.  
Tijdokstraat 28  
B-8380 Zeebrugge  
Belgium

H. De Vlieger  
Tel. 011-32-50-54-6144

Ecofix Canada Inc.  
394 Isabey, Suite 110  
Ville Saint-Laurent, Quebec  
Canada H4T 1V3

A. Bensoussan  
Tel. (514) 737-6541

OHM Remediation Services of Canada Ltd.  
2192 Wyecroft Road  
P.O. Box 7010  
Oakville, Ontario  
Canada L6J 6L5

D.Z. Maat  
Tel. (416) 847-1700

**APPENDIX D**  
**SOURCES OF ADDITIONAL INFORMATION**

## SOURCES OF ADDITIONAL INFORMATION

## Environnement Canada

General

Lynn Cleary

Tel. (514) 283-7000

Director

St. Lawrence Centre

105 McGill Street

Montreal, Quebec

H2Y 2E7

Technology development

Yvan Valiquette

Tel. (514) 283-3557

Technology Development Branch

Environmental Protection Direction

Environment Canada

685 Cathcart Street, 8th Floor

Montreal, Québec

H3B 1M6

Sediment remediation technologies

René Rochon

Tel. (514) 283-0676

Restoration Technologies

Technology Development Branch

Environmental Protection Direction

Environment Canada

685 Cathcart Street, 8th Floor

Montreal, Québec

H3B 1M6

Cleanup technologies

Gérald Girouard

Tel. (514) 283-6536

Pollution Abatement Technologies

Technology Development Branch

Environmental Protection Direction

Environment Canada

685 Cathcart Street, 8th Floor

Montreal, Québec

H3B 1M6

**Lakes Environment Office**General

Griff Sherbin  
Environment Canada  
25 St. Clair Avenue East  
Toronto, Ontario  
M4T 1M2

Tel. (416) 973-6467

Removal of contaminated sediment

Ian Orchard  
Conservation and Protection  
Environment Canada  
25 St. Clair Avenue East  
Toronto, Ontario  
M4T 1M2

Tel. (416) 973-1089

Treatment of contaminated sediment

Craig Wardlaw  
Wastewater Technology Centre  
P.O. Box 5068  
Burlington, Ontario  
L7R 4L7

Tel. (416) 336-4855

**Great Lakes National Program Office**

Paul Horvatin  
US Environmental Protection Agency  
Great Lakes National Program Office  
77 West Jackson Blvd.  
Chicago, Illinois 60604

Tel. (312) 353-3612

**US Army Corps of Engineers (USACE)**

Mark E. Zappi  
Environmental Engineer  
Environmental Engineering Division  
US Army Corps of Engineers  
Waterways Experiment Station  
3903 Halls Ferry Road  
Vicksburg, Mississippi 39180-6199

Tel. (601) 643-2586



**Superfund Innovative Technology Evaluation (SITE) Program**

General

John Martin  
SITE Program  
Risk Reduction Engineering Laboratory  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Technology profiles/demonstration project results/emerging program reports

ORD Publications Unit  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Tel. (703) 487-4650

Bioremediation technologies

R. Lewis  
Risk Reduction Engineering Laboratory  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Tel. (513) 569-7856

Soil washing technologies

R. Traver  
Releases Control Branch  
US Environmental Protection Agency  
2890 Woodbridge Avenue, Bldg. 10 (MS-104)  
Edison, New Jersey 08837

Tel. (201) 321-6677

Thermal desorption, solvent extraction, vacuum extraction and dechlorination technologies

M. Gruenfeld  
Releases Control Branch  
US Environmental Protection Agency  
2890 Woodbridge Ave., Bldg. 10 (MS-104)  
Edison, New Jersey 08837

Tel. (908) 321-6625

Incineration and pyrolysis technologies

D.A. Oberacker  
Risk Reduction Engineering Laboratory  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Tel. (513) 569-7510

In situ vitrification technologies

S. James  
Risk Reduction Engineering Laboratory  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Tel. (513) 569-7877

Stabilization/solidification technologies

T. Lyons  
Risk Reduction Engineering Laboratory  
US Environmental Protection Agency  
26 West Martin Luther King Drive  
Cincinnati, Ohio 45268

Tel. (513) 569-7589

**APPENDIX E**

**GLOSSARY**

## GLOSSARY

**Absorption.** Penetration of a substance into or through the bulk of a solid or liquid.

**Acid.** A hydrogenated chemical compound that in aqueous solution liberates positive hydrogen ions. An acid reacts with a base to give a salt and water (neutralization) and has a pH of less than 7.

**Acidification.** A change in an ecosystem's physicochemical components provoked by introducing acidic substances into the environment.

**Activated carbon.** A highly porous form of charcoal treated to obtain a very large surface area per unit volume. Widely used to adsorb (hence remove) gases, vapours, odours, toxic substances or dissolved organic matter. Commercial activated carbon comes in granular or powdered form.

**Activated sludge.** Sludge floc produced by extended aeration of wastewater. Because of the microorganisms it contains, activated sludge can break down organic matter into stable substances.

**Adsorption.** The adherence or concentration of substances to or at the surfaces of bodies with which they are in contact.

**Aerator.** A device or equipment for introducing air into water, wastewater or sewage sludge.

**Aerobic.** Describes microorganisms that can thrive only in the presence of atmospheric air or air naturally or artificially dissolved in water.

**Agitator.** Equipment that mixes and aerates liquids mechanically or by injection of air.

**Anaerobic.** Describes microorganisms that thrive or are not destroyed in the absence of air or free oxygen.

**Anion.** A negatively charged ion.

**Bacteria (s. bacterium).** Single-celled organisms that generally lack chlorophyll and multiply by cell division. Bacteria exist singly, in chains or in clusters.

**Base.** A compound that in aqueous solution liberates hydroxyl ions.

**Basket centrifuge.** A centrifugal device for dewatering that has a perforated containing surface.

**Bioaccumulation.** Increasing retention of a substance in the tissues of an organism throughout its life.

**Bioassay.** Method for testing biological effect of a substance in water by observing changes in a biological activity.

**Bioconcentration.** Retention of a substance in the tissue of an organism such that at some point in the life of the organism concentration level in its tissue exceeds that in the surrounding environment.

**Biochemical.** Describes a chemical change resulting from biological activity.

**Biochemical oxidation.** Oxidation that results from biological activity and involves chemical combination of oxygen and organic matter.

**Biochemical oxygen demand.** A test that measures quantity of oxygen consumed by microorganisms during biological oxidation of organic matter in water under specified physical, chemical and biological conditions. Dissolved oxygen content is one of the main indicators of degree of pollution of a waterway or lake.

**Biochemical process.** See biological process.

**Biodegradable.** Capable of being broken down by living organisms.

**Biological oxygen demand.** See biochemical oxygen demand.

**Biological process.** Process whereby vital activities of bacteria or other microorganisms in search of food break down complex organic compounds into simple, more stable substances.

**Biological treatment.** A treatment process that uses microorganisms to break down toxic contaminants in waste into less toxic compounds.

**Biosphere.** That part of the earth and the atmosphere surrounding it (upwards at least to a height of 10 000 m, and downwards to the depths of the ocean and a few hundred metres below the land surface) where living organisms are found.

**Bioturbation.** Agitation and disruption of sedimentary structures by activity of organisms churning up sediment or burrowing into it.

**BOD.** See biochemical oxygen demand.

**Bowl centrifuge.** A centrifugal device for dewatering in which the contained surface is not perforated.

**Carbon monoxide.** A colourless, almost odourless gas formed during incomplete combustion of carbonaceous compounds (car exhaust, for example). In living organisms, it combines with haemoglobin, making it no longer available to carry oxygen from lungs to tissue. This means carbon monoxide can cause a lack of oxygen (hypoxia). One important source of carbon monoxide is passive cigarette smoke.

**Carcinogen.** A substance that is a cancer-causing agent.

**Cation.** A positively charged ion.

**Centrifuge.** A rotating device for separating liquids of different densities or liquids from solids by centrifugal force.

**Characterization.** Precise identification of distinctive elements of a substance, an environment or a process.

**Chelation.** A chemical process involving formation of a heterocyclic ring compound which contains at least one metal cation or hydrogen ion in the ring.

**Chelating agent.** A liquid or resinous solid that renders ions (usually from metals) inactive by absorbing them through chelation. Chelating agents can be regenerated by placing them in contact with concentrated acids that solubilize the contaminants.

**Chemical treatment.** A treatment process that alters the chemical structure of a toxic waste contaminant to reduce the waste's toxicity, mobility, or volume.

**Chlorinated organics (organochlorines).** Synthetic, chlorine-containing organic compounds used for a variety of purposes: insecticides, pesticides (DDT, for example), fungicides, coolants and so forth. Organochlorines are generally toxic and persistent.

**Clarification.** Filtration, settling, decantation or any other process for rendering a liquid clear.

**Clarifier.** Basin or tank where clarification occurs.

**Classifier.** A device for separating materials into their constituents according to particle size (hydrocyclones, fluidized bed classifiers and air sand collectors) or particle density.

**Clay.** Highly cohesive soil composed of particles less than 0.002 mm in diameter.

**Clean technology.** One of the following: a technology that is a new, less polluting production process; a technology that recovers lost raw materials and recycles them back into the manufacturing process; a technology that uses waste as raw material for secondary production.

**Coagulation.** Aggregation of fine particles (colloids) suspended in a liquid.

**Combustion.** Thermal reaction in which an element combines with oxygen and volatile and combustible constituent elements (such as organic matter and water) evaporate.

**Composting.** Biological decomposition of organic matter to render it stable and suitable for agricultural uses.

**Containment.** Response action that involves construction of a barrier to prevent migration of contaminated waste.

**Contaminant.** Any foreign deleterious matter in water, air or other environmental media.

According to the Quebec *Environment Quality Act*, a contaminant is "solid, liquid or gaseous matter, a microorganism, a sound, a vibration, rays, heat, an odour, a radiation or a combination of any of them likely to alter the quality of the environment in any way."

**Criminal liability.** Subject to an obligation whose nonfulfillment entails penalty under the law. The purpose is to prevent behaviour contrary to the interests of society in situations explicitly identified by law. Violation must be proved beyond reasonable doubt.

**Decanter.** See settling tank or basin.

**Digester.** A tank where sludge is subjected to intensified bacterial action until it is decomposed or has been reduced to the point at which the solids are relatively nonputrescible and inoffensive.

**Digestion.** Use of bacteria to decompose sludge; entails gasification, liquefaction and partial mineralization.

**Dioxin.** A group of about 75 chemical byproducts that belong to the chlorodibenzo-paradioxin family. The dioxin generally considered most toxic is 2,3,7,8-tetrachlorodibenzo-paradioxin.

**Dissolved solids.** Dissolved material in natural water and wastewater.

**Dumping.** Indiscriminate disposal of solid waste.

**Ecology.** The study of relationships among living organisms and between living organisms and their nonliving environment.

**Ecosystem.** An ecological unit within the biosphere composed of living organisms (plants and animals, biocenosis) and nonliving resources (biotope). Ecosystems are dynamic functional biosphere systems within which living species are both producers and consumers in food chains.

**Ecotoxicity.** Capacity of a substance to have a toxic impact not only on living species but also on their organization, their interactions and their interaction with nonliving resources (biological imbalances). Ecotoxicity refers in particular to long-term toxic effects.

**Electrolyte.** A substance which dissociates into two or more ions when dissolved in water

**Elutriation.** The process of washing dispersed or suspended granular or sludgy material with water followed by decanting and supernatant removal. The process can be repeated until desired results are obtained.

**Environment.** The whole complex of natural (physical, chemical and biological) and cultural or social conditions that can affect living organisms and human activities.

According to the Quebec *Environment Quality Act*, the environment is "water, atmosphere and soil or a combination of any of them or, generally, the ambient milieu with which living species have dynamic relations."

**Enzyme.** Proteins which catalyze reactions with a high degree of specificity and efficiency.

**Epidemiology.** The study of factors influencing occurrence, distribution, development, prevention, and control of disease.

**Evaporation.** The process by which water passes from a liquid state in surface streams or soil to vapour.

**Extraction.** The removal of one or more components from a liquid mixture by use of a solvent (acid, base and so forth).

**Filter press.** A device for separating solids from liquids by forcing the liquid through a cloth or other filtering material.

**Fixation.** A general process whereby chemicals are added to a waste matrix to prevent target compounds such as heavy metals from leaching out of the matrix.

**Flammable.** Capable of being easily ignited and of burning with extreme rapidity. Now used technically in preference to inflammable.

**Flocculation.** Agglomeration of colloidal matter. Clusters thus formed are relatively easy to remove by decanting.

**Flotation.** A method of removing suspended solids in water or wastewater by causing them to float to the surface, generally by injection of air.

**Food chain.** A structured feeding hierarchy whereby energy in the form of food is passed from an organism in a lower trophic level to one in a higher level. Trophic levels from lowest to highest are as follows: primary producers (plants), primary consumers (herbivores or plant eaters), secondary consumers (carnivores or meat eaters), tertiary consumers (meat eaters) and decomposers.



**Furans.** Family of substances similar to dioxins in composition and toxicity.

**Grizzly.** A coarse screen used for rough sizing and separation of large particles (150 mm, for example).

**Groundwater.** All water found below ground surface. Groundwater constitutes most of our freshwater reserves.

**Half-life.** The amount of time required for concentration of a substance to decrease to half its original value in a lake, a body of water and so forth.

**Halogen.** Any of the elements of the halogen family--fluorine, chlorine, bromine, iodine and astatine.

**Halogenated organic.** A hydrocarbon molecule in which at least one hydrogen atom has been replaced by a halogen.

**Hazardous material.** Any substance that because of its properties (flammable, corrosive, toxic, radioactive and so forth) poses a hazard to the environment or to human health or safety and that requires special disposal or handling techniques to make it harmless or less dangerous.

**Heavy metal.** Any metal with a high atomic weight (chromium, nickel, cadmium, lead, silver, gold, mercury, bismuth, copper and so forth) that can be precipitated by sulphuric acid. Heavy metals are often toxic and tend to accumulate in the food chain.

**Hydrocarbon.** An organic compound containing only hydrogen and carbon. Crude oil consists, for the most part, of a complex mixture of hydrocarbons.

**Hydrocyclone.** A device that uses centrifugal action to extract fine particles suspended in water.

**Hydrophile.** A substance that has an affinity for water.

**Hydrophobe.** A substance that lacks an affinity for water and repels or fails to adsorb or absorb it.

**Hydrosphere.** All the water of the earth. The hydrosphere consists mainly of the oceans but includes lakes, rivers, glaciers and ice sheets and covers three quarters of the earth's surface.

**Immiscible.** Pertains to liquids that will not mix with each other.

**Incineration.** Destruction of organic domestic waste, process sludges, industrial waste and so forth by combustion.

**Industrial effluent.** All water discharged from an industrial process and the material it contains.

**Inflammable.** See flammable.

**Inorganic matter.** Matter of mineral origin.

**Inorganics.** Generic term for chemical compounds that generally cannot be destroyed by incineration and that do not contain carbon, except in a noncombustible form; in other words, matter other than plant or animal.

**In situ treatment.** The process of treating a contaminated matrix (soil, sludge, groundwater or sediment) in place without excavating it. In situ processes can be physical, chemical, thermal, or biological.

**Interstitial water.** See pore water.

**Ion.** An atom or molecule which by loss or gain of one or more electrons has acquired a net electric charge.

**Lagoon.** A basin or pond into which wastewater or sludge is introduced to facilitate its treatment.

**Leaching.** The process by which contaminants are dissolved and carried away when they come in contact with a liquid that acts as a solvent (often water). In a sanitary landfill, wastes are leached mainly by rainwater.

**Lime.** Calcium oxide, produced by heating crushed limestone (mostly composed of calcium carbonate), to a temperature of about 900°C.

**Microorganism.** A very small plant or animal organism that is invisible or barely visible without a microscope.

**Mineralization.** Decomposition of organic matter into mineral material.

**Mobility.** The ability of a contaminant affected by physical or chemical processes to migrate from its source.

**Mutagen.** Any substance or influence that modifies genetic characteristics by altering arrangement or amount of genetic material.

**Natural resources.** All natural products, ecosystems, abiotic elements and balances composing the earth, including the various forms of natural energy.

**Neutralization.** A chemical reaction between  $H^+$  and  $OH^-$  ions in which water is formed.

**Nitrogen oxides.** A family of contaminants frequently found in photochemically polluted air (Los Angeles smog, for example). Nitrogen dioxide is harmful to human lungs.

**Nonrenewable resource.** All natural resources available in limited quantities and liable to be used up completely at the current rate of consumption.

**Organic matter.** Matter of animal or plant origin, or to be more exact, compounds based on carbon chains or rings. Most carbon compounds are organic. Most organic matter is combustible and much of it is volatile.

**Organics.** Chemical compounds based on carbon chains or rings which are generally combustible and are derived from living organisms.

**Organochlorines.** See chlorinated organics.

**Organohalogens.** See halogenated organics.

**Orphan site.** Contaminated site whose owner is insolvent or unknown.

**Oxidation.** Chemical process which can lead to fixation of oxygen (combustion), loss of hydrogen ( $\text{H}_2\text{S}$  to  $\text{S}$ ) or increase in positive valence.

**Oxidation-reduction potential.** See redox potential.

**Ozone.**  $\text{O}_3$ , a triatomic gaseous form of oxygen that is a powerful oxidant and can be used as a bactericide or virucide.

**PAH.** Polycyclic aromatic hydrocarbon. A hydrocarbon molecule with two or more carbon rings.

**PCB.** Generic name for polychlorinated biphenyls, organic compounds containing two benzene nuclei with two or more substituent chlorine atoms.

**Pesticide.** A general term for synthetic chemical agents (organochlorines in particular) produced industrially and used for pest control: insecticides, algicides, fungicides, herbicides and so forth.

**pH.** A measure of the acidity or basicity of a solution or soil expressed as the negative logarithm of hydrogen ion ( $\text{H}^+$ ) concentration.

**Photosynthesis.** A complex physiological process whereby plants containing chlorophyll produce organic molecules from carbon dioxide and water in the presence of radiant energy.

**Physical treatment.** A treatment process that alters the physical structure of a toxic waste contaminant to reduce waste toxicity, mobility, or volume.

**Polar.** Describes a compound formed by transfer of electrons.

**Pollutant.** Any substance or body that contaminates an environment. A physical, chemical or biological agent that deleteriously alters natural balance.

According to the Quebec *Environment Quality Act* a pollutant is "a contaminant or a mixture of several contaminants present in the environment in a concentration or quantity greater than the permissible level determined by regulation of the Government, or whose presence in the environment is prohibited by the regulation of the Government."

**Pollution.** Contamination of a natural environment as a result of indirect or direct introduction of toxic substances by humans. The act of releasing undesirable substances into an environment. The deterioration of an environment as a result of introducing pollutants.

According to the Quebec *Environment Quality Act*, pollution is "the condition of the environment when a pollutant is present."

**Polychlorinated biphenyl.** See PCB.

**Polycyclic aromatic hydrocarbon.** See PAH.

**Polymer.** Complex chemical compounds consisting of identical repeated constituent units. Synthetic polymers are extensively used in plastics.

**Pore water.** A generic term for water contained in pore spaces between the grains of surface soil or sediment at the bottom of a waterway.

**Pozzolan.** Reddish or blackish, alveolar, slaggy rock of volcanic origin used as an aggregate to make light concretes or as a secondary constituent of cement.

**ppb.** Parts per billion (see ppm).

**ppm.** Parts per million. A measure of concentration that usually indicates the number of volume parts of a substance per million parts of air. The unit commonly used to represent degree of pollutant concentration where concentrations are small; larger concentrations are given in percentages.

**Precipitation.** Chemical reaction that causes dissolved matter to separate from its solvent and settle.

**Pretreatment.** First step in treating wastewater, sediment and so forth in preparation for more complex treatment.

**Pyrolysis.** Heating in the absence of oxygen causing break down of the heated material into less heavy liquid or gas fractions that can be used as fuel or as raw materials. Pyrolysis can be used in waste destruction to recover waste heat energy in the form of a gas.

**Quality assurance.** Duplication of all or a portion of analytical tests conducted to ensure desired levels of accuracy and precision are obtained.

**Quality control.** Duplication of a portion of chemical analyses performed (generally in an outside or independent laboratory) to estimate overall quality of results and determine what, if any, changes must be made to achieve or maintain required level of quality.

**Reactives.** Compounds that react spontaneously and violently with water or air.

**Recovery.** Separation of products or material from waste streams for reuse or recycling.

**Recycling.** Reintroduction of recovered material into the process initially used to produce it. Ground glass can be used to manufacture new glass, for example, used paper to manufacture new paper or scrap iron to manufacture steel.

**Reduction.** Application of more effective methods so less raw material is wasted, and implementation of measures that reduce waste (use of porcelain instead of paper or styrofoam cups, for example).

**Redox potential.** Index, analogous to pH, giving a quantitative measure of oxidation or reduction potential of soil or sediment under oxidizing or reducing conditions.

**Regeneration.** Treatment that restores original condition and primary qualities of a spent or used substance so it can be used again for the same purpose (oils and solvents can be regenerated, for example).

**Remediation technologies.** Technologies designed to treat process waste streams--air, water or solid streams. Unlike clean technologies, remediation technologies come at the very end of a process.

**Renewable resource.** Any natural resource considered inexhaustible because it is continuously renewed (solar energy, for example).

**Residual.** Any material remaining after a chemical or physical process or transformation. Byproduct of an industrial process that cannot be put to other uses (as energy, as fill, as raw material for some other industry and so forth).

**Residue.** See residual.

**Resuspension.** Remixing of sediment and contaminants with water as a result of storms, currents, organism activity or human activities such as dredging.

**Reuse.** Use of a material or product more than once. For example, a soft drink bottle is reused when it is returned to the bottling company to be refilled. Recovered material may also be

reused by introducing it into other production cycles: glass waste can be incorporated in road pavements for example or recycled paper and rubber can be used to make insulation slabs.

**rH.** See redox potential

**Salt.** A chemical compound composed of a positive ion other than  $H^+$  and a negative ion other than  $OH^-$ . Salts can be formed in a number of ways, among others, when an acid reacts with a base, a metal, an oxide or a salt.

**Sand.** Noncohesive soil composed of particles 0.06 to 2.00 millimetres in diameter.

**Sanitary landfill.** Site where solid waste is buried.

**Saturated zone.** A subsurface zone in which water fills the interstices and is under pressure greater than atmospheric pressure.

**Screen.** A mesh generally of wire designed to retain small particles.

**Sediment.** Layer of material from any source (rock, organic matter or volcanic matter) transported by water from the place of origin to the place of deposition. In watercourses, sediment is the alluvial material carried in suspension or as bed load.

**Settling.** Gravity separation of suspended solids from fluid so the solids can then be removed or the clarified liquid collected.

**Settling basin or tank.** Tank or basin in which water velocity is reduced to allow suspended solid to settle by gravity.

**Sieve.** A device that uses mesh to remove particles above a given size from a fluid flow.

**Silt.** Cohesive soil composed of particles 0.002 to 0.006 millimetres in diameter.

**Sludge.** Pumpable wastewater treatment residues with high moisture content accumulated on the bottoms of settling basins.

**Sludge dewatering.** Partial removal of water from sludge by drainage, evaporation, compression, centrifugation, vacuum suction, pressing, flotation in presence of acid or other methods that do or do not require heat. Dewatering turns sludge from a liquid to a semisolid that can be handled with a shovel.

**Solidification.** The process of converting soil, sludge, sediment or liquid waste into a solid monolithic product that is more easily handled and that reduces volatilization and leaching of contaminants from the waste or matrix treated.

**Solids.** All dissolved and undissolved, volatile and nonvolatile matter in water supply systems or wastewater.

**Sorption.** Physical or chemical adsorption or absorption.

**Special waste.** Waste that is not hazardous waste within the meaning of the *Hazardous waste regulation*, that derives from the tanning, petroleum refining, metallurgy, mineral chemistry, organic chemistry or surface treatment and coating industries, and that generates a leachate in which concentrations of phenol compounds, cadmium, chromium copper, nickel, zinc, lead, mercury, oil or grease are higher than standards prescribed by section 30 of the *Hazardous waste regulation*.

**Spill.** Any accidental or voluntary short-term release into the environment of material liable to disturb the environment.

**Stabilization.** The process of reducing hazardous potential of a waste by chemically or physically converting toxic contaminants into their least mobile or reactive form.

**Steam stripping.** Removal of contaminants by injecting steam into the contaminated matter. The contaminant-loaded steam is then removed and condensed.

**Stripping.** Removal of light and volatile fractions from a liquid.

**Sulphate.** A generic term for a salt whose anion is  $\text{SO}_4$ . Sulphates occur naturally or are produced by action of sulphuric acid.

**Surface active agent.** See surfactant.

**Surfactant.** A substance that acts like soap in reducing surface tension of water; surfactants are surface active agents that concentrate at air-water, oil-water and solid-liquid interfaces.

**Suspended matter.** See suspended solids.

**Suspended solids.** Solids that will settle or can be removed by filtering.

**Sustainable development.** Practices promoting resource development that meets the needs of this generation without damaging prospects for future generations to meet theirs.

**Synergism.** An interaction of elements such that their combined effect is greater than the sum of their individual effects.

**TER.** See teratogen.

**Teratogen.** A substance that produces deformation in the foetus in the womb.

**Thermal treatment.** A treatment process designed to oxidize hazardous organic substances to carbon dioxide and water.

**TOC.** See total organic carbon

**Total organic carbon (TOC).** A measure of the total quantity of carbon from organic matter only in a given sample. To obtain a TOC value, the sample is burned and carbon dioxide generated is measured.

**Toxic substance.** A substance liable to cause death, illness, behaviour anomalies, cancer, genetic mutation, physiological or reproductive abnormalities or physical deformities in an organism or its progenitors or which may become toxic after concentration in the food chain or when combined with other substances.

**Toxicity.** The capacity of a material to cause changes or disturbances in living organisms that have harmful effects, the most serious of which is death of the organism. Toxicity is a function of substance concentration and length of exposure. There are two types of toxicity--acute or short term and chronic or long term.

**Treatability test.** The testing of a remedial alternative in the laboratory or field to obtain data necessary for a detailed evaluation of its technical, economic and environmental feasibility.

**Treatment train.** A complete treatment process that includes pretreatment, primary treatment, residuals and sidestream treatments (air, liquid and solid streams) and posttreatment. Some treatment trains include technologies that can treat inorganic as well as organic contaminants.

**Trommel.** A revolving cylindrical screen with internal lifting blades designed to physically remove particles 5 to 6 millimetres in diameter.

**Turbidity.** Condition of a liquid due to fine, visible material in suspension, which impedes the passage of light through the liquid.

**Unsaturated zone.** See vadose zone.

**Vadose zone.** A subsurface zone containing water below atmospheric pressure and air or gases at atmospheric pressure. Also known as unsaturated zone.

**VOC.** See volatile organic compound.

**Volatile organic compound.** All carbon compounds (apart from carbon oxides, metal carbons, carbonates and cyanides) likely to be found in the atmosphere at ambient pressures and temperatures. Definitions of volatile organic compounds often refer to particular sampling and analysis techniques. (CUM, USEPA, for example).



**Waste.** Residues or discarded material from manufacturing processes and other normal community activities.

According to the Quebec *Environment Quality Act*, waste is "solid, liquid or gaseous residue from industrial, commercial or agricultural activities, rubbish, household garbage, used lubricant, demolition debris, pathological waste material, bodies of animals, motor vehicle wrecks, used tires, radioactive waste material, empty containers and waste material of any kind other than mining residues."

**Waste reclamation.** Any treatment that restores economic value to waste by making it useful as a source of energy or of recovered raw materials.

**Waste treatment.** Any process to which waste is subjected to make it less harmful to the environment, easier to handle or transport or suitable for subsequent use.

**Water table.** The surface of a body of unconfined groundwater at which pressure is equal to that of the atmosphere.

**Zeolite.** A group of natural hydrated aluminosilicates with an open three-dimensional crystal structure. In industry, zeolites are used as selective absorbants (solvent drying and gas treatment), as molecular sieves (hydrocarbon separation) and as catalysers (petroleum cracking).

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