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REVIEW OF REMOVAL, CONTAINMENT AND TREATMENT TECHNOLOGIES FOR REMEDIATION OF CONTAMINATED SEDIMENT IN THE GREAT LAKES

by

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The Water Quality Act of 1987, which amended the Federal Water Pollution Control Act, authorized a program specifically aimed at contaminated sediment problems in the Great Lakes. Section 118, paragraph (c)(3), directs the US Environmental Protection Agency (USEPA) Great Lakes National Program Office (GLNPO) to "carry out a 5-year study and demonstration projects relating to the control and removal of toxic pollutants in the Great Lakes, with emphasis on the removal of toxic pollutants from bottom sediments." The Act specified that priority Areas of Concern for implementation of demonstration projects were Saginaw Bay, Michigan; Sheboygan Harbor, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River New York.

The GLNPO strategy and program to fulfill the expectations of Section 118 has been named "Assessment and Remediation of Contaminated Sediment" (ARCS). One

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objective for the ARCS program is to evaluate and demonstrate remedial options, including removal, immobilization, and advanced treatment technologies, as well as the "no-action" alternative.

The purpose of this study was to identify technologies that may be feasible for remediating Great Lakes contaminated sediment and that should be considered for demonstration under the ARCS program. Technologies reviewed include those involving removal of contaminated sediment with subsequent transport, treatment, containment, or disposal, and those for nonremoval alternatives, such as in situ treatment or containment of the contaminated sediment. Principal sources of information for the review are technology assessments for management of hazardous waste or contaminated sediment published by the USEPA, the Corps of Engineers, the International Joint Commission Great Lakes Water Quality Board, and others. Published information is supplemented with recent data and experiences from Superfund sites and from work performed by US Army Engineer Districts and Divisions in developing alternatives for management of highly contaminated sediments.

PREFACE

This study was conducted as a part of the Assessment and Remediation of Contaminated Sediment (ARCS) Program developed by the US Environmental Protection Agency (USEPA), Great Lakes National Program Office (GLNPO), pursuant to Section 118(c)(3) of the Water Quality Act of 1987. This report was prepared at the US Army Engineer Waterways Experiment Station (WES) in cooperation with the US Army Engineer Division, North Central (NCD), for the GLNPO under an interagency agreement between the USEPA and the US Army Corps of Engineers. The study was conducted between December 1988 and February 1990.

Project manager for the GLNPO was Mr. David Cowgill. Mr. Jan A. Miller was the ARCS program manager for NCD. Dr. Thomas D. Wright was the ARCS program manager for WES. The study was conducted under technical guidance from the ARCS Program's Engineering/Technology Work Group, chaired by Dr. Steve Yaksich, US Army Engineer District, Buffalo, Buffalo, NY.

The report was prepared by Messrs. Daniel E. Averett and Bret D. Perry and Ms. Elizabeth J. Torrey of the Water Supply and Waste Treatment Group (WSWTG), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES, and Mr. Jan A. Miller, NCD. Dr. M. John Cullinane and Mr. Mark Zappi, WSWTG, provided technical review of the report. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

The study was conducted under the general supervision of Mr. Norman R. Francingues, Jr., Chief, WSWTG; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL.

COL Larry B. Fulton, EN, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
atmospheres, standard	101.325	kilopascals
British thermal units (mean)	1,055.87	joules
centipoises (dynamic viscosity)	0.001	pascal-seconds
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	meters
gallons (US liquid)	3.785412	cubic decimeters
inches	2.54	centimeters
miles (US nautical)	1.852	kilometers
miles (US statute)	1.609347	kilometers
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per ton	0.0005	kilograms
square feet	0.09290304	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

REVIEW OF REMOVAL, CONTAINMENT, AND TREATMENT TECHNOLOGIES FOR REMEDIATION OF CONTAMINATED SEDIMENT IN THE GREAT LAKES

PART I: INTRODUCTION

Background

1. Industrial, agricultural, and municipal discharges of pollutants to the Great Lakes over many years have contaminated bottom sediments in the rivers, harbors, and nearshore areas of the Great Lakes. Improved controls for point and nonpoint source discharges have reduced the pollutant loads from these sources, and cleaner waters have been achieved. However, the accumulation of contaminants, particularly toxic substances, in bottom sediments is an important factor in continued impairment of water quality and may contribute to toxic effects in aquatic biota and, potentially, in human receptors. Areas in the Great Lakes system where beneficial uses of the waterways remain seriously impaired have been designated as "areas of concern" (AOCs) by the International Joint Commission (IJC). Public support for control of toxic contaminants in these AOCs has prompted increased attention by Government agencies and environmental organizations toward development of remedial action plans to deal with contaminated sediment.

2. The Water Quality Act of 1987, which amended the Federal Water Pollution Control Act, authorized a program specifically aimed at the contaminated sediment problems in the Great Lakes AOCs. Section 118, paragraph (c)(3), directs the US Environmental Protection Agency (USEPA) Great Lakes National Program Office (GLNPO) to "carry out a 5-year study and demonstration projects relating to the control and removal of toxic pollutants in the Great Lakes, with emphasis on the removal of toxic pollutants from bottom sediments." The Act specified that priority AOCs for implementation of demonstration projects were Saginaw Bay, Michigan; Sheboygan Harbor, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River, New York.

3. The GLNPO strategy and program to fulfill the expectations of Section 118 has been named "Assessment and Remediation of Contaminated Sediment" (ARCS). The following objectives were developed for the ARCS Program (Horvatin 1989):

a. To assess the nature and extent of bottom sediment contamination at US Great Lakes AOCs.

b. To evaluate and demonstrate remedial options including removal, immobilization, and advanced treatment technologies, as well as the "no-action" alternative.

c. To provide guidance to the various levels of government in the United States and Canada in the implementation of Remedial Action Plans (RAPs) for the AOCs in their jurisdictions, as well as direction for future evaluations in other areas, including how to assess the need for action and the options available, and how to select the appropriate remedial measures.

4. The US Army Corps of Engineers (USACE) has been dealing with contaminated sediment problems in the Nation's navigation waterways for many years. Maintenance of adequate depths for these waterways requires periodic dredging to remove sediment deposits. The direct link between shipping and industrial or population centers involves the USACE in contaminated sediment problems. Environmental considerations dictate assessment of appropriate dredging technologies to minimize contaminant mobility during removal and application of contaminant controls during dredged material disposal. The Dredged Material Research Program carried out by the USACE Waterways Experiment Station (WES) in the 1970s identified and evaluated environmental concerns for dredged material disposal. Current research programs, including the Environmental Effects of Dredging Programs and the Improvement of Operations and Maintenance Techniques Program, continue to develop and evaluate techniques and procedures for dredging and dredged material disposal. The USACE has also been involved in recent demonstrations of dredging and dredged material disposal alternatives at the New Bedford Superfund Site and Calumet River.

5. Recognizing the USACE's expertise in dealing with contaminated sediment, the GLNPO and the USACE joined in an interagency agreement (IAG) providing for USACE support in achieving ARCS objectives. The USACE organizations involved in this work are the North Central Division (including the Buffalo, Chicago, and Detroit Districts) and the WES. The IAG outlined an initial program and scope of work consisting of eight elements. Element 5 of this program was entitled "Review of Technical Literature and Databases for Previous Technology Assessments/Demonstrations with Emphasis on Great Lakes Applicability." The results of work performed for program element 5 is the subject of this report.

Purpose and Scope

6. The purpose of this study is to identify technologies that may be feasible for remediating Great Lakes contaminated sediment and that should be considered for demonstrations under the ARCS program. Technologies reviewed include those involving removal of contaminated sediment, with subsequent transport, treatment, containment, or disposal, and those for nonremoval alternatives, such as in situ treatment or containment of the contaminated sediment. Principal sources of information were technology assessments for the management of hazardous waste or contaminated sediment, published by the USEPA, the USACE, the IJC Great Lakes Water Quality Board, and others. Published information is supplemented with recent data and experiences from Superfund sites and from work performed by USACE Districts and Divisions in developing alternatives for management of highly contaminated sediments.

Approach

7. This study is a screening-level assessment of technologies for remediation of contaminated sediments. An extensive list of technologies that have broad applicability for controlling, removing, or destroying contaminants in water, soils, sludges, or sediments was developed. Commonly reported process options for each technology type were considered. Because of the endless variations of process options and the large number of proprietary process options continually under development, an all-inclusive list was not within the scope of this study. Options were selected primarily from the technical literature in lieu of vendor advertisements. The available literature includes an ample number of process options for demonstrations that could be implemented as innovative applications for contaminated sediment and that could be completed within the time and budget of the ARCS program.

8. A brief description of each technology or process option is provided. Technologies were evaluated on the basis of the following factors:

a. State of development.
b. Availability.
c. Effectiveness.
d. Implementability.
e. Cost.

A rating system was developed to select the most promising technologies for demonstrations under the ARCS program. Priority for evaluation under ARCS should go to those technologies with greater potential for application on a full scale. Bench- and/or pilot-scale demonstrations are logical precursors to a full-scale demonstration or full-scale implementation at an AOC.

Organization of the Report

9. Part II of the report provides information about the contaminants present at the selected priority AOCs, describes the classification scheme for the technologies, and defines the rating factors. Part III presents results of the assessment and screening of technology types and process options, including a rating for each process option. Part IV summarizes the recommendations for technologies to be considered for demonstration under the ARCS program. Appendix A briefly describes each process option, discusses status of development and availability, and presents available performance and cost information for each process option considered in the screening process. (Tables and discussions of technology types and process options in the main text and in Appendix A are generally presented in alphabetical order for ease of reference and to avoid an impression of ranking technology types or process options.)

PART II: FACTORS CONSIDERED IN THE REVIEW OF TECHNOLOGIES

10. This part of the report presents additional background information and describes the procedure used in evaluating the technologies considered for the ARCS program. First, general sediment characteristics are briefly reviewed to provide a basis for considering technology types. Second, important definitions and the classification scheme used for technologies assessed by this report are described. Third, the migration pathways that should be considered in evaluating performance during each component or phase of the process train (e.g., removal, transport, treatment) of a remedial action are discussed. Finally, the development of evaluation factors for the technology assessment and the procedure for conducting the assessment are described.

Sediment Characteristics

11. Sediment chemical and physical characteristics vary widely from one AOC to another and also within an AOC. Selected characteristics for the Ashtabula, Buffalo, Grand Calumet, Saginaw, and Sheboygan AOCs are presented in Table 1. These values are averages based on data covering a large area. Chemical characteristics are generally more heterogenous than physical characteristics, and chemical concentrations may span several orders of magnitude. Any AOC will have smaller areas where the contaminant concentrations are much greater or much less than these averages. Polychlorinated biphenyls (PCBs) and heavy metals have been identified as contaminants of concern for all five AOCs. The PCB problems are more notable at Ashtabula, Sheboygan, and Grand Calumet. Grand Calumet has the greatest heavy metals concentrations of any of the AOCs, and Buffalo and Grand Calumet are notable for the concentrations of polynuclear aromatic hydrocarbons (PAHs). Sediments for the AOCs are also contaminated with other organic priority pollutants, but generally concentrations are less than 1 mg/kg.

12. Sediment properties that influence the interaction between sediment and contaminants include type and amount of clay, cation exchange capacity, organic matter content, pH, the amount of active iron and manganese, oxidation-reduction conditions, sulfide and sulfate concentrations, and salinity. Fine-grained sediments are commonly found to be more contaminated than coarse-grained material because of the greater surface area-to-weight ratios for finer particles and because of the stronger affinity of the smaller organic

and clay particles for contaminants. However, separation of the sand fraction from a contaminated sediment does not always produce a clean sand and a contaminated silt/clay fraction. Location of the sediment with respect to the pollution source, sediment transport phenomena, and degree of agglomeration of the finer particles affect the contaminant distribution with grain size. Site-specific fractionation is required to determine whether the sand is comparatively free of contamination. Table 1 shows that average fine-grained fractions for Grand Calumet and Saginaw were 70 and 30 percent, respectively. Values for 30 Saginaw samples ranged from 2 to 86 percent.

13. Water content or percent solids is an important variable for the design, operation, and economics of many process options for handling contaminated material. The in situ water content of the sediment represents the initial condition for evaluation of a technology. Mechanical dredging produces a dredged material with a water content near that of the in situ sediment. Hydraulic dredging increases the dredged material slurry volume by a factor of two to five. Many treatment technologies are efficient only for water contents much greater than or less than that of the in situ sediment. Therefore, the treatment technology may favor a particular removal option, or pretreatment of the dredged material may be necessary prior to treatment.

Environmental Pathways Affected by Remedial Actions

14. Contaminants in sediment can be transported to other environmental media under existing conditions and during remedial action. Short- and long-term releases from disposal areas following completion of remedial actions must also be considered. Migration pathways refer to the passage of contaminants from one media to another with the ultimate receptor being man. Pathways for contaminant transport discussed here are surface water, groundwater, air, plant uptake, animal uptake, and direct human contact. The number and types of pathways affected depend on site-specific characteristics and the type of remedial alternative employed.

Surface water

15. Contaminated sediment impacts on surface water are one of the major concerns driving the ARCS program. In a review of the impacts of bottom sediments from Grand Calumet River and Indiana Harbor Canal on water quality, Brannon et al. (1989) reported that, although sediments often are a sink for contaminants rather than a source, environmental conditions may change,

allowing for desorption of contaminants from in situ sediment by diffusive processes, or disturbance of bottom sediments may allow for resuspension of sediment and associated contaminants with subsequent desorption and dissolved release to the water column. No remedial alternative can remove, contain, or treat in situ contaminated sediment without some disturbance of the sediment, and hence some contaminant release to the overlying water column. A performance objective for remedial alternatives is to minimize the magnitude of this release. Surface water may also be affected by removal alternatives that include treatment or disposal on the shore or at an in-lake containment area. Water entrained by hydraulic dredges is separated from the dredged material in confined disposal facilities or by other dewatering processes and usually is released to surface waters as an effluent. Many other treatment technologies produce a wastewater discharge that may be released to surface waters. Leachate from dredged material within a disposal site may move through dike walls or through the bottom of a disposal site and enter surface waters. Once contaminants become mobile in surface water, transport to other environmental media, including aquatic plants and animals, air, and humans through ingestion or body contact, is possible.

Groundwater

16. Groundwater impacts are primarily associated with storage or containment facilities for contaminated sediment. Because sediment is initially supersaturated with water, placement of sediment or dredged material above the water table will generally produce leachate during the dewatering process. Additional leachate from a site can be produced by precipitation on the contaminated dredged material in a disposal area. Leachate from these facilities can potentially impact groundwater in the vicinity of the site. Subsequently, contaminants in the groundwater may be transferred to plants, animals, or humans.

Air

17. Contaminant transport from in situ sediment to air is a relatively slow process because most contaminants must first be released to the water phase prior to reaching the air. Thibodeaux (1989) discussed volatilization of organic chemicals to air during dredging and disposal and identified four locales where volatilization may occur:

a. The dredging site or other water area where suspended solids concentrations are elevated.

b. A ponded disposal facility with a quiescent, low suspended solids concentration.

c. Sediment exposed directly to air.

d. Vegetation-covered sediment.

Volatilization is favored in the order of conditions c, a, b, and d. Volatilization of contaminants is also a consideration for many other technologies that may enhance exposure of sediment contaminants to air. Airborne emissions must be considered for protection of workers and others who could inhale contaminants released through this pathway. Once a contaminant reaches the atmosphere, it has the potential for transport and distribution by any of the other pathways.

Animal uptake

18. Contaminants in sediment are accessible to the aquatic organisms that live or feed there. The same is true for dredged material placed in a disposal site. Once the contaminant enters the food chain, its concentration in the animal's tissue may increase through the biomagnification process. In the process of releasing contaminants through excretion or death, animals may increase the mobility of the contaminant in a water body or in a disposal site. High levels of contaminants in fish tissue, which may impact humans eating the fish, is a major impairment to water quality for the AOCs in the Great Lakes.

Plant uptake

19. Plant uptake presents a similar problem to animal uptake. Plants may take up contaminants from sediment or dredged material and store the contaminants in their biomass. The contaminants are then accessible to consumption by animals or recycling in the environment.

Direct human contact

20. Direct human contact is important for in situ sediment where the contaminated areas are near the shore and recreational activities may place humans in direct contact with the contaminants. Human contact is also important in planning remedial alternatives. Workers who construct disposal facilities in contaminated areas or who operate removal or disposal processes for contaminated dredged material have the potential for coming into contact with the sediment. Adequate safety measures for these workers are an essential component of a remedial action plan.

Classification of Technologies

Alternatives

21. A remedial action for a contaminated sediment problem will usually involve combining several appropriate technologies into an overall scheme for achieving a cleanup objective. Such combinations are often called remedial action alternatives for Superfund projects (USEPA 1988a). An alternative includes the various combinations of technologies needed to address each contaminated medium associated with the project. For a contaminated sediment project, the environmental media that should be considered are the in situ sediment and surface water for nonremoval alternatives and, for removal alternatives, the dredged material slurry, dredged material solids, disposal site effluent, disposal site runoff, disposal site leachate, contaminated surface waters, air emissions, and residual solids following treatment.

Components

22. An alternative for remediation of contaminated sediment usually involves several phases or components. For example, removal of contaminated sediment and placement in a confined disposal facility may include the following components: removal, transport, disposal, and effluent treatment. Alternatives involving sediment treatment may be removal, transport, pretreatment, treatment, and disposal. This report classifies technologies under six components: removal, transport, pretreatment, treatment, disposal, and effluent (including surface runoff) or leachate treatment. Technologies for nonremoval alternatives can generally be covered as a single component, which will be termed simply "nonremoval." Many combinations of technology types are possible. Examples of process trains for removal alternatives are illustrated in Figure 1.

Technology types

23. Because the focus of this report is on technologies for remediation of contaminated sediments for Great Lakes AOCs, broad general categories of operations, such as mechanical dredging, hydraulic dredging, chemical treatment, biological treatment, or confined disposal, will be called technology types. Figure 2 illustrates the technology types that have been selected to be discussed in this report for each component.

Process options

24. Technology types may be further broken down. For example, dredging is a technology for removing contaminated sediments. However, a number of

different extraction techniques are available, which have also been referred to as technologies. Subcategories of technology types, which more specifically define processes or operations, will be referred to as process options. Many process options, particularly for treatment technologies, may also include several unit operations such as mixing, heating, decanting, etc., but these will not be separately evaluated and will be discussed only within the descriptions of process options.

Overall classification scheme

25. The classification hierarchy for the review of cleanup technologies is much the same as prescribed for Superfund projects (USEPA 1988a). The three levels are as follows:

Alternative component
  Technology type
    Process option

Evaluation and screening of technologies for demonstration under the ARCS program will be performed at the process option level. Future work will identify appropriate combinations of process options as potentially feasible remedial action alternatives.

Objectives for Alternative Components

26. To assess the effectiveness of the available process options, an objective for performance of the process is desirable. Since a single process seldom satisfies the overall cleanup objective, the efficiency of contaminant removal, destruction, or containment is not always appropriate as the sole evaluation criterion. This is particularly true for the pretreatment component, which by definition is only a preparatory step in the cleanup scheme. The paragraphs below will present key objectives for each component.

Removal

27. The primary objective of the removal step is to excavate contaminated sediment from the waterway. Other important objectives are:

- a. To remove contaminated sediment without excessive removal of clean sediment.
- b. To minimize sediment resuspension and contaminant release to the water column.
- c. To maximize solids concentration for the dredged material.
- d. To accomplish the removal step with a reasonable production rate and cost.

e. To function properly under site-specific conditions.

f. To be compatible with treatment and/or disposal process options.

These objectives are not necessarily mutually supporting, and a single process option will not likely score highest for all of the objectives. Therefore, trade-offs for the advantages and disadvantages of each process option are generally developed. Site and sediment characteristics will have a significant impact on the final selection of process options for removal.

Transport

28. The transport component relocates dredged material from the waterway to a treatment or disposal site. Objectives for this component are as follows:

a. To reliably contain the contaminated dredged material between the removal site and the treatment or disposal site, i.e., take adequate precautions against spillage or leakage of the material.

b. To be compatible with removal and disposal or treatment options.

c. To minimize the chance for human contact with the contaminated material.

Pretreatment

29. Objectives for the pretreatment component are dependent on treatment or disposal options following in the process train. However, for the pretreatment options discussed in this report, the objective of this step is usually one of the following:

a. To provide a suitable material for further treatment and/or disposal operations.

b. To enhance or accelerate settling of the dredged material solids.

c. To reduce the water content of the dredged material solids.

d. To separate coarser, potentially cleaner, solids from the fine-grained, more contaminated solids (particle classification).

e. To reduce the overall cost for the remedial action.

Treatment

30. Treatment of dredged material to destroy, remove, immobilize, or otherwise detoxify the contaminated material at a reasonable cost should be a goal for remedial responses at AOCs. Specific treatment objectives include the following:

a. To destroy toxic organic contaminants by conversion to nontoxic end products.

b. To remove heavy metal or organic contaminants from contaminated dredged material, thereby concentrating toxic material into a media of smaller volume (extraction), and/or to reduce the volume of solids for further treatment or disposal.

c. To reduce the mobility of contaminants in dredged material to a level compatible with acceptable risks.

d. To be compatible with removal and final disposal options.

e. To be achievable at acceptable capital and operating costs.

f. To minimize contamination of other environmental media.

g. To avoid addition of potentially toxic materials or the production of toxic materials during the treatment process.

Disposal

31. The disposal component should provide for long-term containment and isolation of contaminated dredged material or for beneficial use of residual clean material produced by a treatment process. These and other performance objectives are listed below:

a. To provide for containment of contaminated dredged material with minimal losses of contaminants to the environment.

b. To provide for beneficial use or disposal of residual clean material following treatment processes.

c. To be compatible with removal options.

d. To be achievable at acceptable capital and operating costs.

e. To minimize opportunities for human contact or plant and animal uptake of contaminants.

Effluent/leachate treatment

32. Effluent treatment may often be required for wastewaters produced by treating or disposing of highly contaminated sediment. Effluent includes release of water decanted from settling processes, surface runoff, and releases from other treatment operations. Leachate treatment is a less likely scenario because other control measures are available to minimize contaminant concentrations in leachate and leachate volumes. Where effluent or leachate treatment is required, the following objectives apply:

a. To provide adequate effluent quality to comply with applicable water quality standards and other regulatory requirements.

b. To avoid further contamination of other environmental media.

c. To be compatible with removal, treatment, or disposal options.

d. To be achievable at acceptable capital and operating costs.

Development of the Screening Process

33. The purpose of this report is not to simply describe technologies for remediation of contaminated sediment, but to assess the appropriateness of the technologies for demonstration under the ARCS program. Funding and time constraints for the current ARCS program limit the number and scope of demonstrations. Therefore, an extensive list of recommended technologies is not desirable. Because of the myriad of technologies, the influence of site-specific factors, the various types of environmental media, the types and concentrations of contaminants, and the somewhat generic nature of this investigation, a detailed, objective comparison of all process options is not possible. It is possible to develop guidelines to screen process options and achieve the objectives of this study.

Rating schemes from the literature

34. Other investigators have faced a similar problem in seeking alternatives for cleanup of Superfund sites and for other areas where disposal of contaminated sediment is an issue. Cullinane et al. (1986) developed a "Dredged Material Alternatives Selection Strategy" that included a screening methodology for technologies and alternatives. This method considered a list of evaluation factors and criteria by which the factors were measured or compared. The factors selected were costs, technical effectiveness/efficiency, operation and maintenance, reliability, implementability/availability, environmental concerns, safety, regulatory requirements, and public acceptance. Costs, technical effectiveness/efficiency, and operation and maintenance were identified as quantifiable factors, whereas the remainder of the factors were stated to be nonquantifiable. The criteria for all of the criteria except for costs were subjective evaluations producing a relative numeric ranking.

35. USEPA (1988a) in its current "Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA" prescribes only three factors for screening of alternatives or process options for Superfund sites: effectiveness, implementability, and costs. Effectiveness is defined as follows:

- a. The potential effectiveness of process options in handling the estimated areas or volumes of media and meeting the remediation goals identified in the remedial action objectives.
- b. The potential impacts to human health and the environment during the construction and implementation phase.

c. The reliability of the process with respect to the contaminants and conditions at the site.

Implementability is defined by USEPA as the technical and administrative feasibility of implementing a technology process option. Implementability includes the ability to obtain the necessary permits; the availability of adequate capacity for treatment, storage, and disposal; and the availability of necessary equipment and skilled workers to implement the technology. The cost criterion for screening of technologies under CERCLA (the Comprehensive Environmental Response Compensation and Liability Act) is a relative evaluation of capital and operation and maintenance costs. E. C. Jordan Co. (1989) used the CERCLA methodology to screen technologies for remediation of highly contaminated sediments at the New Bedford Harbor Superfund site. Once technologies are combined into alternatives, a more extensive list of factors is prescribed by USEPA for detailed analysis of Superfund alternatives. The nine factors are overall protection of human health and the environment; compliance with appropriate, relevant, and applicable regulations; long-term effectiveness and permanence; reduction of toxicity, mobility, or volume; short-term effectiveness; implementability; cost; state acceptance; and community acceptance.

36. The US Army Engineer (USAE) District, Chicago (in preparation), used eight weighting factors to rank technologies for treatment of dredged material from the Indiana Harbor and Canal. These factors were safety, availability, process limitations, processing rate, effectiveness/efficiency, contaminant specificity, reliability, and a factor designated as "other." In a manner similar to Cullinane et al. (1986), relative numeric rankings were defined for each factor. Safety, process limitations, and processing rate were rated heavier than the remaining factors.

37. Carpenter and Wilson (1988) presented a rating system to determine which PCB treatment processes were more desirable for "immediate thorough test and evaluation." Scores were based on five criteria: the probability of cleaning sediments to 2 ppm PCB concentration or less, the availability of a test system, the test effort required, the time required to provide a commercial-size treatment system, and the probable cost of treatment using the process.

38. All of the investigations discussed above addressed the CERCLA factors of implementability, effectiveness, and cost. Additional factors were operation and maintenance, safety, availability, process limitations,

processing rate, contaminant specificity, reliability, test effort required, and time required to produce a commercial size unit. While all of these factors are important considerations for a detailed analysis of alternatives, most of them are encompassed by the three CERCLA factors. Operation and maintenance may be included as part of the overall cost. Availability, safety, process limitations, regulatory requirements, and processing rate are components of an implementability rating. Contaminant specificity is important to selection of processes for a specific site where it is often necessary to provide controls for a number of different contaminants, both organic and inorganic. A number of process options are effective for treating an array of organic compounds or for several inorganic constituents. However, few options will control both organic and inorganic contaminants, and multiple treatment process options are often required. Contaminant specificity is addressed in the process option description, but is not included as a separate rating factor. Reliability can be considered as part of effectiveness. Public acceptance is difficult to address without a specific site in mind and input from the local community. Test effort required will be considered in the final selection of demonstratable technologies, but is less important for the initial screening step. Time required to produce a commercial-size unit can be considered under implementability.

Selected evaluation factors

39. For the sake of simplicity and because of the nonsite-specific nature of this evaluation, the screening of process options for this study uses the three factors effectiveness, implementability, and costs to produce a composite rating for each process option identified for evaluation. Definitions for these factors are those defined in CERCLA guidance (USEPA 1988a). Because these factors are difficult to quantify for a screening-level assessment, relative rating criteria on a numerical scale of 1 to 4 are used for each factor.

40. Effectiveness. Effectiveness ratings are defined as follows:

- a. Rating = 4. Process option can achieve the performance objective with greater than 99 percent efficiency. The process is highly reliable.
- b. Rating = 3. Process option can achieve the performance objective with 70 to 99 percent efficiency. The process is moderately reliable.
- c. Rating = 2. Process option can achieve the performance objective with 40 to 70 percent efficiency. The process is minimally reliable.

d. Rating = 1. Process option is less than 40 percent efficient in achieving performance objectives. The process is not reliable.

41. Implementability. Implementability ratings are defined as follows:

a. Rating = 4. The process option is commercially available, has proven applicability to contaminated soils or sediments, and has been field demonstrated at process rates and material characteristics similar to dredged material.

b. Rating = 3. The process option is commercially available, has proven applicability to contaminated soils or sediments, and has been demonstrated on a pilot scale for soils or sediment.

c. Rating = 2. The process option has been demonstrated on a bench scale to be applicable to contaminated sediment or dredged material, and adequate information is available to proceed to a pilot-scale demonstration. Innovative technologies developed in laboratory studies may be assigned this rating.

d. Rating = 1. The process option is conceptual or emerging and requires additional developmental work for application to contaminated sediment or dredged material.

42. Costs. A rating for costs would ideally include development of capital and operation and maintenance (O&M) cost estimates for various production rates. Capital and O&M costs are usually rolled up into a single figure using a present worth analysis. However, such an exercise for this screening step would be very difficult in view of the limited cost data for dredged material treatment options and because site-specific factors impact costs for most technologies. The sediment volume used for the cost estimate can have a significant effect on the cost of a process; however, the existing database is inadequate to relate volume treated to costs. Costs can be sufficiently evaluated using relative rating factors similar to those for effectiveness and implementability. The cost ratings will be based on ranges of costs per unit volume of sediment removed using reported costs when available and the best judgment of the authors where no cost data were found. Because of the various combinations of alternative components that make up a remedial alternative, the incremental cost for each component will be used. Ratings selected for costs are as follows:

a. Rating = 4. Unit cost for the process option is less than $20 per cubic yard.

b. Rating = 3. Unit cost for the process option is in the range of $20 to $100 per cubic yard.

c. Rating = 2. Unit cost for the process option is between $100 and $200 per cubic yard.

d. Rating = 1. Unit cost for the process option is greater than $200 per cubic yard.

43. Composite score. A composite rating or score for each technology will be calculated by simple addition of the ratings for each of the three factors, i.e., all factors are weighted equally. The factors and composite score for each technology will be tabulated and presented in individual tables grouped by technology type. The technology types for each alternative component are shown as Figure 2.

44. Additional information. In addition to the subjective ratings for effectiveness, implementability, costs, and composite score, each rating table will include the following headings:

a. Technology. The name of each process option or technology identified during the literature review will be listed.

b. State of development. State of development will be noted as demonstrated, pilot, or conceptual. Demonstrated technologies have been applied to a contaminated media on a field scale at processing rates that could accommodate a contaminated sediment problem. Pilot technologies have been demonstrated on a pilot scale for contaminated soil or sediment. Conceptual processes have been shown to be effective on a laboratory scale for contaminated sediment or soil.

c. Applied to dredged material. A simple yes or no is recorded to indicate that the process has or has not been demonstrated on a full scale for dredged material. Where dredged material testing has been performed on a pilot or bench scale, this is also indicated.

d. Availability. This column is noted as available, proprietary, or foreign to indicate if the process is available from a number of vendors in the United States, if it is a patented or proprietary process, or if it is a foreign technology. Where the process is in the developmental state, availability will be denoted as "emerging."

Decision criteria

45. The final column in the tabulated evaluations for the technologies and process options reviewed has the heading "Consider for ARCS Program." A "yes" in this column indicates that the process option has a high potential for meeting the goals of the ARCS program and should be considered for demonstration. For a process to receive a "yes," the following criteria must generally be met:

a. The process option must have the first, second, or third highest composite score within that technology type. Where the second or third highest scores are 3 or more points lower than the top score, only the first or second highest rated process option will be recommended. The margin of 3 is based on the possibility of error in the ratings, which are often opinions of the authors based on best engineering judgment in lieu of available data, and the impacts of site-specific factors on applicability of process option. Exceptions to this rule may occur where the treatment objectives of the process options differ, favoring one technology because of lower cost or higher effectiveness for different contaminant problems.

b. Process options that receive a "1" rating for any one of the three evaluation factors will not be recommended. One exception that is made to this rule provides for a second tier of processes for ARCS consideration. Where processes costs are estimated to be more than \$200 (but less than \$500) per cubic yard and have a high composite score, they will be recommended as "yes (II)." The rationale for this rating is that some processes may have a high cost because they have not had the opportunity for full development.

c. Process options that are available only from foreign vendors generally will not be recommended for consideration because of logistical and administrative problems in testing foreign technologies. Foreign technologies may be considered in a later stage of the ARCS program.

46. The purpose of the comparative evaluation is to present a framework for consideration and screening of the more than 250 process options reviewed during this study. Review of this information by the participants in the ARCS program should provide for refinement of the ratings and for additions of process options that are not widely reported in the literature.

PART III. ASSESSMENT AND SCREENING OF TECHNOLOGIES

47. This part of the report presents the results of the assessment and screening of technologies and process options reviewed during this investigation. Alternative components are subdivided into technology types. Technology types are further subdivided into process options. Discussion of the screening results is presented at the technology level. A narrative description of each process option is provided in the appendix.

Removal Component

48. The removal or excavation of sediment from a stream, lake, harbor, or other waterway is commonly called dredging. Dredging involves mechanically penetrating, grabbing, raking, cutting, or hydraulically scouring the bottom of the waterway to loosen or dislodge the sediment. Once loosened, the sediment or dredged material is lifted to the surface of the waterway by mechanical devices such as buckets or by hydraulic suction. Mechanically removed dredged material may be placed in scows or barges for transport to a disposal site, whereas hydraulically removed material may be placed in a hopper dredge or pumped through a pipeline to a disposal site. Thus, most dredges may be categorized as mechanical or hydraulic dredges based on the basic means of moving the material. A number of equipment options are available for each category. Selection of dredging equipment for a remedial action depends on the following factors (US Army Engineer District, Chicago (in preparation) and McLellan et al. 1989):

a. Volume and depth of material to be dredged. The volume to be removed affects the production requirements and the transport requirements that provide for a cost-effective project. A shallow depth of material to be dredged may favor equipment that can precisely remove the thin layer of contaminated material. The goal of a removal operation is to effectively remove the contamination without excessive overcutting.

b. Physical characteristics of the sediment. Particle size is particularly important since finer grained materials are more susceptible to resuspension and transport during removal. The degree of compaction, cohesiveness, and bulk density of the sediment can also affect the type of dredge selected.

c. Debris. Sediment often contains large rocks, stone, timbers, tires, car bodies, and other discarded materials. In areas of cargo loading/unloading, pockets of coal, iron ore pellets, or other bulk materials may occur from spillage. Larger debris cannot be removed by hydraulic dredges, and smaller debris may clog hydraulic pipelines or damage pumps. Mechanical dredges will generally remove large debris along with the sediments; however, increased resuspension may result for such operations.

d. Physical site restrictions. Water depths, channel widths, obstructions, overhead restrictions, and access to the site may limit the size of equipment, i.e., width, length, and draft, that can be used for a site. In some cases, material may be removed by operating equipment from shore.

e. Distance to the disposal site. Where long distances are involved, pipelines may not be practicable, favoring transport in scows or barges of mechanically removed material with a high solids content.

f. Compatibility with disposal operations. Mechanically removed material is often at near in situ density or water content and may not require costly dewatering and effluent treatment operations in preparation for dredged material treatment or disposal. On the other hand, treatment operations that require a feed high in water content (a slurry) may favor hydraulically dredging the material.

g. Availability of equipment. A variety of dredging equipment has been designed for waterway maintenance in the Great Lakes. However, some equipment touted as being more "innovative" is foreign equipment that is not readily available in the United States.

h. Cost of equipment use. The more competitive production equipment can be used for remediation at much lower costs than specialized dredges.

i. Contamination level of the sediments to be dredged. Contaminants high in concentration, toxicity, or mobility may dictate extraordinary care and expense in the selection of a removal option. Releases of contaminants to the waterway during dredging are a primary concern.

49. Technologies for the removal of contaminated sediment include the following:

a. Selection of appropriate hydraulic dredges.

b. Selection of appropriate mechanical dredges.

c. Use of operational controls during dredging operations.

d. Use of turbidity containment technologies during sediment removal.

Process options available for each of these technologies are listed in Table 2.

Hydraulic dredges

50. Hydraulic dredges remove and transport sediment in liquid slurry form. They are usually barge mounted and carry diesel or electric-powered

centrifugal pumps with discharge pipes ranging from 6 to 48 in.* in diameter. The pump produces a vacuum on its intake side, and atmospheric pressure forces water and sediments through the suction pipe. The slurry is transported by pipeline to a storage, treatment, or disposal area. Hopper dredges are included in the category of hydraulic dredges for this report even though the dredged material is simply pumped into the self-contained hopper on the dredge rather than through a pipeline. Normally, hopper dredges are allowed to overflow in order to produce a more economical load. The Corps has eliminated the overflow from hopper dredging in areas where this overflow was shown to pose a significant environmental impact.

51. Results for the assessment of hydraulic dredges are presented in Table 3. All of the dredges listed are commercial pieces of equipment and by their nature have been used for dredged material. Several of these dredges which have been reported to be effective in removing contaminated material are foreign manufactured. Japanese dredges include the Clean-up, Oozer, and Refresher dredges. The matchbox suction head is a Dutch design that is being marketed in the United States as the Beane Sweep. Other special-purpose dredges that are not widely available in the construction industry are the Delta, Eddy pump, Pneuma pump, and Waterless dredges. Cutterhead and horizontal auger pipeline dredges and hopper dredges are widely available from a number of manufacturers. The USAE District, Chicago (1989), reported that 33 hydraulic dredges ranging in size from 8 in. to >20 in. and six hopper dredges with capacity of 3,600 or 16,000 cu yd were operating on the Great Lakes as of June 1989.

52. Effectiveness of the dredges is based on studies of resuspension by the Corps of Engineers and others. With proper operation, most of these dredges could remove contaminated sediment with greater than 99 percent efficiency. However, the fact that there is little quantitative data for the airlift, Delta, Eddy pump, hand-held hydraulic, and plain suction dredges reduced the ratings of these dredges to a 3. The horizontal auger dredge, when tested at the New Bedford Superfund Pilot project, resuspended more sediment than the cutterhead or the matchbox.

53. Implementability for the dredges varies depending on their availability and adaptability to a variety of site conditions. Foreign dredges

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 5.

were given a 1 for this factor. The cutterhead, being the most commonly used dredging plant nationwide, was rated the highest (rating of 4). Dredges with limited production rates (airlift and plain suction) or extremely large plants (dustpan) were assigned lower ratings.

54. Costs for dredging are affected by production rate, size of the project, availability of equipment, operational constraints, and other site specific factors. With the exception of the foreign dredges, costs for hydraulic dredges are expected to be less than $20/cu yd. The USAE District, Chicago (in preparation), reported dredging costs for the Great Lakes as tabulated below.

Volume (1,000 cy)	Disposal Method*	No. of Operations	Unit Cost $/cu yd
		Hopper	
<100	0	2	7.79
>100	0/C	3	5.15
		Pipeline	
<50	B/C	8	11.66
50-100	B/C	4	7.44
>100	B/C	1	5.82
		Mechanical	
<50	0/U	2	10.89
50-100	C	4	10.30
>100	0/C	4	10.01

Source: USAE Division, North Central. Costs include contracts for dredging and transportation, preparation of plans and specifications, contract management, and monitoring. Costs do not include confined disposal facility construction/operation/maintenance.

* Code definitions: 0 = open lake, B = beach nourishment, U = upland, unconfined, C = confined.

55. Cleanup dredging is best represented by those costs associated with dredging and confined disposal. The costs include transporting the dredged material to a disposal site and off-loading. Dredges with a composite score of 10 or higher should be considered for the ARCS program. This includes 9 of the 15 dredges in Table 3. Application of additional factors to address site-specific conditions will narrow the list for application to a particular AOC.

Mechanical dredges

56. Mechanical dredges remove bottom sediment through the direct application of mechanical force to dislodge and excavate the material at almost in situ densities. Backhoe, bucket (such as clamshell, orange-peel, and dragline), bucket ladder, bucket wheel, and dipper dredges are types of mechanical dredges. Sediments excavated with a mechanical dredge are generally placed into a barge or scow for transportation to the treatment or disposal facility.

57. Results of the assessment of mechanical dredges are presented in Table 4. These options represent construction equipment that has been used as the primary means for removing sediment from waterways in the Great Lakes Basin. The USAE District, Chicago (in preparation), reported that 77 mechanical dredges were working on the Great Lakes in 1989. Mechanical dredges offer the important advantage of removing the bottom material at near in situ density with little additional water entrained by the process. The high solids content provides dividends on the treatment end of the remedial action by reducing dewatering and water treatment requirements. Mechanical dredges generally produce greater resuspension rates compared to hydraulic dredges. A closed- bucket clamshell has been shown to reduce resuspended sediment concentrations in the upper water column, but it may actually generate a larger plume than a conventional clamshell (McLellan et al. 1989). Effectiveness for most of these options was assigned a rating of 2 because the contaminated sediment is pulled through the water column, spilling and leaking contaminated solids. The clamshell, backhoe, and closed-bucket were given a more favorable rating because careful operation of these dredges can perhaps reduce resuspension rates. All of the mechanical dredges are easy to implement, with the backhoe and the clamshell having a slight edge compared to the others in Table 4. Costs for clamshell dredging are shown in paragraph 54.

Operational controls

58. Operational control technologies are methods of reducing the amount of sediment resuspended by dredging operations. Controls considered for this assessment include management of project operations, work boat controls, use of positioning equipment, and adjustments in cutter speed, depth of cut, and swing speed or speed of advance. Management techniques, work boat controls, and use of positioning equipment are applicable to most removal operations; whereas, applications of cutter speed, depth of cut, and swing speed or speed of advance are limited to a cutter-type hydraulic dredge. Sediment resuspension during dredging of contaminated sediment at the New Bedford

Superfund Pilot site was found to be greatly dependent on the operational mode of the dredges and on contributions by support and monitoring operations for the shallow estuary (USAE Division, New England 1989).

59. Results of the assessment of operational controls for removal operations are presented in Table 5. All of these options have been demonstrated for dredging operations and are readily available. No single option will eliminate resuspension during dredging, but they all can contribute to a reduction in resuspension and contaminant release. Quantification of the reduction is not well documented and depends on site conditions. All of these controls are easy to implement where they are applicable, e.g., cutter speed for cutterhead dredges. Work boat controls present problems in shallow areas where prop wash is difficult to avoid during dredge positioning or anchor movement. These controls can affect production and increase the cost of removal, but the additional cost is relatively small compared to most barrier options. All of these controls should be considered during field demonstrations of remedial actions.

Turbidity containment technologies

60. A number of process options have been suggested to help contain resuspended sediment and contaminants released during excavation or dredging. Success with these has varied, and their application is very site specific. At sites where the geometry of the harbor/waterway permits and where contaminant levels are unusually high, structural barriers may be warranted. Dikes, sheet piling, caissons, and other enclosures have all been suggested and could be effectively used depending on site-specific characteristics. Nonstructural barriers include oil booms, pneumatic barriers, sediment traps, silt curtains, and silt screens. Obviously, the design and installation of barriers must provide for necessary ingress/egress for dredging and support equipment. Hydraulic dredging within an impermeable wall must have provisions for addition of slurry-makeup water for the dredge. Provisions may also be necessary for removal of the barrier once remediation is completed.

61. Results of the assessment of process options for barriers are presented in Table 6. All of these options have been demonstrated on a field scale for dredging or construction activities and are common construction items readily available in the construction industry. Effectiveness of these options is not well documented for contaminated materials. Silt curtains are inefficient barriers for waterways subject to currents because the water flow carries the fine suspended solids under the curtain or through windows in the

fabric. Wind can also severely impact silt curtains (USAE Division, New England 1989). Structural barriers are more effective than others, but effectiveness is downgraded because of the disturbances of contaminated sediment during construction and removal of such structures. Effectiveness of pneumatic barriers is rated the lowest because they may actually increase sediment and contaminant mobility. Implementability of caissons, dikes, and sheet piles are given a low rating (2) because they could be used only for small projects with shallow water depths and their constructability depends on suitable foundation materials. Costs for the structural options are highly site specific, and costs per cubic yard for these options are difficult to estimate but are projected to be quite high. The ratings given in Table 2 reflect relative costs among the options listed.

62. The feasibility of barrier options is site specific. Barrier options recommended for consideration in the ARCS demonstration program are dikes, oil booms, sediment traps, sheet piling, silt curtains, and silt screens.

Transport Component

63. This section addresses management techniques to control contaminated materials while in transit to a disposal site. The primary emphasis during this component or phase of the overall remediation process is toward spill/leak prevention. Accidental release of contaminated materials into a previously uncontaminated environment may have adverse environmental, monetary, and public relations consequences. Primary transportation methods used to move dredged material include the following: pipelines, barges or scows, hopper dredges, railways, and trucks. Controls for each of these transport modes are listed in Table 7.

Barges/scow transport

64. Barges and scows have been one of the most widely used methods of transporting large quantities of dredged material over long distances. Typical barge capacities range from less than 100 to 2,000 cu yd. Barge movement of material is reasonably cost effective and is adaptable to most dredging operations. Primary controls to prevent spread of contaminated materials when using barge transport include barge selection, route/navigation controls, loading/unloading procedures, and decontamination of equipment.

65. Results of the assessment of controls for barge/scow transport of contaminated sediment are shown in Table 8. These controls have been

demonstrated for industrial operations, and have been applied on the Great Lakes for transport of contaminated sediments to CDFs. Loading and unloading controls are routinely applied at CDFs. When handling highly contaminated sediment, these controls should be considered to prevent spills, to protect workers, and to avoid environmental degradation. The use of route or navigation controls was rated lower for implementability because this option is site specific in terms of availability of alternate routes and may not always be available for a contaminated site. Costs for the controls are a minor component for a remedial action involving contaminated materials. All the process options listed in Table 8 should be considered for the ARCS program.

Hopper dredge controls

66. Controls for hopper dredge transport are the same as for barge/scow transport, i.e., hopper selection, decontamination, loading/unloading controls, and route/navigation controls. However, loading of hopper dredges is a special case because of a choice of operational procedures during filling of the hopper dredge. For clean sediment dredging, a hopper dredging operation allows excess water to overflow the hopper, providing additional capacity for dredged material solids. This procedure is inappropriate for highly contaminated sediment and has been totally banned by some States bordering the Great Lakes.

67. Results of the assessment of hopper dredge control technologies are presented in Table 9. The most critical element for maintaining effectiveness for hopper dredges is to eliminate hopper overflow when handling highly contaminated sediment. Decontamination of a hopper dredge and use of alternative routes may cause implementation problems. Costs for these options are relatively low. All these options should be considered by the ARCS program.

Pipeline controls

68. Controlling contaminated dredged material during pipeline operations requires review of two aspects of the pipeline system--pump and pipeline. The pump is critical as it is the prime mover for the dredged material, and as such, must withstand the stress of handling materials of varying consistencies. The pipeline acts as the conduit for dredged material to flow into a designated containment area. Pipelines must be able to accommodate the dredged material under pressure as well as resist external environmental stresses.

69. Pipelines are commonly used to transport bulk materials over relatively short distances. For navigation dredging, pipelines may be up to

3 miles in length. Longer pipelines usually require one or more booster pumps along the way to maintain head and to keep solids in suspension.

70. Results of the assessment of controls for pipeline transport are presented in Table 10. A means of detecting breaks in the line is an important operational control. Planning and design should include assessment of the most appropriate route for the pipeline and selection of a pipe material suitable for the level of protection required. These controls are identified as ways to prevent unexpected contaminant releases, and all should be considered when transporting contaminated material by pipeline.

Rail transport

71. Rail transport is normally used only when the distance to disposal sites is very large (>50 to 100 miles). Rail cars may be used to move consolidated dredged material from local disposal sites to locations where the material may be reused. The control measures applicable for rail transport are similar to other transport means. Control of dust by using covers is important as the material may remain in the rail car for lengthy time periods in rail yards, dry out, and begin to present a dust problem.

72. Results of the assessment of controls for rail transport are given in Table 11. These control measures have been applied for minimizing contaminant releases during transport of hazardous materials. However, no cases of rail transport of contaminated dredged material are known, and these control measures have not likely been applied to dredged material. Route selection may be difficult to implement because of limited alternatives. Decontamination of rail cars could produce contaminated wastewater that requires additional treatment. If rail transport is a selected option, the controls listed in Table 11 should be considered.

Truck transport

73. Trucks are used for dredged material when the distance from the dredging site is beyond the range normally used for overland pipelines and less than the distance for rail car transport. Trucks have been used to transport mechanically dredged sediments to Great Lakes CDFs. Controls associated with transporting dredged material by truck parallels those for barge/scow transport. Federal, state, and local regulations govern the maximum size and weight of trucks. During loading operations, care must be exercised to ensure that the truck is not overloaded for the route over which it must traverse. A material high in moisture content will significantly add to

the shipping weight compared to unsaturated material, as well as necessitating additional round trips to move the same amount of solids.

74. Results of the assessment of control options for truck transport are presented in Table 12. These options have been demonstrated for handling contaminated materials, including dredged materials on the Great Lakes. Because of the proximity of truck routes to the public, all of these controls should be considered for hauling contaminated dredged material. Selection of a vehicle with a sealed bed to prevent losses of liquid is a primary consideration.

Pretreatment Component

75. Pretreatment technologies are defined for the purposes of this report as technologies that prepare dredged material for additional treatment or disposal. These technologies are designed to accelerate treatment in a disposal site, to reduce the water content of the dredged material, or to separate fractions of the dredged material by particle size. Pretreatment technology process options are dewatering, particle classification, and slurry injection. They are primarily applicable to hydraulically dredged sediment. Process options for the pretreatment component are listed in Table 13.

Dewatering

76. Dewatering technologies are processes used in support of detoxification or destruction technologies. The primary purpose of these processes is to reduce the moisture content of slurries or sludges to expedite the handling and to prepare the material for further treatment or disposal. The water generated during dewatering generally contains contaminants as well as suspended solids, and further treatment should be considered. Table 14 lists the dewatering processes assessed and presents the results of the assessment. All of these processes have been demonstrated for applications with CDFs or for use in manufacturing, mining, or waste treatment industries. However, the mechanical processes, such as filters, centrifugation, or thickening, have not been widely applied to dredged material.

77. Most mechanical dewatering processes reduce the moisture of the feed material to a level comparable to in situ sediment (about 50 percent by weight) and work best with homogeneous waste streams. Processes rated most effective (rating = 4) were the belt filter press, centrifugation, and chamber filtration. Solar evaporation as a stand-alone process is suitable only for

arid climates and was rated as ineffective for the Great Lakes region. Implementability for processes other than settling ponds is poor primarily because of the high processing rates required for most removal operations. Filtration processes often have problems with clogging of the filtration medium with fines or oily materials. Temporary storage in a CDF may be required to equalize flows and concentrations prior to further dewatering by one of the mechanical processes. Evaporation requires heating the sediment, which was judged to be infeasible as a treatment process for large quantities of dredged material. Dewatering processes will increase the cost of disposal and were rated as 3 for costs. Recommendation of a dewatering process depends greatly on how it will benefit a subsequent treatment process. Costs of many treatment processes, particularly thermal processes, rise dramatically with increasing water content, to levels exceeding the costs of dewatering. With exception of the evaporative processes, the dewatering processes are recommended as potential pretreatment processes for remedial actions of contaminated sediment.

78. Confined disposal facilities (CDFs) are engineered structures that have been designed to retain dredged material solids and, in the case of hydraulic dredging, to provide acceptable suspended solids concentrations for discharges to receiving waters. These facilities are discussed in more detail under "Disposal Component" but are discussed here as a pretreatment technology. Wastewater treatment controls that may be applied for CDF effluent or leachate are discussed under "Effluent/Leachate Treatment Component" (see paragraphs 128-129).

79. When used as a pretreatment process, CDFs may serve several functions. They may provide temporary storage for dredged material awaiting treatment, allow for settling and dewatering of dredged material solids, and separate coarse-grained or oversized material from fine-grained material. Dredged material dewatering has traditionally been accomplished in ponds or CDFs, which rely on seepage, drainage, consolidation, and evaporation. This option is generally effective and economical, but it requires long time periods and rehandling of the material when feeding to a follow-on treatment process. Subsurface drainage, surface drainage, and wick drains may be used at a CDF to promote drainage or seepage, dewatering, and consolidation. Contaminant releases via seepage, drainage, and volatilization during the dewatering process must also be considered. Controls that may also be applied to CDFs used as pretreatment facilities are discussed in the disposal section

(see paragraphs 110-117). The primary purpose for most of these controls is to minimize the loss of leachate through the dikes and bottom of the CDF, either by reducing infiltration of precipitation and pore water through dewatering and/or collecting the drainage or by providing a barrier to leachate percolation beyond the bounds of the site. All of these controls have been applied or proposed at one or more CDFs on the Great Lakes. The implementability and effectiveness of these controls are highly specific to the CDF location and the sediment characteristics.

80. All of the control options (except for evaporation and solar evaporation) in Table 14 are recommended for evaluation by the ARCS program. Evaluation of these controls will provide information for use of CDFs for pretreatment as well as for treatment.

Particle classification

81. A number of particle classification or separation technologies are available to classify contaminated soils or slurries according to particle size. Separation by grain size is important in the management of soils and sediments contaminated with toxic materials since the contaminants tend to sorb primarily onto fine-grain clay and organic matter. Theoretically, the small-grain solids of a specific size or less could be treated, while the relatively noncontaminated coarser soils and sediments could be disposed without restrictions. The most appropriate solids separation technology for a given site depends on the volume of contaminated sediments; composition of the sediments, such as size, gradation, percent clays, and percent total solids; characterization of the contaminants; types of dredging or excavation equipment used; and site location and surroundings, including available land area. Particle classification options include screening processes that depend on size alone, processes that depend on particle size and density or density alone, and processes that depend on conductive or magnetic properties of the particles.

82. Results for the assessment of particle classification processes are presented in Table 15. All of these processes have been demonstrated, primarily in the mining and mineral-processing industry. Some have been applied to dredged sand and gravel deposits to separate various products. Hydrocyclones have been demonstrated for dredged material (Van Der Burgt 1985, as cited in Cullinane et al. 1986). Confined disposal facilities that receive hydraulically dredged material often serve the purpose of impoundment basins, which remove coarse material at the upstream end near the pipeline inlet and

allow the fine material to be deposited toward the downstream end of the CDF. The Duluth-Superior CDF effected particle classification and recovered sand that was used for road construction. The processes listed represent generic equipment available from a variety of sources.

83. Effectiveness of each of these processes is dependent on the characteristics of the feed material and is difficult to quantify. The distribution of contaminants with respect to particle size determines the benefits of particle classification. Table 15 rates the well proven and reliable processes slightly ahead of the more unusual processes, such as heavy media separation. Grizzlies are designed to remove only coarse material, but this may be an important pretreatment process for the removal of cobbles and debris that can interfere with other operations or processes. Implementation of most of these options for hydraulically dredged material is rated as a 2 because they cannot easily accommodate the volume, flow variability, and solids loading for many contaminated sediment problems. Mechanically dredged material may easily blind sieves and screens and is not appropriate for the processes designed for slurries. Particle size reduction may be necessary when feeding high-technology treatment processes. Costs for these processes depend on material characteristics. The dynamic processes are expected to cost substantially more than the processes that have few moving parts. If the processes could recover a usable product such as clean sand, net costs could be reduced. Most of these processes could be applicable for specific sites and sediment characteristics or to meet the pretreatment requirements of certain treatment processes. Additions of chemical flocculants in combination with processes such as flotation offer a high potential for contaminant removal.

Slurry injection

84. Slurry injection is included as a separate technology type to point out the opportunity to take advantage of the mixing process available in the pipeline from a hydraulic dredge. The slurry injection options include the injection of chemicals or microorganisms into the dredged material slurry. These technologies are used as a pretreatment step either to add chemicals that condition the sediment for further treatment and/or accelerate the settling of the suspended solids or to provide nutrients or microbes that will enhance biodegradation of organics.

85. Results of assessment of slurry injection to facilitate pretreatment or treatment are presented in Table 16. Injection of polymers into a dredge pipeline has been demonstrated to produce improved settling of dredged

material slurry. Laboratory studies have shown that cationic polymers are more effective than anionic or nonionic polymers (Schroeder 1983), but optimum polymer selection should be evaluated on a site-specific basis (Wang and Chen 1977). Polymers are used more efficiently when added to CDF effluent as a secondary process rather than as a slurry treatment process (Schroeder 1983). Effectiveness is rated as a 2 for this process. Higher efficiencies for specific contaminants may be achieved using selective flocculation agents. Biological treatment systems often depend on adequate quantities of nutrients to support biological growth. If dredged material were nutrient deficient, it could be easily amended by injection of nutrients into the pipeline. Because most contaminated dredged materials have more than enough nutrients, this process option was not recommended in Table 16. Addition of seed microorganisms cultured to degrade a toxic material could also be accomplished by slurry injection. The cost of "super bugs" may add significantly to the cost of the process. Injection of microbes and nutrients is a conceptual idea because systems for biological treatment of large quantities of contaminated dredged material have not been demonstrated. If pilot-scale studies demonstrate the performance of biodegradation in a CDF-type environment, the ARCS program should consider a field application of the injection of microbes, since laboratory studies cannot easily simulate slurry injection.

Treatment Component

86. This section discusses the various treatment technologies available for the decontamination/detoxification of contaminated sediment. These processes are being marketed for application to contaminated wastes regulated under the Resource Conservation and Recovery Act and for remedial actions at Superfund sites with contaminated soils or sediment. Source materials for review of these processes include USEPA publications on hazardous waste technologies, reports published under the Superfund Innovative Technology Evaluation (SITE) program, feasibility studies for Superfund sites dealing with contaminated sediment, and publications dealing with remedial actions for Great Lakes sediments. Many of the process options are not stand-alone processes, but are components of a system that may involve multiple treatment processes to address multiple contaminant problems. Most of these processes also require one or more of the pretreatment processes discussed above. Technology types for the treatment component are listed below.

a. Biological.
b. Chemical.
c. Extraction.
d. Immobilization.
e. Radiant energy.
f. Thermal.

Process options for the treatment component are listed by technology type in Table 17.

Biological processes

87. Biological degradation technologies use bacteria, fungi, or enzymes to break down PCBs, pesticides, and other organic constituents into innocuous or less toxic compounds. The microorganisms may be indigenous microbes, conventional mutants, or recombinant DNA products. Laboratory tests using biodegradation often are reported as treating one contaminant in otherwise clean sediment. Such tests are unreliable when applied to sediments containing several contaminants, since toxic effects of the other contaminants may adversely affect the reliability and effectiveness of the treatment process. Biological degradation proceeds with slower reaction rates than thermal or chemical degradation, thus requiring treatment periods that may be longer than are feasible for dredged material (USAE District, Chicago (in preparation)).

88. Results of the assessment of biological processes are presented in Table 18. The concept of biodegradation of organic materials is fundamental knowledge in the waste treatment field. The state of development for the generic processes is indicated as "demonstrated" because they have been successfully applied to a variety of contaminated media problems. Laboratory-scale studies and limited field studies have been conducted for some of the proprietary processes, and research in this area is one of the most active topics for toxic waste treatment. Biodegradation processes have not been applied and evaluated for dredged material other than on a bench scale. Several of the conceptual processes are proprietary processes that may be available on a pilot scale, and new vendors continue to enter this market.

89. The highest rating for effectiveness of these processes is a 3, because it is doubtful that 99-percent destruction can be achieved by biological processes. Because of the dependence of biological processes on carefully maintained environmental conditions, reliability of these processes is questionable. Implementability for most of these processes is difficult because of the developmental nature of these processes for contaminated sediment and

because of long time periods and large systems that will likely be required for treatment of contaminated sediment. Costs for implementation of these systems for dredged material are not well documented, because they have not been widely applied on a large scale. One bioreacter process, Bio-Clean, which is being considered for the Hudson River (Sanders 1989), is estimated to cost $130 to $270 per cubic yard. A potentially lower cost would be incurred if biodegradation can be conducted in a CDF. The composite scores for these processes range from 6 to 9. The ARCS program should consider the more generic type processes that have the highest composite rating (9).

Chemical processes

90. Chemical treatment technologies use chelating agents, bond cleavage, acid or base addition, chlorine displacement, oxidation, or reduction in the destruction, detoxification, or removal of contaminants found in contaminated media. Few of these technologies have been used for treatment of organic and heavy metal contaminants in sediment. Chemical treatment technologies considered include chelation, chemical hydrolysis, detoxification, nucleophilic substitution, oxidation of metals and organics, reduction of metals and organics, and thionation.

91. Results of the evaluation of chemical technologies is presented in Table 20. Most of these processes have been used in the chemical industry where a limited number of chemical compounds are involved or where the medium to be treated is primarily water. For contaminated sediments, identification of a particular chemical reaction that treats a specific contaminant is difficult. The objective of chemical processes, such as chelation, hydrolysis, oxidation, or reduction, is to change the form of a toxic material in order to render it less toxic or to change its solubility, stability, separability, or other properties affecting handling or disposal (USEPA 1987). Often a reaction that treats one contaminant increases the mobility of others. Chelation may be used in solution mining for removal of metals or may form metal complexes that resist mobilization, depending on the chelating agent selected. Detoxification is a generic process that covers development of contaminant-specific chemical reactions for a specific waste problem.

92. Several of the processes have been evaluated in the laboratory for soils, but the only option in Table 19 that has been evaluated on a field scale is nucleophilic substitution. The USEPA developed a nucleophilic substitution process that uses alkali metal polyethylene glycol to dechlorinate PCBs. Several modifications for this process have been developed, and a pilot

demonstration for PCB-contaminated soil has been completed demonstrating 99.999-percent reduction of PCBs at a cost of $200 per ton (Chan, Kornel, and Rogers 1989). The process has also been tested on a lab scale for PCB sediment from New Bedford Harbor, Massachusetts. Because of the limited application, complexity, and expense of other chemical processes, nucleophilic substitution is the primary chemical treatment process retained for further consideration. Oxidation of organics and chelation may be considered as other alternatives for further development.

93. Implementability for chemical processes is difficult because of materials handling and process control requirements that have not been fully demonstrated for application to dredged material. Costs for these processes have not been reported and are difficult to quantify, but they are expected to exceed $100/cubic yard.

Extraction processes

94. Extraction is the removal of contaminants from a medium by dissolution in a fluid that is later recovered and treated. Soil flushing and soil washing are other terms that are used to describe extraction processes for hazardous waste treatment. Soil flushing usually denotes an in situ treatment process whereby the extractant solvents are passed through the soils using an injection/recirculation process. Soil washing involves excavation of the soil and treatment in tanks, reactors, or other vessels (USEPA 1987). Extraction processes can be selected for removal of organics or inorganics, but seldom are both classes of compounds removed by the same fluid. Extraction fluids include water, acids, bases, complexing and chelating agents, surfactants, kerosene, methanol, ethanol, isopropanol, furfural, dimethylformamide, toluene, dimethyl sulfoxide, ethylene diamine, freon mixtures, and carbon dioxide or propane at supercritical conditions. A key element of an extraction process is the ability to separate the contaminant from the solvent so that the solvent can be recovered for reuse in the process. Also important is the toxicity of the solvent. Most processes require multiple extraction cycles to achieve high removal efficiencies. Follow-on treatment processes are required to treat or dispose of the concentrated contaminant stream.

95. Extraction processes are being actively developed for removal of contaminants from soils. Table 20 lists the process options evaluated for this study. The B.E.S.T. (Best Extraction Sludge Treatment), BioTrol, CF Systems (propane), in situ vacuum extraction, and in situ steam/air stripping processes are being evaluated under the USEPA SITE program. The CF Systems

process was evaluated in a pilot test for New Bedford Harbor where 90-percent PCB removal efficiency was achieved at a cost of $148 per ton (USEPA 1989a). The B.E.S.T. process has been evaluated on a bench scale for Indiana Harbor and New Bedford Harbor sediments. The PCB removal efficiency for the New Bedford sediment was greater than 99 percent (Allen and Ikalainen 1988); PCB removal efficiency for the Indiana Harbor sediment was greater than 90 percent with a 0.5-ppm residual (USAE District, Chicago (in preparation)). The low-energy (acetone/kerosene) process was evaluated for sediments from Waukegan Harbor on a laboratory scale. Acid leaching is used in industry to extract metals from solids, but implementing this process for large volumes of dredged material containing organic materials may generate wastewater streams that complicate the remediation project. Acid leaching, B.E.S.T., CF Systems, low-energy, and surfactant processes are recommended for further consideration by the ARCS program. Acid leaching was retained because of the limited availability of other processes for removing heavy metals from sediment.

96. Implementability for most of these processes is difficult because of the lack of full-scale development for handling sediment and the problems of solvent recovery and potential toxicity of residual solvents. Costs are not well documented, but are expected to exceed $100/cubic yard.

Immobilization technologies

97. Immobilization technologies, as discussed in this report, are defined as technologies that limit mobility of contaminants for sediment placed in a confined site or disposal area. The environmental pathway most affected by these processes is transport of contaminants in leachate to groundwater or surface water. Most of the immobilization processes listed in Table 21 fall into the category of solidification/stabilization (S/S) processes. The objectives of S/S are generally to improve the handling and physical characteristics of the material, decrease the surface area of the sediment mass across which transfer or loss of contaminants can occur, and/or limit the solubility of contaminants by pH adjustment or sorption phenomena (Cullinane, Jones, and Malone 1986).

98. Much of the development work for S/S came out of the nuclear industry where the goal was solidification of radioactive waste. However, requirements for control of toxic contaminants have resulted in application of S/S processes to a wide range of disposal problems. Because heavy metal contaminants cannot be destroyed and because extraction of heavy metals from soils is a complex process, S/S is often selected for remedial actions involving heavy

metal contamination. Solidification/stabilization can also be effective for some organics. Binding of the free liquid in dredged material by S/S processes can reduce contaminant loss by minimizing the volume of leachate leaving the site. Because of limited understanding of the physical and chemical mechanisms for immobilization of contaminants by S/S processes, selection of process options and formulations is based on laboratory treatability studies of the specific material to be treated and selected S/S processes.

99. All of the common S/S processes listed in Table 21 have been demonstrated on a pilot or full scale for contaminated soils problems. The S/S technology is also applicable in the treatment of solid residues from treated dredged materials. The USEPA SITE program in 1988 included seven S/S process options (USEPA 1988b). Bench-scale evaluations of S/S have been performed on a number of contaminated sediments for lime-based pozzolan, Portland cement-based pozzolan, silicate compounds, and proprietary processes. Sites evaluated include Indiana Harbor (Environmental Laboratory 1987), New Bedford Harbor (Myers and Zappi 1989), Everett Bay (Palermo et al. 1989), and the Marathon Battery Superfund site. Full-scale application of S/S processes to sediment is limited to application of proprietary processes in Japan (Sil-B) and for the Chesapeake Bay (Trident/Firmix). The selected remedy for the Marathon Battery Superfund site, which involved sediment contaminated with nickel and cadmium, was to excavate the sediment, solidify/stabilize the material, and place the product in a landfill. Ground freezing is a conceptual process that requires significant maintenance and is inappropriate for contaminated sediment. Macroencapsulation and thermoplastic microencapsulation are energy-intensive processes that can be considered for small volumes, but are difficult and expensive to implement for contaminated sediment. The remaining S/S processes should be considered for the ARCS program. In situ S/S is listed as a separate process option, but it actually is an option for implementation of the other S/S processes in lieu of mixing sediment and reagents in a batch or continuous mixing plant. Rather than mixing reagents and dredged material in a mechanical facility, the reagents are injected and/or mixed with the dredged material within a disposal area or within a scow during transport of dredged material to a disposal area. The S/S processing can be performed either immediately after excavation or following consolidation and dewatering in a disposal area.

100. Effectiveness of S/S processes is usually evaluated in terms of reduction of leaching potential. Reductions are process and contaminant

specific with immobilization of some contaminants accompanied by increased mobility of other contaminants (Myers and Zappi 1989). Implementability for most of these processes was rated better than chemical or extraction processes because they are not as sensitive to process control conditions. The opportunity for in situ S/S within a CDF is also an advantage. Costs for these processes are generally less than $100/cu yd. The S/S process options recommended for ARCS are chloranan encapsulation, in situ processes, lime-based pozzolan, cement-based pozzolan, proprietary processes, and sorption processes.

Radiant energy processes

101. Radiant energy processes use either simulated or natural radiant energy (ultraviolet light, UV) in the photodegradation of organic contaminants in sediment. Since UV light cannot penetrate sediment or opaque solutions, the contaminants must first be extracted from the sediment and then subjected to the UV irradiation. Two processes that have integrated the extraction step and the UV destruction step are the light activated reduction of chemicals (LARC) and the Ozonics ultrasonics/hydrogen-ozone/UV processes. LARC uses isopropanol for extraction, and ultrasonics uses ultrasound above 20 kHz. Wilson (1987) indicated that the LARC process was not being further developed by its proprietor, and performance of the Ozonics process for treating contaminated sediment was unknown. Photolysis is also listed as a generic process for destruction of organic compounds because a number of other combinations of extractants and reducing agents in combination with UV light are possible. Ratings for these processes are shown in Table 22. Because of the unproven field-scale performance and the development nature of these processes, their implementability was rated at the bottom of the scale, and they are not recommended for evaluation under the ARCS program.

Thermal processes

102. Processes included in this report under the thermal technology type are incineration processes, pyrolytic processes, vitrification processes, supercritical and wet air oxidation, and other processes that require heating the sediment several hundreds or thousands of degrees above the ambient temperature. The processes evaluated are listed in Table 23. These processes are generally the more effective options for destroying organic contaminants, but they are also the more expensive.

103. A number of alternative incineration processes are available: fluidized bed, circulating bed combustor, high-temperature slagging, infrared

(Shirco), molten salt, multiple hearth, plasma arc, Pyretron, and rotary kiln. Fluidized bed and rotary kiln are the more widely available processes and have been used to treat hazardous materials. Pyretron, Shirco, and circulating bed combustor are being evaluated under the SITE program for hazardous wastes. Incinerators have not been applied to contaminated dredged material to date, but they have been selected for remediation of several Superfund sites involving contaminated sediment. Incinerators typically achieve destruction/removal efficiencies greater than 99 percent for organic contaminants. Heavy metals in incinerated materials generally pass through the process, except that some of the more volatile metals, such as lead and mercury, can volatilize from the higher temperature processes, requiring removal from the flue gas and subsequent treatment or disposal. The oxidation state of some metals originally in the sediment may change during incineration and become more mobile in the ash than they were in the sediment. Sediments containing high concentrations of fine-grain particulates produce high particulate loadings in the flue gases. Dredged material may require particle size reduction prior to feeding most of these incineration processes. Implementability of incineration processes is difficult because of long and tedious permitting requirements when used for hazardous materials and because of poor community acceptance of incineration processes. Reported costs for incineration vary widely. Carpenter (1986) estimated incineration costs as $1,300/cu yd; the USAE District, Chicago (in preparation), estimated incineration to cost $200/cu yd for rotary kiln incineration of a large volume of Indiana Harbor sediment. The low fuel value and high water content of sediment contributes to the increased costs of incineration for sediment. In general, incineration processes fall into the most expensive category of processes (rating = 1). However, rotary kiln and circulating bed combustors will be retained because of the need to gain operational experience with incineration processes for contaminated sediments. Five other incineration options are indicated in Table 23 as a second, more expensive tier for consideration by ARCS.

104. The other large subset of the processes listed in Table 23 is the pyrolysis or vitrification option. In contrast to incineration, pyrolysis involves heating the material in the absence of oxygen. Volatile materials are driven off and collected or destroyed by secondary processes, and metals, salts, and other nonvolatile materials melt into molten glass. Vitrification processes use high-voltage graphite electrodes to provide the primary heat source. Molten material exiting these processes cools into a solid glasslike

material that will not measurably leach organic or inorganic contaminants. Pyrolysis systems are available from a number of commercial sources, but vitrification is a relatively new concept that has not been widely applied because of the high energy costs and consumable electrodes (Wilson 1987). The high water contents of sediment contribute to increased costs. Battelle has developed an in situ vitrification process where the electrodes are inserted into the soil or sediment, and off gases are captured by an enclosure over the surface of the soil. A bench-scale evaluation of in situ vitrification for the New Bedford Harbor sediment confirmed that greater than 99-percent efficiency of PCB destruction could be achieved at a cost of $290 to $330 per ton (Reimus 1988). The cost for pyrolysis and vitrification options eliminates them for the first tier recommendation. However, because of their effectiveness and potential for treating sediments, they are included the second tier (II) of process options for evaluation by ARCS.

105. Other process options in Table 23 that use lower temperatures are Eco Logic, low-temperature thermal stripping, Taciuk, supercritical water oxidation, radio frequency heating, and wet air oxidation. EcoLogic relies on heating the sediment in the presence of hydrogen or another reducing agent to dechlorinate organic contaminants. A field test for this process is scheduled to take place in 1990 for a harbor project for the Canadian Department of Defense. Low-temperature thermal stripping is a process for removal of more volatile organic compounds. Units from at least two manufacturers are available. For applicable contaminants, relatively high removal efficiencies can be achieved. High moisture content increases the cost of the process. The Taciuk process, using higher temperatures, is reported to be effective for stripping PCBs from sediment and has been selected as a component of the Superfund remediation efforts at Waukegan Harbor. Supercritical water oxidation uses temperature and pressure for the supercritical state of water and oxygen to oxidize organics. The absence of air emissions is an advantage of this process (USAE District, Chicago (in preparation)). Large-scale units or long-term continuous operations for this process have not been demonstrated (USEPA 1987). Capital and operating costs are expected to be very high. Wet air oxidation uses lower temperatures and pressures than supercritical water oxidation. This process has been widely used for municipal sludge treatment. However, destruction of highly chlorinated materials, such as PCBs, is less efficient than the more aggressive processes. Bench-scale testing of wet air oxidation for Indiana Harbor sediments indicated a 52-percent removal

efficiency for PCBs (USAE District, Chicago (in preparation)). Radio frequency heating is a conceptual process for which limited information is available.

106. Table 23 shows that four of the lower temperature thermal processes should be further considered initially by ARCS: Eco Logic, low-temperature thermal stripping, Taciuk, and wet air oxidation. These processes were selected by the rating procedure because they may be implemented at a lower cost than incineration processes.

Disposal Component

107. The disposal component of a remedial action provides for long-term containment of contaminated dredged material or for containment or beneficial use of residual, relatively clean solids produced during pretreatment or treatment of contaminated dredged material. Technology types and process options for this component are presented in Table 24. The three types are beneficial use, confined disposal, and open-water disposal. Beneficial use and open-water disposal options will generally be considered as a secondary process for residuals from primary treatment processes or for less contaminated materials. Process options for confined disposal and landfilling may be used alone following removal and transport to contain contaminated dredged material, or may follow treatment or pretreatment processes.

Beneficial use

108. Beneficial use is generally encouraged for noncontaminated or moderately contaminated sediments dredged for navigation. Examples of beneficial uses for dredged material are listed in Table 25. Many of these beneficial uses may be applicable to sediments treated or processed by the above technologies. However, many of these uses could accommodate moderate contaminant loads without impairment of the use compared to the impairments caused by sediments in waterways. Beneficial uses most sensitive to contaminants are those that involve active contact, either by the public, plants, or animals, with the sediment--agriculture, horticulture, and forestry; aquaculture; beach nourishment; and habitat development. The other uses in Table 25 generally use sediment as fill material, which can be covered or capped to prevent direct contact with the contaminants. These techniques can also be considered for the residuals from treatment processes, but physical and chemical changes

or residual extraction fluids may impair potential uses such as agriculture or aquaculture.

109. Rating these processes is difficult because of the differences in objectives for different sediment or residual types and the site-specific nature for some of these uses. Table 25 shows that ratings for effectiveness and cost were assigned the same number for all of the uses. In some cases the expense of the activity may be offset by income from the developed use. The factor that is most distinguishable for the beneficial use options is implementability. Port facilities, commercial facilities, beach nourishment, aquaculture, and habitat development are easier to implement because of the proximity and availability of such uses to the waterways. Port and commercial construction were rated higher because the material is usually isolated from direct contact with plants and animals. Other uses are often long distances from the site and often require dewatering for transport and use. However, none of these uses should be arbitrarily ruled out as a disposal option for contaminated sediment or residuals.

Confined disposal

110. The most widely used disposal option for dredged material is a confined disposal facility. Confined disposal facilities are engineered structures designed to retain dredged material solids, and in the case of hydraulic dredging, to provide acceptable suspended solids concentrations for discharges to receiving waters. (See paragraph 78 for discussion of CDFs as a pretreatment technology type.) In 1970, Congress authorized the Corps of Engineers to construct, operate, and maintain CDFs for the disposal of contaminated dredged material from authorized commercial navigation projects. Twenty-seven CDFs have been constructed around the Great Lakes by the Corps of Engineers under this authority. CDFs are used for the disposal of about half of the sediments dredged from Great Lakes harbors and waterways.

111. Confined disposal facilities may be located entirely upland above the water table, partially in-water adjacent to the shore, or completely surrounded by water. The principal design criterion of CDFs has been to retain as high a percentage of the fine-grained sediment particles as practicable. This principle was based on the findings of the Dredged Material Research Program, which demonstrated that most chemical contaminants associated with sediments could be effectively contained through efficient solids containment. Since most contaminants in sediment remain attached to solid particles during dredging and placement in the CDF, this process is reasonably efficient for

containment of contaminants. Contaminants are potentially lost via effluent, leachate through the bottom of the CDF, seepage through the CDF dikes, volatilization to the air, and uptake by plants and animals living or feeding in the CDF. A number of control measures are available to minimize impacts of losses by these pathways. A management strategy (Francingues 1985) has been developed by the Corps that identifies standardized testing procedures for dredged materials to determine appropriate disposal controls.

112. A CDF is neither a conventional wastewater treatment facility nor a conventional solid waste disposal facility. What makes it different are the physical and chemical properties of the waste stream. Wastewater treatment facilities are designed to receive water with low levels of solids. Solid waste facilities are designed to receive solids with very little water. Dredged sediments typically contain 10 to 50 percent solids. An effective CDF must borrow features from both the wastewater treatment facility and the solid waste disposal facility in a combination that is unlike either.

113. Wastewater treatment controls that may be applied at a CDF are discussed for the Effluent/Leachate Treatment Component (paragraphs 128-129). Controls similar to those used for solid waste disposal facilities that may be applied at a CDF are listed in Table 26. All of these controls have been applied or proposed at one or more CDFs on the Great Lakes. The implementability and effectiveness of these controls is highly specific to the CDF location and the sediment characteristics.

114. The implementability of controls such as subsurface barriers (liners or slurry walls), groundwater pumping, and subsurface drainage is practical for upland CDFs but limited for in-water CDFs. The low permeability of fine-grained sediments following compaction can reduce the need for subsurface barriers in many cases, but it can also limit the effectiveness and implementability of groundwater pumping and subsurface drainage controls.

115. A cover or cap can be highly effective in reducing leachate generation by avoiding rainfall infiltration, isolation from bioturbation and uptake by plants and animals, sequestering of volatilization of contaminants from the surface, and eliminating the detachment and transport of contaminants by rainfall and runoff. A layer of clean material can achieve the last three benefits mentioned. However, prevention of infiltration requires a barrier of very low permeability, such as a flexible membrane or a compacted clay layer, both of which are more difficult to implement for any disposal facility. Other leachate control measures include groundwater pumping, liners,

subsurface drainage, slurry walls, and surface drainage. Liners are used for land disposal of regulated hazardous wastes, but have not been used for less contaminated dredged material because of the inherent low permeability of fine-grain dredged material, the retention of contaminants on solids, and the difficulty and expense of constructing a reliable liner system for wet dredged material, particularly for in-water or nearshore sites. Leachate collection techniques, such as groundwater pumping and subsurface drainage, have been evaluated in a limited number of situations, but these techniques appear to have limited feasibility for in-water sites. Slurry walls can be used to provide barriers to leachate movement from a CDF. To be effective, the barrier should tie in to a geologic formation with very low permeability.

116. Operational techniques for CDFs include management of the site during and after disposal operations. Mobilization of contaminants from dredged material can be affected by the oxidation state of the solids. In sulfurous marine sediments, most metals are much less mobile when maintained in an anaerobic reduced condition. On the other hand, aerobic sediments generally offer improved conditions for biodegradation of organic contaminants. Aerobic sediments generally present the greatest potential for volatilization of contaminants (Thibodeaux 1989). Ponded conditions that normally exist in in- water CDFs can limit volatile loss. Maintaining ponded water on the site produces a hydraulic gradient that increases the potential for movement of leachate through the site. Whether to cultivate or inhibit plant and animal propagation is also an issue. Management of the site both during and after disposal requires evaluation of numerous trade-offs for the site and contaminant-specific conditions for each project.

117. For almost every sediment remediation plan (except the no-action and nonremoval alternatives), a CDF (or equivalent) will be a necessary component because economical dredging operations have far greater capacities than most available pretreatment or treatment options. For a sediment remediation plan, a CDF can be considered as a secure area where one or more components of the remediation plan, including pretreatment, treatment, effluent/leachate treatment, and sediment or treated residue disposal, are conducted. In this case, which differs from the conventional perception of a CDF, the environmental controls at the CDF must be specific to the remediation components employed. For this reason, all of the control options identified are recommended for evaluation by the ARCS program. It must be recognized that use of capping, operational techniques, and/or surface drainage controls will be

cheaper than the options for treatment of contaminated sediment and will also provide greater containment efficiency than many of the treatment options. A multilayered liner system is the most costly of these controls. A double membrane liner system for a 100,000-cu yd upland CDF proposed for New Bedford sediment increased the disposal cost by $13/cu yd (Averett et al. 1989). Installation of a compacted clay liner system would cost much more. Lining an in-water CDF would also cost more compare to an upland site and would be very difficult to implement.

118. Sanitary landfills are generally designed for disposal of solid waste from residential and commercial sources and may be appropriate for cleaner dredged material or for treated residuals. Beneficial use of the dredged material as cover material improves the chances for acceptance in sanitary landfills, where capacity is often limited. Solid wastes that meet the definition of hazardous wastes under the Resource Conservation and Recovery Act and that are approved for land disposal must be disposed of in a landfill constructed and operated according to more stringent RCRA standards, which include double liners and a leachate collection system. Although dredged materials are not defined as hazardous wastes, the contaminants present may limit disposal in conventional (sanitary) landfills, thereby requiring consideration of RCRA facilities as a landfill option. Sediments with PCB concentration greater than 50 ppm are regulated by the Toxic Substances Control Act (TSCA) and must be disposed in an appropriately regulated facility. These facilities must have appropriate State and/or Federal permits. The offsite landfill facilities evaluated are listed in Table 26.

119. Effectiveness of offsite landfills is good for conventional landfills and excellent for RCRA and TSCA facilities. Implementability is reduced by the requirement to dewater or solidify the material and by the limited availability of sites. Disposal in TSCA or RCRA facilities is a costly alternative. However, for small volumes of highly contaminated materials, RCRA facilities may be a viable option. Where PCB concentration exceeds 50 ppm, TSCA requires that existing TSCA facilities be considered.

Open-water disposal

120. About half of the sediments dredged from the Great Lakes are determined to be noncontaminated and are disposed unconfined in open water. However, open-water disposal of contaminated sediments in the Great Lakes is prohibited. In the last 5 years, methods to limit the mobility of pollutants in contaminated sediments disposed by open-water methods have been

demonstrated and employed on the east and west coasts. Applications of capping on the Great Lakes have been limited. Therefore, this section focuses on engineered options for open-water disposal of moderately contaminated dredged material and residual solids from treatment or pretreatment processes. This section addresses removal, transport, and placement of the contaminated material followed by clean sediment capping. In situ capping is discussed under nonremoval technologies.

121. The long-term environmental effects associated with open-water disposal of contaminated sediments can be controlled by covering or encapsulating the contaminated sediment with clean dredged material or fill. By returning contaminated sediment to the waterway, stable geochemical and geohydrologic conditions are maintained in the sediment, minimizing release of contaminants to surface water, groundwater, and air. Placement of a clean cap or cover on top of the contaminated sediment minimizes diffusion and convection of contaminants into the water column and prevents bioturbation or uptake by aquatic organisms.

122. Capping has been demonstrated as a technology for disposal of contaminated sediments in marine waters. The Marine Board (1989) concluded that capping of contaminated sediments "offers a promising means of effectively isolating and containing associated contaminants." Morton (1989) described controls and monitoring of capping projects in deep marine waters and concluded that capping is a feasible mitigation measure for the marine environment. Capping was also demonstrated for contaminated sediments in the Duwamish Waterway (Truitt 1986). Capping of contaminated sediment in shallow water was selected as a remedy for the St. Paul Waterway Remedial Action and Habitat Restoration Project because it created few adverse impacts and provided greater environmental benefits than other remedial action alternatives (Ficklin, Weitkamp, and Weiner 1989). The contained aquatic disposal option is an alternate method for shallow sites, where the disposal site is first excavated to construct a hole for placement and subsequent capping of the contaminated sediment. This option has been demonstrated for contaminated sediment in Rotterdam Harbor and was piloted for the New Bedford Superfund Pilot Study (USAE Division, New England 1989). A contained aquatic disposal alternative for Indiana Harbor was evaluated in Environmental Laboratory (1987).

123. The effectiveness, implementability, and cost for capping suggest that this process option be considered by ARCS for cleaner materials and residuals from treatment or pretreatment processes. To reduce short-term

effects on the water column during open-water disposal, hydraulically dredged material may be discharged below the surface using a gravity downpipe or submerged diffuser. Such equipment not only reduces effects on the upper water column, but it also assists in accurate placement of the contaminated material and the cap in the disposal site. Site selection is also included as an option for consideration because the characteristics of the site are important to the design of the project and potential environmental impacts.

124. All of the control techniques listed in Table 27 are recommended for consideration under the ARCS for remediation of contaminated sediments in the Great Lakes. Although these techniques may not be suitable for highly contaminated sediments, they represent effective disposal options for many AOC sediments or process residuals and should not be overlooked in developing remedial action plans. They rate highly because of ease of implementation, lack of upland requirements, comparatively low cost, and highly effective contaminant containment efficiency. The principal disadvantages for the open-water disposal options are the concern for impacts on ecosystems at the disposal site, long-term stability and effectiveness of the cap, and the complications that may occur if remediation of the disposal site should be required in the future.

Effluent/Leachate Treatment Component

125. The objective of effluent or leachate treatment is to remove residual contaminants from the liquids produced as discharges from an active CDF, surface runoff from a CDF, leachate from a CDF, effluent from dewatering processes, or effluent from treatment processes. Contaminants in these streams will be present in a wide range of concentrations depending on their source, and individual sources are often highly variable in terms of concentrations and flows. Most of the contaminants for these streams are associated with suspended solids and will be removed by effective suspended solids removal. Another characteristic of these streams is their "mixed bag" of contaminants, both organic and inorganic, and conventional as well as potentially toxic contaminants. These characteristics may require more than one treatment process. Commonly used industrial wastewater treatment processes are available to achieve effluent limits for most contaminants. However, applications of treatment processes for dredged material effluents have been generally

limited to removal of suspended solids and contaminants associated with these particulates.

126. Three treatment technology types are defined for this component: metals removal processes, organic treatment processes, and suspended solids removal processes. Many of these processes concentrate contaminants into another medium, which must also be treated or disposed. Table 28 lists the process options considered for evaluation. The process descriptions provided in Appendix A and the following discussion focus on suspended solids, toxic organics, and heavy metals. Conventional contaminants, such as nutrients, ammonia, oxygen-demanding materials, and oil and grease, may also be a concern for dredged material effluents. Most of the processes for dissolved organics removal are suitable for these contaminants. Costs for these processes in terms of dollars per cubic yard are difficult to estimate because of the impact of water volume associated with volume of sediment removed and the unknown contaminant concentrations.

Suspended solids removal

127. Suspended solids removal is the most important effluent treatment technology because it offers the greatest benefits in improving effluent quality, not only by reducing turbidity but by removing particulate-associated contaminants. Suspended solids removal processes differ from dewatering processes discussed under pretreatment because for this application the solids concentration is much lower than for a dredged material slurry. Settling mechanisms for these streams are characterized by flocculent rather than zone or compression settling. For CDF effluent treatment, the solids remaining will be clay or colloidal-size material that may require flocculants to promote further settling in clarifiers or sedimentation ponds. Chemical clarification using organic polyelectrolytes has been demonstrated for CDF effluent (Schroeder 1983). Filter dikes, permeable dikes, and sand-filled weirs or cells have been applied full scale at a number of CDFs on the Great Lakes to remove suspended particulates. These processes should be considered for field demonstrations as a component of an overall remedial action. Suspended solids removal technologies for the effluent/leachate component are evaluated in Table 29. With the exception of clarifiers and ultrafiltration, the process options in Table 29 have acceptable effectiveness, implementability, and costs for application under the ARCS program.

Metals removal

128. Metal removal processes are evaluated in Table 30. Most of these processes are commonly used for industrial wastewater treatment. Processes that are developmental and less likely choices are biological ion exchange, electrocoagulation, and ultrafiltration. Flocculation is effective for removal of metals associated with particulate matter. Polymers and inorganic flocculants have been demonstrated to be effective for removal of suspended solids from dredging effluents, but removal of dissolved heavy metals has not been evaluated in field applications. Ion exchange and precipitation are probably two of the more efficient metals removal processes, but they must generally be designed for specific metals and often require major investments in operational control for efficient operation. Use of natural or manmade wetlands is a relatively new concept for retention of heavy metals and other contaminants from effluents, which could represent a viable option for some sites and contaminants. Flocculation/coagulation, ion exchange, permeable treatment beds, precipitation, and wetlands are the more highly rated options for effectiveness, implementability, and cost and are recommended for consideration by ARCS.

Organic treatment

129. A long list of process options for treatment of dissolved organic contaminants is presented in Table 31. The applicability and effectiveness of these options are greatly dependent on concentration and flow rate of the effluent. Mechanical biological wastewater treatment processes were eliminated because it is doubtful that sufficient organic matter would be available to support biological growth and because operation of biological systems under the conditions of fluctuating flows and extremes of temperature would be difficult. Biological processes such as nitrification, nutrient catabolism, and photosynthesis are important degradation mechanisms for nutrients, oxygen-demanding materials, and other organics in confined disposal facilities. The principal process for dissolved refractory organic contaminants that has been applied to dredged material effluent is carbon adsorption, which was applied to a PCB spill on the Duwamish Waterway in the 1970s (Hand et al. 1978). Air and steam stripping could be used for volatile contaminants, but these are generally not a problem for contaminants originating in sediment. Ultraviolet oxidation and ozonation processes offer destruction of organic contaminants, are being extensively investigated in the field for a wide range of contaminants, and should be considered for evaluation under ARCS. Wetlands also

offer potential for retention and degradation of organic contaminants and should be considered for remediation of contaminated sediments.

130. Table 31 presents the ratings for organic treatment processes applicable to effluent and leachate. The more effective process options are carbon adsorption; oxidation processes including ozonation, UV/hydrogen peroxide, and UV/ozone; oil separation; powdered activated carbon treatment (PACT); resin adsorption; steam stripping; and wetlands. All of these processes could be implemented for contaminated sediment projects. Reverse osmosis, steam stripping, and PACT were screened out because of higher costs. The other more effective processes are recommended for consideration by ARCS.

Nonremoval Alternative

131. Technologies for a nonremoval alternative are considered briefly. However, the options available for remediating contaminated sediment in place are limited because of potential impacts to the water column and aquatic biota during implementation and because in situ implementation for most of the treatment options in situ is unproven. Four categories are considered for nonremoval: containment, treatment, no action, and restricted use. Although the latter two are not actual technologies, they are included to indicate that certain actions should be considered even if remedial action is not taken. CERCLA projects require evaluation of the no-action alternative. Options considered for these four categories are given in Table 32.

Containment

132. Containment options considered for remediation of in situ sediment are clean sediment capping, Armorform, geomembrane capping, and structural isolation. Capping as a control measure for contaminated dredged material has been widely practiced and evaluated, particularly on the East Coast. In contrast to the capping option discussed as an open-water disposal option, in situ capping does not involve removing the contaminated sediment from its existing location. This option is effective, economical, and constructible. Implementation can be a problem where water depths are insufficient to place a cap and still maintain other uses of the waterway, or where hydrodynamic forces require armoring of the cap to maintain its stability. Armorform is a proprietary product that could be appropriate for small areas. Geomembrane capping is a poor choice because it is unreliable and difficult to implement. Structural isolation might include permanently closing off a portion of the

waterway, rerouting flow, or constructing a new channel. These options are rated in Table 33. Sediment capping, Armorform, and structural isolation should be considered for ARCS field demonstrations.

In situ treatment

133. Options for in situ treatment are evaluated in Table 34. In situ stabilization and grout injection are the only options for which field demonstrations for contaminated sediment were documented. Japanese researchers have reported applying the Sil-B solidification technology to in situ sediment. To do this, a box frame was driven into the river bottom, the water was excavated, and reagents were added and mixed with the sediment. The frame could be moved to adjacent areas to expand the treatment area. This concept of isolation of the bottom sediment from the water column during treatment could be performed with a number of treatment options, including other solidification/stabilization processes and perhaps certain extraction processes. Caissons or coffer dams are available to serve as the treatment chamber. Application of such an operation in the Great Lakes could develop this concept further and should be considered by ARCS. Anaerobic biodegradation under in situ conditions is being intensively investigated (Marine Board 1989) and should be considered by ARCS as an area where the potential for reducing remedial action costs is high.

No action

134. No action consists of leaving the contaminated sediment in place with the hopes that environmental degradation will not worsen until future remedial actions are feasible. Brannon et al. (1989) reviewed the impacts on water quality if contaminated sediments were left in place in Grand Calumet River/Indiana Harbor Canal. These investigators discussed the influence of contaminated sediment on sediment oxygen demand, equilibrium partitioning, and sediment resuspension and transport. In areas with highly contaminated sediment, no action will likely result in continued impairments to water quality. A monitoring program should be established to ensure that the rates of contaminant release and the area of influence of the contaminants are not accelerating. Table 35 indicates that ARCS should consider this option as a continuance of the assessment program currently under way for existing conditions.

Restricted use

135. Restricted-use options include fencing and warning signs, navigation relocation, and seasonal restrictions (Table 36). Fencing, warning

signs, and seasonal restrictions are aimed solely toward public health, where humans may contact the sediment directly or consume contaminated fish. Navigation relocation could reduce sediment resuspension created by ships or boats. This option is difficult to enforce and does not affect sediment and contaminant transport by other forces such as hydrodynamic effects.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

139. Process options for remediation of contaminated sediment in the Great Lakes were screened on the basis of status of development, availability, effectiveness, implementability, and costs. Several process options were retained for each technology type, and any of the technology types could be applicable to one or more AOCs. The top-rated process options for the technology types are shown in Figures 3-9. Obviously, there are many possible combinations of process options that can be incorporated into a remedial action plan. Few of these processes have been applied to contaminated sediment on a full scale. Most testing of the treatment technology process options for contaminated sediment have been performed on a bench scale, with limited pilot-scale applications. A database that would allow for design and development of performance and cost data for application of most of these processes to contaminated sediment is not available. Therefore, further testing and evaluation of these process options are justified to advance the technological data gaps that now exist for incorporation of these technologies into remedial action plans for contaminated sediment.

Recommendations

140. The process options identified in Figures 3-9 are recommended as candidates for addressing the objective for the ARCS program of evaluating and demonstrating remedial options for Great Lakes contaminated sediment (see Part I). Additional processes will likely surface during the course of the ARCS program, but these recommendations should provide adequate guidance for initial selection of processes for evaluation and/or demonstration. A strategy for selection of appropriate process options for various types of contaminated sediment situations should be developed. Included in this strategy will be identification of a number of process trains illustrating how the process options can fit together into a remedial action plan.

141. The next step is to plan for and implement demonstrations for the selected process options to the extent of financial and administrative constraints. The GLNPO has defined demonstrations as including bench-, pilot-, or full-scale evaluations or applications of remedial action technologies.

USEPA (1988a), in guidance for Superfund projects, described bench- and pilot-scale demonstrations as follows:

- a. Bench testing is usually performed in a laboratory using a small volume of material to define the individual parameters, particularly the chemical variables for treatment technologies, of a process option for the waste, in this case contaminated sediment. Laboratory testing on a small volume allows economical evaluation of the effects of a large number of process variables and waste characteristics on performance. "Care must be taken in attempting to predict the performance of full-scale processes on the basis of these tests."
- b. Pilot studies are intended to simulate the physical as well as chemical parameters of a full-scale process and are performed on a much larger scale than bench tests. The objective of pilot tests is to "bridge the gap between bench-level analyses and full-scale operation," and they "are intended to more accurately simulate the performance of the full-scale process." Pilot tests are sized to minimize the physical and geometric effects of test equipment on treatment performance and to simulate effects such as mixing, wall effects, generation of residues, etc.

The CERCLA guidance suggests that pilot studies are not required for well-developed technologies except when treating a new waste type or matrix that could affect the physical operating characteristics of a treatment unit. Pilot tests are also important where there is a need to evaluate secondary effects of the remedial actions, such as is the case with dredging or air emissions from treatment or disposal processes.

142. The SITE program is designed to accelerate the development, demonstration, and use of new or innovative technologies for cleaning up Superfund sites. Within this overall program, USEPA has identified a Demonstration Program and an Emerging Technologies Program. The Demonstration Program involves demonstration and evaluation of the technology on a field scale to provide engineering and cost data, whereas the Emerging Technologies Program tests and evaluates technologies from bench-scale through pilot-scale to assess basic feasibility of the process.

143. Many of the processes recommended for consideration in this report have been evaluated on a pilot scale for a limited number of sites with contaminated soils, but practically none for contaminated sediment. Material handling problems in field evaluations are often the downfall of promising treatment concepts. The only way to evaluate dredging techniques for removal operations is on a field scale using prototype dredging equipment. The ARCS program should set a goal to proceed to pilot scale with whatever technologies

are selected for evaluation. Pilot studies for most of the treatment processes will require initial bench-scale testing to plan and design the pilot study. The pilot study should evaluate as many of the pre- and post-treatment steps as are logistically and economically feasible.

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Table 1

Sediment Chemical and Physical Characteristics

Parameter	Average values, mg/kg				
	Ashtabula[1]	Buffalo[2]	G. Calumet[3]	Saginaw[4]	Sheboygan[5]
Arsenic	10	10	50	5	6
Cadmium	1	3	10	2	1
Chromium	20	80	400	30	20
Copper	30	100	200	20	20
Iron	30,000	40,000	100,000	9,000	10,000
Lead	20	200	800	50	20
Manganese	400	700	2,000		300
Mercury	0.1	2	0.7	0.1	0.1
Nickel	30	40	100	10	10
Silver			0.5		
Zinc	100	500	4,000	200	50
PCBs	2	3	9	1	300
PAHs	10	40	3,000		1
Pesticides, chlorin.		0.4			
Total organic carbon			400,000	30,000	
Oil and grease	700		60,000	2,000	
Cyanide	0.3		1		
Percent solids (weight)	60		50	60	
Percent volatile solids	4			3	
Percent fines (< No. 200)			70	30	
Approximate volume, cu yd			1,000,000		
In-place density, g/cu cm				2	

Note: Average values are based on limited data sets. This table is intended to present a general picture of the order of magnitude of concentrations for selected contaminants.

Sources: [1] US Army Engineer District, Buffalo
[2] Buffalo River RAP
[3] US Army Engineer District, Chicago
[4] US Army Engineer District, Detroit
[5] Blasland and Bouck Engineers 1988

Table 2

Process Options for the Removal Component

Turbidity Containment	Hydraulic Dredges	Mechanical Controls	Operational Controls
Caissons	Airlift	Backhoe	Cutter speed
Dikes	Clean-up system	Bucket ladder	Depth of cut
Oil booms	Cutterhead	Bucket wheel	Management of project operations
Pneumatic barriers	Delta	Clamshell	Positioning equipment
Sediment traps	Dustpan	Closed bucket clamshell	Swing speed/speed of advance
Sheet piling	Eddy pump	Dipper	Work boat controls
Silt curtains	Hand-held hydraulic	Dragline	
Silt screens	Hopper	Orange-peel	
	Horizontal auger		
	Matchbox suction head		
	Oozer pump		
	Pneuma pump		
	Refresher system		
	Suction		
	Waterless		

Table 3

Removal Component - Hydraulic Dredge

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Airlift	Demonstrated	Yes	Available	3	2	4	9	No
Clean-up system	Demonstrated	Yes	Foreign	4	1	3	8	No
Cutterhead	Demonstrated	Yes	Available	4	4	4	12	Yes
Delta	Demonstrated	Yes	Proprietary	3	3	4	10	Yes
Dustpan	Demonstrated	Yes	Limited	3	2	4	9	No
Eddy pump	Demonstrated	Yes	Proprietary	3	3	4	10	Yes
Hand-held hydraulic	Demonstrated	Yes	Available	3	3	4	10	Yes
Hopper	Demonstrated	Yes	Available	3	3	4	10	Yes
Horizontal auger	Demonstrated	Yes	Available	3	3	4	10	Yes
Matchbox suction head	Demonstrated	Yes	Proprietary	4	2	4	10	Yes
Oozer pump	Demonstrated	Yes	Foreign	4	1	3	8	No
Pneuma pump	Demonstrated	Yes	Proprietary	4	3	4	11	Yes
Refresher system	Demonstrated	Yes	Foreign	4	1	3	8	No
Suction	Demonstrated	Yes	Available	3	2	4	9	No
Waterless	Demonstrated	Yes	Proprietary	4	3	4	11	Yes

Table 4

Removal Component - Mechanical Dredge

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Backhoe	Demonstrated	Yes	Available	3	4	4	11	Yes
Bucket ladder	Demonstrated	Yes	Available	2	3	4	9	No
Bucket wheel	Demonstrated	Yes	Available	2	3	4	9	No
Clamshell	Demonstrated	Yes	Available	3	4	4	11	Yes
Closed-bucket clamshell	Demonstrated	Yes	Available	4	4	4	12	Yes
Dipper	Demonstrated	Yes	Available	2	3	4	9	No
Dragline	Demonstrated	Yes	Available	2	3	4	9	No
Orange-peel	Demonstrated	Yes	Available	2	3	4	9	No

Table 5

Removal Component - Operational Control

Process Option	State of Development	Applied to Dredged Material	Availability	Rating Effectiveness	Rating Implementability	Rating Costs	Rating Composite Score	Consider for ARCS Program
Cutter speed	Demonstrated	Yes	Available	2	4	4	10	Yes
Depth of cut	Demonstrated	Yes	Available	2	4	4	10	Yes
Management of project operations	Demonstrated	Yes	Available	2	4	4	10	Yes
Positioning equipment	Demonstrated	Yes	Available	2	4	4	10	Yes
Swing speed/speed of advance	Demonstrated	Yes	Available	2	4	4	10	Yes
Work boat controls	Demonstrated	Yes	Available	2	3	4	9	Yes

Table 6

Removal Component - Turbidity Containment

				Rating				
Process Option	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program
Caissons	Demonstrate	Yes	Available	3	2	1	6	No
Dikes	Demonstrated	Yes	Available	3	2	2	7	Yes
Oil booms	Demonstrated	Yes	Available	2	4	4	10	Yes
Pneumatic barriers	Demonstrated	Yes	Available	1	2	3	6	No
Sediment traps	Demonstrated	Yes	Available	2	3	4	9	Yes
Sheet piling	Demonstrated	Yes	Available	3	2	2	7	Yes
Silt curtains	Demonstrated	Yes	Available	2	3	4	9	Yes
Silt screens	Demonstrated	Yes	Available	2	3	4	9	Yes

Table 7

Process Options for the Transport Component

Barge/Scow Controls	Hopper Dredge Controls	Pipeline Controls	Rail Controls	Truck Controls
Barge selection	Hopper selection	Decontamination	Car selection	Decontamination
Decontamination	Decontamination	Leak detection	Decontamination	Loading/unloading
Loading/unloading	Loading/unloading	Pipeline routing	Loading/unloading	Route selection
Route/navigation	Route/navigation	Pipeline selection	Route selection	Truck selection
		Pump controls		
		Redundancy of safety devices		

Table 8

Transport Component - Barge/Scow Control

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Barge selection	Demonstrated	Yes	Available	4	3	3	10	Yes
Decontamination	Demonstrated	Yes	Available	3	2	4	9	Yes
Loading/unloading controls	Demonstrated	Yes	Available	3	3	4	10	Yes
Route/navigation controls	Demonstrated	Yes	Available	3	2	3	8	Yes

Table 9

Transport Component - Hopper Dredge Control

				Rating				
Process Option	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program
Hopper selection	Demonstrated	Yes	Available	4	3	3	10	Yes
Decontamination	Demonstrated	No	Available	3	2	4	9	Yes
Loading/unloading controls	Demonstrated	Yes	Available	3	3	4	10	Yes
Route/navigation controls	Demonstrated	Yes	Available	3	2	3	8	Yes

Table 10

Transport Component - Pipeline Control

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Decontamination	Demonstrated	Yes	Available	3	2	4	9	Yes
Leak detection	Demonstrated	Yes	Available	3	3	4	10	Yes
Pipeline routing	Demonstrated	Yes	Available	3	2	3	8	Yes
Pipeline selection	Demonstrated	Yes	Available	3	3	4	10	Yes
Pump controls	Demonstrated	No	Available	3	3	4	10	Yes
Redundancy of safety devices	Demonstrated	No	Available	4	3	3	10	Yes

Table 11

Transport Control - Rail Transport

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Car selection	Demonstrated	No	Available	4	3	3	10	Yes
Decontamination	Demonstrated	No	Available	3	2	4	9	Yes
Loading/unloading controls	Demonstrated	No	Available	3	3	4	10	Yes
Route selection	Demonstrated	No	Available	3	2	3	8	Yes

Table 12

Transport Component - Truck Control

				Rating				
Process Option	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program
Decontamination	Demonstrated	Yes	Available	3	3	4	10	Yes
Loading/unloading controls	Demonstrated	Yes	Available	3	3	4	10	Yes
Route selection	Demonstrated	Yes	Available	3	2	3	8	Yes
Truck selection	Demonstrated	Yes	Available	4	3	3	10	Yes

Table 13

Process Options for the Pretreatment Component

Dewatering	Particle Classification	Slurry Injection
Belt filter press	Flotation	Chemical Clarification
Carver-Greenfield evaporation	Grizzlies	Microbe addition
Centrifugation	Heavy media separation	Nutrient addition
Chamber filtration	Hydraulic classifiers	
Evaporation	Hydrocyclones	
Gravity thickening	Impoundment basins (CDF)	
Primary settling (CDF)	Magnetic and electrostatic separation	
Solar evaporation		
Subsurface drainage (CDF)	Moving screens	
Surface drainage (CDF)	Shaking tables	
Vacuum filtration	Spiral classifier	
Wick drains (CDF)	Stationary screens	

Table 14

Pretreatment Component - Dewatering

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effectiveness	Implementability	Costs	Composite Score	
Belt filter press	Demonstrated	Yes	Available	4	3	3	10	Yes
Carver-Greenfield evaporation	Demonstrated	No	Available	3	2	3	8	Yes
Centrifugation	Demonstrated	No	Available	4	2	3	9	Yes
Chamber filtration	Demonstrated	No	Available	4	3	3	10	Yes
Evaporation	Demonstrated	No	Available	3	1	2	6	No
Gravity thickening	Demonstrated	No	Available	3	3	3	9	Yes
Primary settling (CDF)	Demonstrated	Yes	Available	3	4	4	11	Yes
Solar evaporation	Demonstrated	Yes	Available	1	3	4	8	No
Subsurface drainage (CDF)	Demonstrated	Yes	Available	3	3	3	9	Yes
Surface drainage (CDF)	Demonstrated	Yes	Available	2	4	4	10	Yes
Vacuum filtration	Demonstrated	Yes	Available	3	3	3	9	Yes
Wick drains (CDF)	Demonstrated	Yes	Available	3	4	3	10	Yes

Table 15

Pretreatment Component - Particle Classification Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating: Effective-ness	Rating: Implement-ability	Rating: Costs	Rating: Composite Score	Consider for ARCS Program
Flotation	Demonstrated	Bench*	Available	3	2	3	8	Yes
Grizzlies	Demonstrated	No	Available	2	3	4	9	Yes
Heavy media separation	Demonstrated	No	Available	2	1	3	6	No
Hydraulic classifiers	Demonstrated	Yes	Available	3	2	3	8	Yes
Hydrocyclones	Demonstrated	Yes	Available	3	3	4	10	Yes
Impoundment basins (CDF)	Demonstrated	Yes	Available	2	3	4	9	Yes
Magnetic\electrostatic	Demonstrated	No	Available	3	2	3	8	Yes
Moving screens	Demonstrated	No	Available	3	2	3	8	Yes
Shaking table	Demonstrated	No	Available	3	2	3	8	Yes
Spiral classifiers	Demonstrated	No	Available	3	2	3	8	Yes
Stationary screens	Demonstrated	No	Available	3	2	3	8	Yes

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* Bench-scale testing has been conducted.

Table 16

Pretreatment Component - Slurry Injection

Process Option	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effectiveness	Implementability	Costs	Composite Score	
Chemical clarification	Demonstrated	Yes	Available	2	3	4	9	Yes
Microbe addition	Conceptual	No	Emerging	3	3	3	9	Yes
Nutrient addition	Conceptual	No	Emerging	1	3	4	8	No

Table 17

Process Options for the Treatment Component Types

Biological	Chemical	Extraction	Immobilization	Radiant Energy	Thermal
Aerobic bioreclamation	Chelation	Acid leaching	Chloranan encapsulation	LARC process	Advanced electric reactor
Anaerobic bioreclamation	Chemical hydrolysis	Acurex	Ground freezing	Ozonic	Blast furnaces
Anaerobic digestion	Detoxification	B.E.S.T. (triethylamine, TEA)	In situ	Photolysis	Circulating bed combustor
Bioreactors	Nucleophilic *substitution*	Biotrol soil washing	Lime-based solidification		Eco Logic
	Oxidation of metals (inorganic)	C.F. Systems - CO_2	Macroencapsulation		Flame Reactor
Composting	Oxidation of organics	CF Systems - propane	Organic polymerization		Fluidized bed incineration
Enzymes	Reduction of metals	Contained recovery of oily wastes (CROW) process	Portland cement-based solidification		High-temperature slagging incineration
	Reduction of organcis	Electroacoustic soil decontamination	Proprietary processes		Industrial kilns

(Continued)

(Sheet 1 of 3)

Table 17 (Continued)

Biological	Chemical	Extraction	Immobilization	Radiant Energy	Thermal
	Thionation	EPA mobile soil washing	Soil cooling		Infrared (Shirco) incineration
		Harbauer semibatch soil washing process	Soil vapor pore volume reduction		In situ vitrification (Battelle)
		Harmon Environmental Services soil washing	Sorption		Liquid injection incineration
		Heidemij mobile soil washing process	Thermoplastic microencapsulation		Low-temperature thermal stripping
		In situ vacuum and steam extraction			Lurgi pelletizing process
		Integrated vapor and steam vacuum stripping			Molten glass vitrification
		Low-energy extraction (acetone-kerosene)			Molten salt incineration
		Mechanical aeration/ extraction			Multiple hearth incineration
		MTA remedial resources soil washing process			Plasma arc incineration

(Continued)

(Sheet 2 of 3)

Table 17 (Concluded)

Biological	Chemical	Extraction	Immobilization	Radiant Energy	Thermal
		O.H. Materials Co. (methanol)			Pyretron incinerator
		Oil CREP (onsite) soil washing			Pyrolysis
		Soilex (kerosene)			Pyrometallurgy
		Steam stripping			Pyroplasma pyrolysis
		Surfactants			Radio frequency heating
					Roasting
					Rotary kiln incineration
					Supercritical water oxidation
					Taciuk
					Vitrification
					Wet air oxidation

(Sheet 3 of 3)

Table 18

Treatment Component - Biological Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effectiveness	Implementability	Costs	Composite Score	
Aerobic bioreclamation	Demonstrated	Bench	Available	3	3	3	9	Yes
Anaerobic bioreclamation	Demonstrated	No	Available	3	3	3	9	Yes
Anaerobic digestion	Demonstrated	Bench	Available	2	2	2	6	No
Bioreactors	Demonstrated	No	Available	3	1	3	7	Yes
Composting	Demonstrated	No	Available	2	2	2	6	No
Enzymes (including fungi)	Conceptual	No	Available	2	1	3	6	No

Table 19

Treatment Component - Chemical Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating: Effectiveness	Rating: Implementability	Rating: Costs	Rating: Composite Score	Consider for ARCS Program
Chelation	Demonstrated	No	Available	3	2	2	7	Yes
Chemical hydrolysis	Conceptual	No	Emerging	2	1	2	5	No
Nucleophilic substitution	Pilot	Bench	Proprietary	4	2	2	8	Yes
Oxidation of metals (inorganic)	Conceptual	No	Emerging	2	1	2	5	No
Oxidation of organics	Pilot	No	Available	3	2	2	7	Yes
Reduction of metals	Conceptual	No	Emerging	2	1	2	5	No
Reduction of organics	Conceptual	No	Emerging	1	1	2	4	No
Thionation	Conceptual	No	Emerging	1	1	2	4	No

Table 20

Treatment Component - Extraction Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Acid leaching	Demonstrated	No	Available	3	2	2	7	Yes
Acurex (hexane/freon)	Pilot	No	Proprietary	3	1	2	6	No
B.E.S.T. (TEA)	Demonstrated	Bench	Proprietary	4	3	2	9	Yes
BioTrol soil washing process	Pilot	No	Proprietary	2	2	2	6	No
C.F. Systems - CO_2	Pilot	No	Proprietary	3	1	2	6	No
C.F. Systems - Propane	Pilot	Pilot	Proprietary	3	2	2	7	Yes
CROW process	Conceptual	No	Proprietary	2	1	2	5	No
Electroacoustic soil decontamination	Conceptual	No	Emerging	2	2	1	5	No
EPA mobile soil washing unit	Pilot	No	Available	2	2	2	6	No
Harbauer semibatch soil washing	Pilot	No	Foreign	3	1	2	6	No
Harmon Env. Serv. soil washing	Bench	No	Proprietary	3	1	2	6	No
Heidemij mobile soil washing	Pilot	No	Foreign	2	1	2	5	No
In situ vacuum and steam	Demonstrated	No	Available	2	1	2	5	No
Integrated vapor and steam vacuum stripping	Demonstrated	No	Proprietary	2	1	1	4	No
Low energy (acetone/kerosene)	Conceptual	Bench	Emerging	3	2	2	7	Yes
Mechanical aeration/extraction	Demonstrated	No	Available	2	2	2	6	No
MTA remedial res. soil washing	Demonstrated	No	Proprietary	2	2	2	6	No

(Continued)

Table 20 (Concluded)

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
O.H. Materials (methanol)	Pilot	No	Available	3	1	2	6	No
Oil CREP (onsite)	Pilot	No	Foreign	2	1	2	5	No
Soilex (kerosene)	Pilot	No	Available	3	2	1	6	No
Steam stripping	Demonstrated	No	Available	2	1	2	5	No
Surfactants	Demonstrated	No	Available	3	2	2	7	Yes

Table 21

Treatment Component - Immobilization Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating Effective-ness	Rating Implement-ability	Rating Costs	Rating Composite Score	Consider for ARCS Program
Chloranan encapsulation	Demonstrated	No	Proprietary	3	2	2	7	Yes
Ground freezing	Conceptual	No	Emerging	2	1	2	5	No
In situ	Demonstrated	No	Available	2	3	2	7	Yes
Lime-based pozzolan	Demonstrated	Bench	Available	3	3	3	9	Yes
Macroencapsulation	Pilot	No	Proprietary	3	1	2	6	No
Organic polymerization	Demonstrated	No	Available	3	1	2	6	No
Portland cement-based	Demonstrated	Bench	Available	3	3	3	9	Yes
Proprietary processes	Demonstrated	Bench	Proprietary	3	3	3	9	Yes
Soil cooling	Conceptual	No	Emerging	1	1	2	4	No
Soil vapor pore volume reduction	Conceptual	No	Emerging	1	2	2	5	No
Sorption	Demonstrated	No	Emerging	3	2	3	8	Yes
Thermoplastic microencapsulation	Pilot	No	Proprietary	3	1	1	5	No

Table 22

Treatment Component - Radiant Energy Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
LARC	Conceptual	No	Proprietary	3	1	2	6	No
Ozonics	Conceptual	No	Proprietary	2	1	2	5	No
Photolysis	Conceptual	No	Emerging	2	1	2	5	No

Table 23

Treatment Component - Thermal Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating			Composite Score	Consider for ARCS Program
				Effective-ness	Implement-ability	Costs		
Advanced electric reactor	Pilot	No	Proprietary	4	2	1	7	Yes (II)*
Blast furnaces	Demonstrated	No	Available	3	2	1	6	No
Circulating bed combustor	Demonstrated	Yes	Available	4	3	2	9	Yes
Eco Logic	Pilot	Pilot	Proprietary	4	3	2	9	Yes
Flame reactor process	Pilot	No	Proprietary	3	2	1	6	No
Fluidized-bed incineration	Demonstrated	No	Available	4	2	1	7	Yes (II)
High-temperature slag incineration	Demonstrated	No	Proprietary	4	2	1	7	Yes (II)
Industrial kilns	Demonstrated	No	Available	3	2	1	6	No
Infrared (Shirco) incineration	Pilot	No	Proprietary	4	2	1	7	Yes (II)
In situ vitrification (Battelle)	Pilot	Bench	Proprietary	4	2	1	7	Yes (II)
Liquid injection incineration	Demonstrated	No	Available	3	1	1	6	No
Low-temperature thermal stripping	Demonstrated	No	Available	3	2	2	7	Yes
Lurgi pelletizing process	Pilot	Yes	Proprietary	3	1	1	5	No
Molten glass vitrification	Conceptual	No	Emerging	3	1	1	5	No
Molten salt incineration	Conceptual	No	Emerging	4	1	1	6	No
Multiple hearth incineration	Demonstrated	No	Available	4	2	1	7	Yes (II)
Plasma arc incineration	Pilot	No	Emerging	3	1	1	5	No

(Continued)

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* See paragraph 45b.

Table 23 (Concluded)

Technology	State of Development	Applied to Dredged Material	Availability	Rating: Effective-ness	Rating: Implement-ability	Rating: Costs	Rating: Composite Score	Consider for ARCS Program
Pyretron incinerator	Pilot	No	Proprietary	3	1	1	5	No
Pyrolysis	Demonstrated	No	Available	4	2	1	7	Yes (II)
Pyrometallurgy	Demonstrated	No	Available	2	2	1	5	No
Pyroplasma process	Pilot	No	Proprietary	3	2	1	6	No
Radio frequency heating	Conceptual	No	Emerging	3	1	1	5	No
Roasting	Conceptual	No	Emerging	3	1	1	5	No
Rotary kiln incineration	Demonstrated	No	Available	4	2	2	8	Yes
Supercritical water oxidation	Pilot	No	Proprietary	4	2	1	7	Yes (II)
Taciuk	Pilot	Pilot	Proprietary	3	3	2	8	Yes
Vitrification	Pilot	Bench	Proprietary	4	3	1	8	Yes (II)
Wet air oxidation	Demonstrated	Bench	Proprietary	2	3	3	8	Yes

Table 24

Process Options for the Disposal Component Technology Types

Beneficial Use	Confined Disposal	Open Water Disposal
Agriculture, horticulture, and forestry	Barrier systems	Capping
Aquaculture	Covers and capping	Site selection
Beach nourishment	Confined disposal facilities	Submerged discharge
Habitat development		
Harbor and port facilities	Groundwater pumping	
	Leachate collection/ detection	
Other construction and commercial use	Operational techniques	
Parks and recreation areas	RCRA landfills	
Residential and urban use	Sanitary landfills	
Solid waste management	TSCA landfills	
Strip mine reclamation		

Table 25

Disposal Component - Beneficial Use Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program*
				Effective-ness	Implement-ability	Costs	Composite Score	
Agriculture horticulture and forestry	Demonstrated	Yes	Available	3	2	3	8	Yes
Aquaculture	Demonstrated	Yes	Available	3	3	3	9	Yes
Beach nourishment	Demonstrated	Yes	Available	3	3	3	9	Yes
Habitat development	Demonstrated	Yes	Available	3	3	3	9	Yes
Harbors/port facilities	Demonstrated	Yes	Available	3	4	3	10	Yes
Other construction/commercial use	Demonstrated	Yes	Available	3	4	3	10	Yes
Parks and recreation	Demonstrated	Yes	Available	3	2	3	8	Yes
Residential/urban use	Demonstrated	Yes	Available	3	2	3	8	Yes
Solid waste management	Demonstrated	Yes	Available	3	2	3	8	Yes
Strip mine reclamation	Demonstrated	Yes	Available	3	2	3	8	Yes

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* Consideration of most of these uses is applicable to cleaner residuals from pretreatment or treatment processes.

Table 26

Disposal Component - Confined Disposal Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating: Effective-ness	Rating: Implement-ability	Rating: Costs	Rating: Composite Score	Consider for ARCS Program
Barrier systems	Demonstrated	Yes	Available	3	3	3	9	Yes
Confined disposal facilities	Demonstrated	Yes	Available	3	4	4	11	Yes
Covers and capping	Demonstrated	Yes	Available	3	3	3	9	Yes
Groundwater pumping	Demonstrated	Yes	Available	2	3	3	8	Yes
Leachate collection/ detection	Demonstrated	Yes	Available	3	3	3	9	Yes
Operational techniques	Demonstrated	Yes	Available	2	4	4	10	Yes
RCRA landfills	Demonstrated	No	Available	4	2	1	7	Yes (II)
Sanitary landfills	Demonstrated	Yes	Available	3	3	3	9	Yes
TSCA landfills	Demonstrated	No	Available	4	2	1	7	Yes (II)

Table 27

Disposal Component - Open-Water Technologies

				Rating				
Technology	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program*
Capping	Demonstrated	Yes	Available	3	3	4	10	Yes
Site selection	Demonstrated	Yes	Available	2	3	4	9	Yes
Submerged discharge	Demonstrated	Yes	Available	2	3	4	9	Yes

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* Open-water disposal process options for the Great Lakes are applicable only for cleaner sediments or treated residuals.

Table 28

Process Options for the Effluent/Leachate Component Technology Types

Metal Removal	Organics Removal	Supsended Solids Removal
Adsorptive filtration	Aerobic biodegradation	Chemical clarification
Biological ion exchange	Air stripping	Clarifiers
Electrocoagulation	Anaerobic biodegradation	Granular media filtration
Flocculation/coagulation	BioTrol aqueous treatment system	Membrane microfiltration
Freeze separation	Carbon adsorption	Settling (CDF)
Ion exchange	Catalytic dehydrochlorination	Ultrafiltration
Permeable treatment	Chemical hydrolysis beds/dikes	Wetlands
Precipitation	Electrolytic reduction	
Reduction of metals	Laser simulated photolysis	
Ultrafiltration	Neutralization	
Wetlands	Oil separation	
	Oxidation of organics	
	Ozonation	
	PACT process	
	Reduction of organics	
	Resin adsorption	
	Reverse osmosis	
	Rotating biological contactor	
	Steam stripping	
	Submerged fixed-film bioreactor	
	Trickling filter	
	UV/hydrogen peroxide	
	UV/ozonation	
	Wetlands	

Table 29

Effluent/Leachate Component - Suspended Solids Removal Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating: Effective-ness	Rating: Implement-ability	Rating: Costs	Rating: Composite Score	Consider for ARCS Program
Chemical clarification	Demonstrated	Yes	Available	3	4	4	11	Yes
Clarifiers	Demonstrated	No	Available	3	2	3	8	No
Granular media filtration	Demonstrated	Yes	Available	3	3	3	9	Yes
Membrane microfiltration	Demonstrated	No	Available	4	3	2	9	Yes
Settling (CDF)	Demonstrated	Yes	Available	3	4	4	11	Yes
Ultrafiltration	Demonstrated	No	Available	4	2	2	8	No
Wetlands	Demonstrated	Yes	Available	4	3	3	10	Yes

Table 30

Effluent/Leachate Component - Metals Removal Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Adsorptive filtration	Conceptual	No	Emerging	3	2	3	8	No
Biological ion exchange	Conceptual	No	Emerging	3	2	3	8	No
Electrocoagulation	Conceptual	No	Emerging	3	2	3	8	No
Flocculation/coagulation	Demonstrated	Yes	Available	3	4	4	11	Yes
Freeze separation	Conceptual	No	Emerging	2	2	2	6	No
Ion exchange	Demonstrated	No	Available	4	3	3	10	Yes
Permeable treatment beds/dikes	Demonstrated	Yes	Available	3	3	3	9	Yes
Precipitation	Demonstrated	No	Available	4	3	3	10	Yes
Reduction of metals	Demonstrated	No	Available	3	2	3	8	No
Ultrafiltration	Conceptual	No	Emerging	3	2	2	7	No
Wetlands	Demonstrated	Yes	Available	3	3	3	9	Yes

Table 31

Effluent/Leachate Component - Organic Treatment Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Aerobic biodegradation	Demonstrated	No	Available	2	2	3	7	No
Air stripping	Demonstrated	No	Available	2	2	3	7	No
Anaerobic biodegradation	Demonstrated	No	Available	2	2	3	7	No
BioTrol aqueous treatment system	Pilot	No	Proprietary	2	2	3	7	No
Carbon adsorption	Demonstrated	Yes	Available	4	3	3	10	Yes
Catalytic dehydrochlorination	Demonstrated	No	Available	2	2	2	6	No
Chemical hydrolysis	Demonstrated	No	Available	2	2	2	6	No
Electrolytic reduction	Conceptual	No	Emerging	2	2	2	6	No
Laser simulated photolysis	Conceptual	No	Emerging	2	2	2	6	No
Neutralization	Demonstrated	No	Available	2	2	3	7	No
Oil separation	Demonstrated	No	Available	2	4	4	10	Yes
Oxidation of organics	Demonstrated	Yes	Available	3	2	3	8	Yes
Ozonation	Demonstrated	No	Available	3	2	3	8	Yes
PACT process	Demonstrated	No	Available	3	2	2	7	No
Reduction of organics	Conceptual	No	Emerging	2	1	2	5	No
Resin adsorption	Demonstrated	No	Available	3	2	3	8	Yes
Reverse osmosis	Demonstrated	No	Available	4	2	1	7	No

(Continued)

Table 31 (Concluded)

				Rating				
Technology	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program
Rotating biological contactor	Demonstrated	No	Available	2	2	3	7	No
Steam stripping	Demonstrated	No	Available	3	2	2	7	No
Submerged fixed-film bioreactor	Conceptual	No	Emerging	2	2	3	7	No
Trickling filter	Demonstrated	No	Available	2	2	3	7	No
UV/hydrogen peroxide	Demonstrated	Yes	Available	3	2	3	8	Yes
UV/ozonation	Demonstrated	No	Available	3	2	3	8	Yes
Wetlands	Demonstrated	No	Available	3	3	3	9	Yes

Table 32

Process Options for the Nonremoval Component Technology Types

Containment	In Situ Treatment	No Action	Restricted Use
Armorform	Aerobic biodegradation	Monitoring	Fencing and warning signs
Clean sediment capping	Anaerobic biodegradation		Navigation relocation
Geomembrane capping	Grout injection		Seasonal restrictions
Structural isolation	In situ stabilization		

Table 33

Nonremoval Component - Containment Technologies

				Rating				
Technology	State of Development	Applied to Dredged Material	Availability	Effective-ness	Implement-ability	Costs	Composite Score	Consider for ARCS Program
Armorform	Demonstrated	Yes	Proprietary	3	3	3	9	Yes
Clean sediment capping	Demonstrated	Yes	Available	3	4	4	11	Yes
Geomembrane capping	Demonstrated	Yes	Emerging	3	2	2	7	No
Structural isolation	Demonstrated	Yes	Available	4	2	2	8	Yes

Table 34

Nonremoval Component - In Situ Treatment Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Aerobic biodegradation	Conceptual	No	Emerging	1	2	3	6	No
Anaerobic biodegradation	Conceptual	No	Emerging	2	2	3	7	Yes
Grout injection	Demonstrated	Yes	Available	2	2	2	6	No
In situ stabilization	Demonstrated	Yes	Available	3	3	2	8	Yes

Table 35

Nonremoval Component - No Action/Monitoring of Pathways

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effectiveness	Implementability	Costs	Composite Score	
Monitoring	Demonstrated	Yes	Available	3	4	4	11	Yes

Table 36

Nonremoval Component - Restricted Use Technologies

Technology	State of Development	Applied to Dredged Material	Availability	Rating				Consider for ARCS Program
				Effective-ness	Implement-ability	Costs	Composite Score	
Fencing and warning signs	Demonstrated	Yes	Available	2	3	4	9	No
Navigation relocation	Demonstrated	Yes	Available	2	2	3	7	No
Seasonal restrictions	Demonstrated	Yes	Available	1	2	4	7	No

REMOVAL	TRANSPORT	PRE-TREATMENT	TREATMENT	DISPOSAL	EFFLUENT/ LEACHATE TRT.	NON-REMOVAL
Turbidity Containment	Barge/Scow	Slurry Injection	Biological	Beneficial Use	Metals Removal	Containment
Hydraulic Dredges	Hopper Dredge	Dewatering	Chemical	Confined Disposal	Organic Treatment	In Situ Treatment
Mechanical Dredges	Pipeline	Particle Classif.	Extraction	Open Water	SS Removal	No Action
Operational Controls	Rail		Immobilization			Restricted Use
	Truck		Radiant Energy			
			Thermal			

Figure 1. Technologies for remediation of contaminated sediment

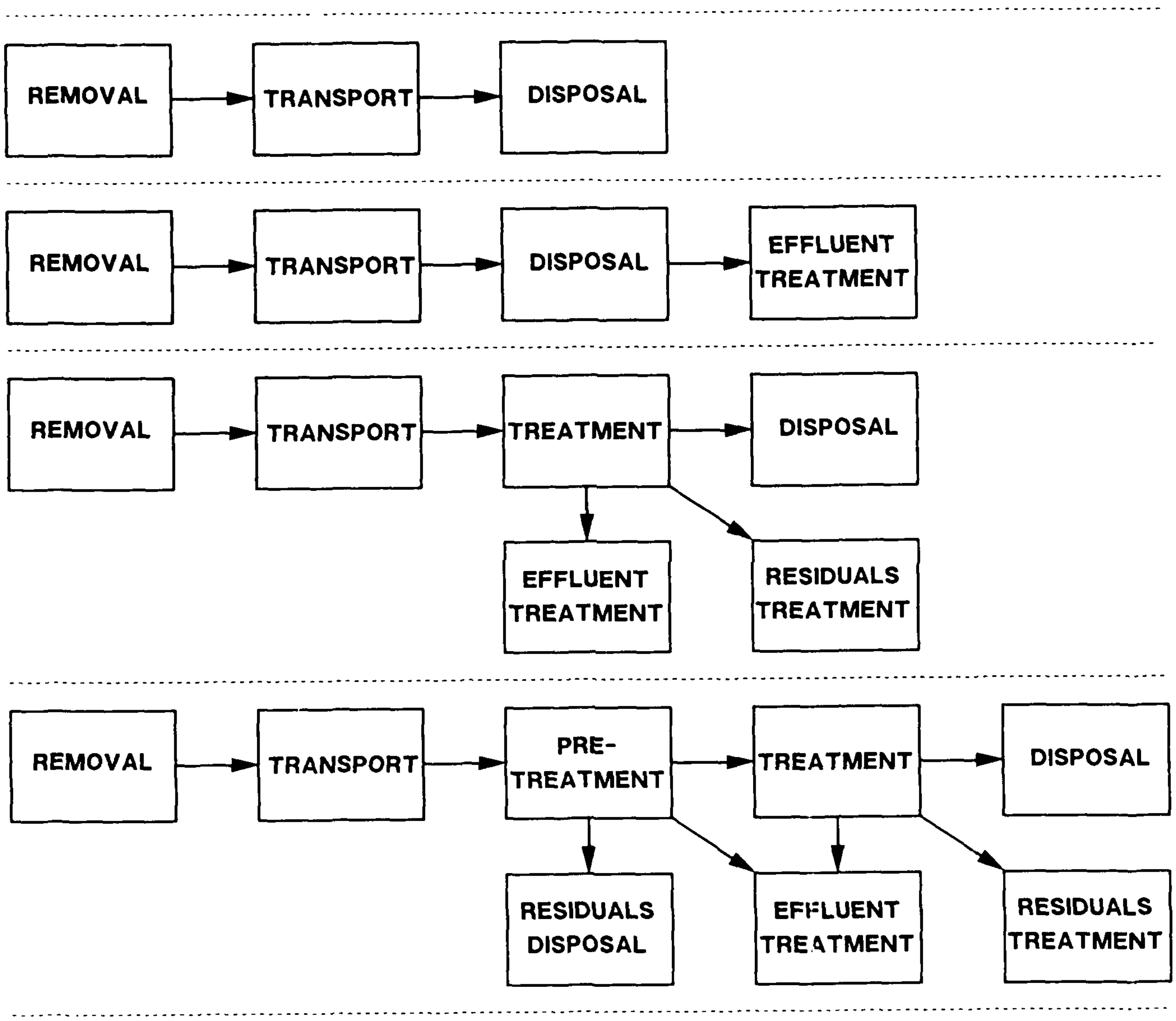


Figure 2. Removal alternatives for remediation of contaminated sediment

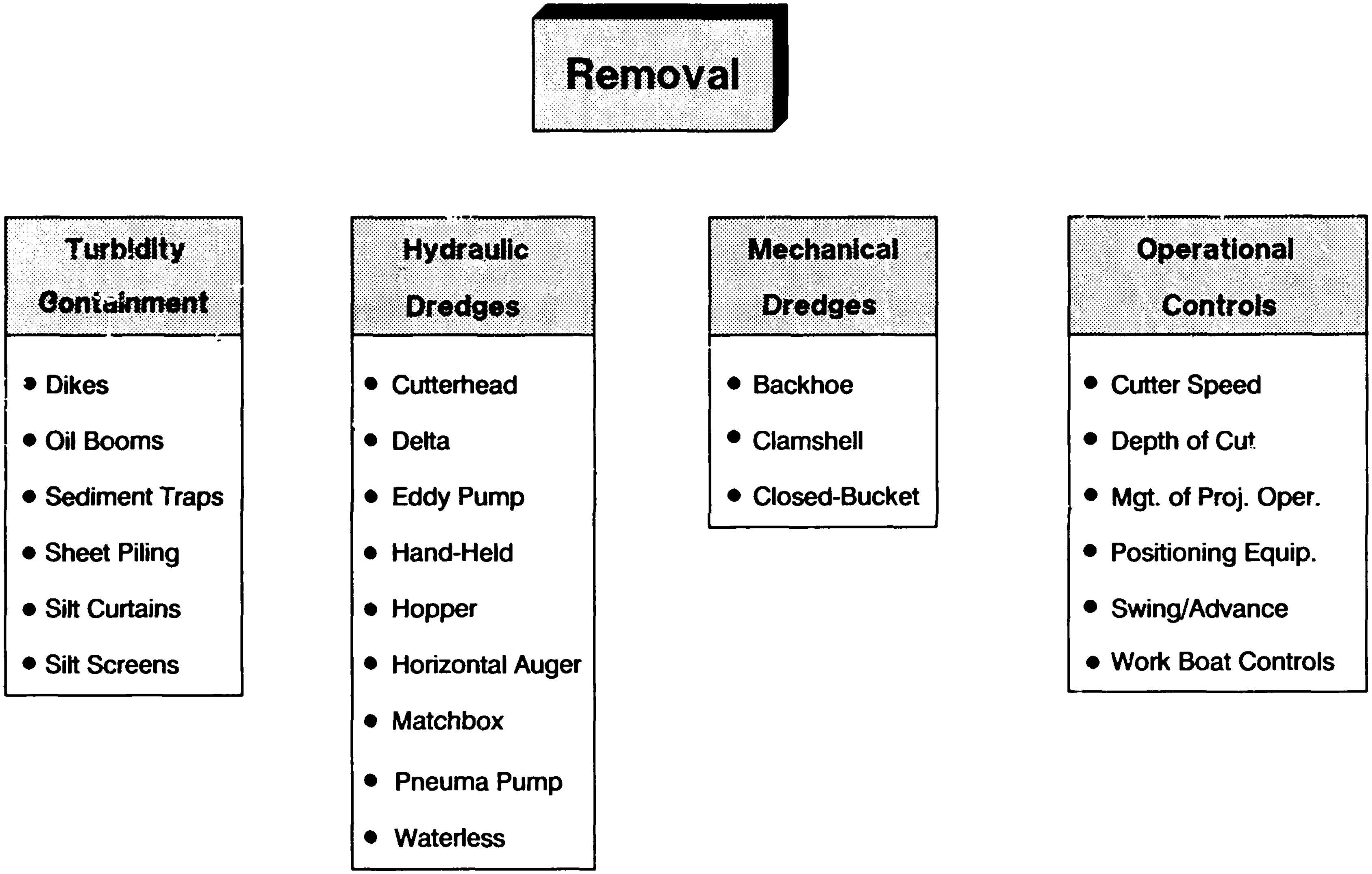


Figure 3. Removal options recommended for evaluation/demonstration by the ARCS program

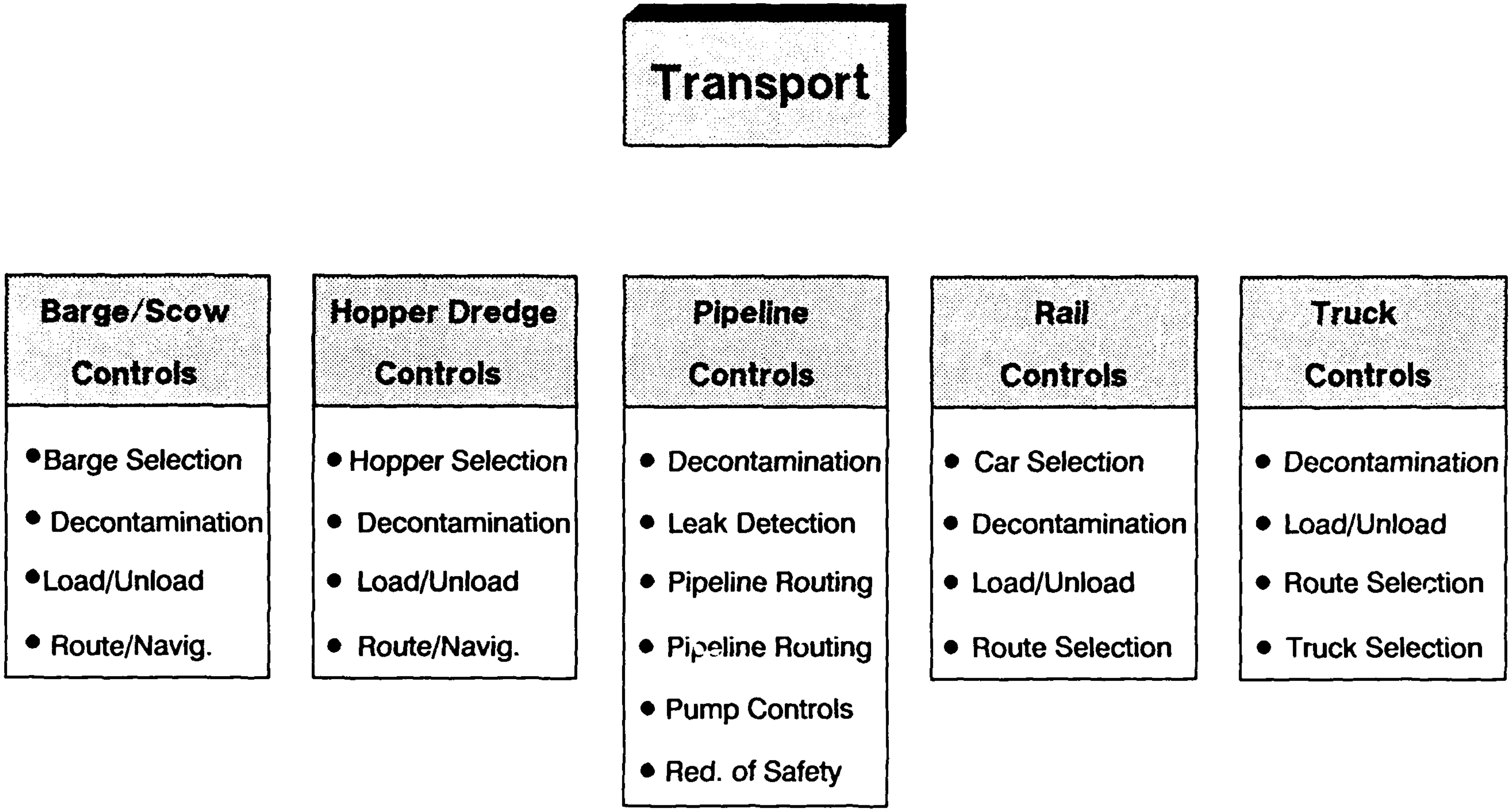


Figure 4. Transport options recommended for evaluation/demonstration by the ARCS program

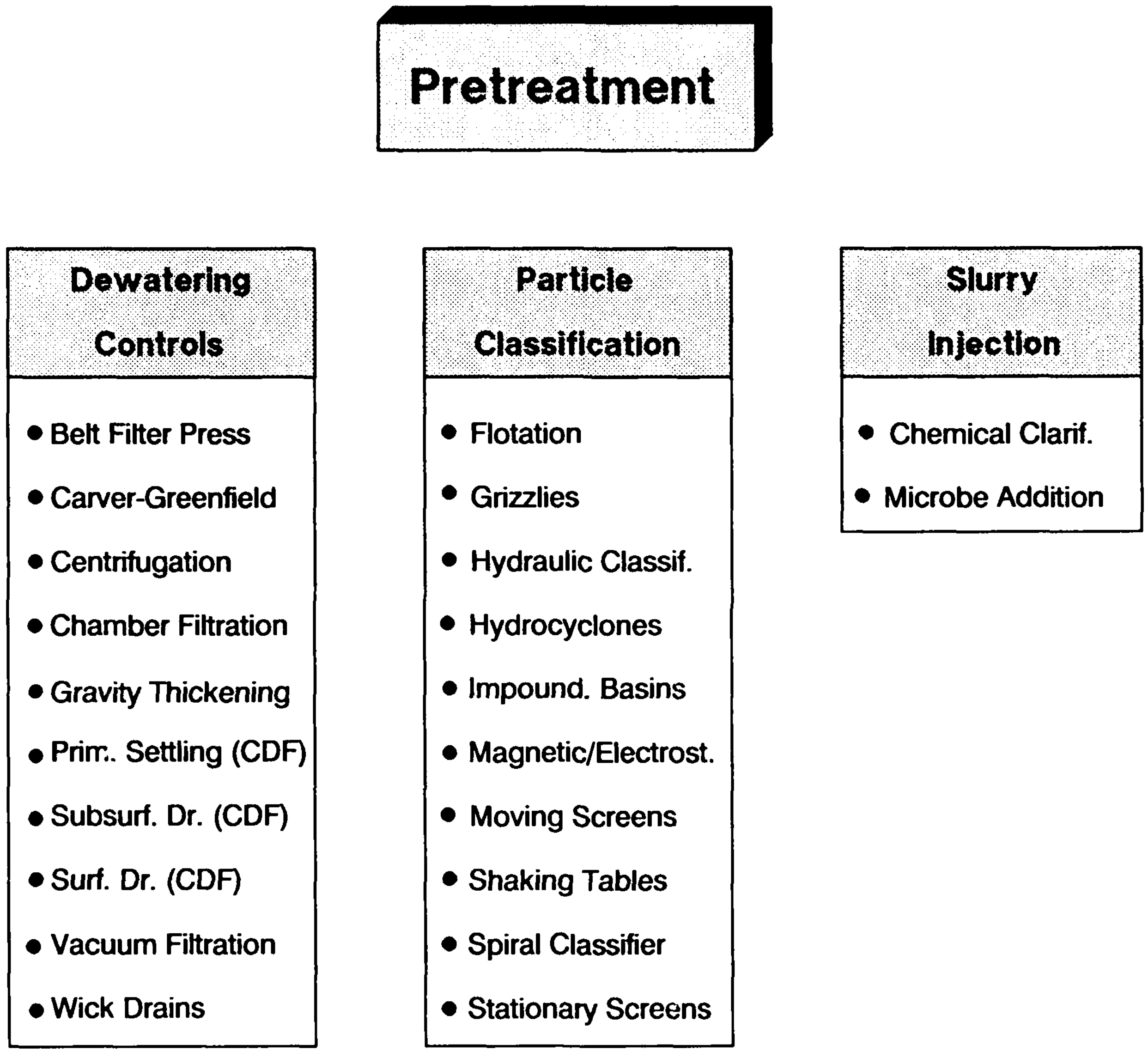


Figure 5. Pretreatment options recommended for evaluation/demonstration by the ARCS program

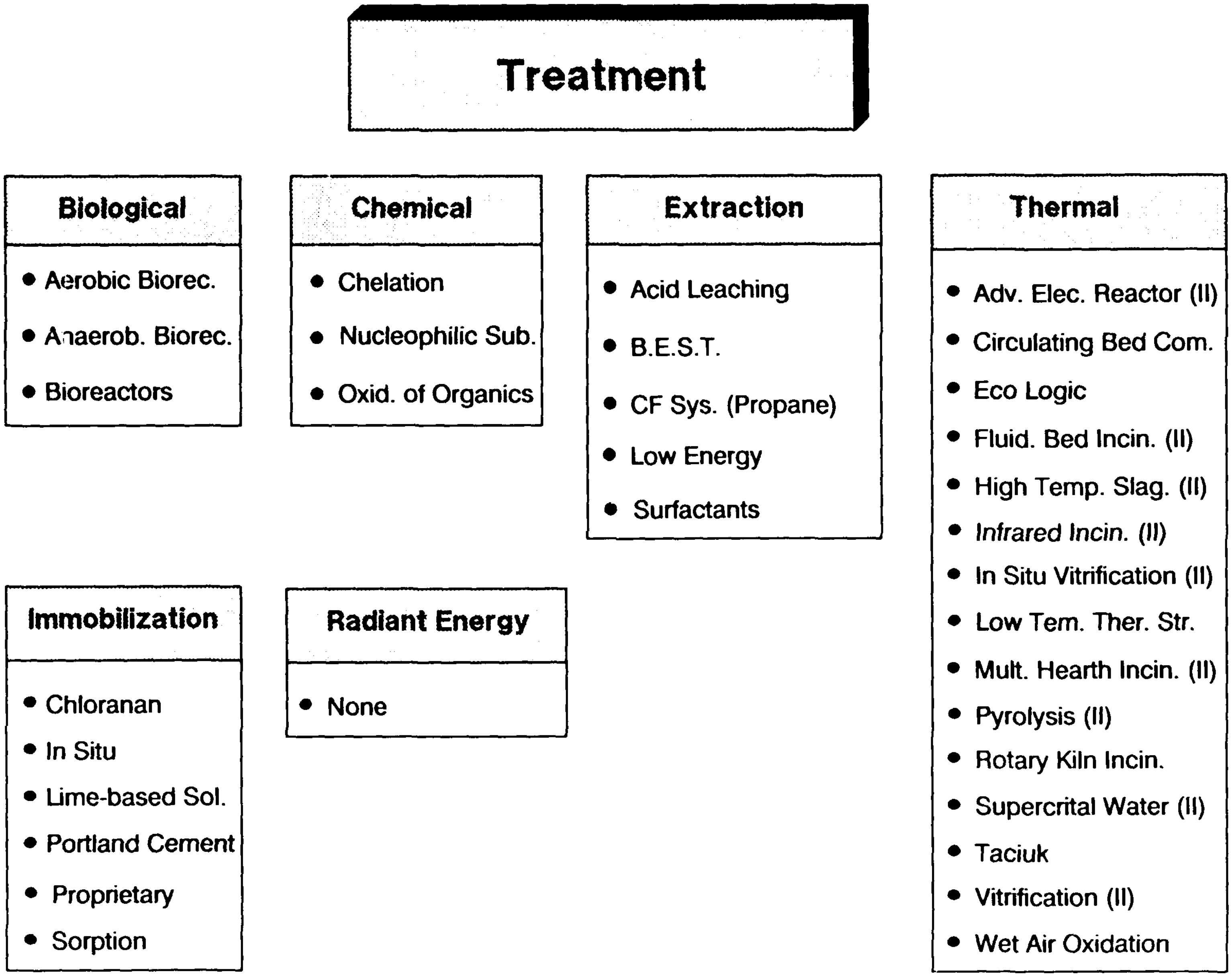


Figure 6. Treatment options recommended for evaluation/demonstration by the ARCS program

Disposal

Beneficial Use

- Agric./Hort./For.
- Aquaculture
- Beach Nourishment
- Habitat Develop.
- Harbor and Port
- Const./Commercial
- Parks/Recreation
- Residential/Urban
- Solid Waste Mgt.
- Strip Mine Reclam.

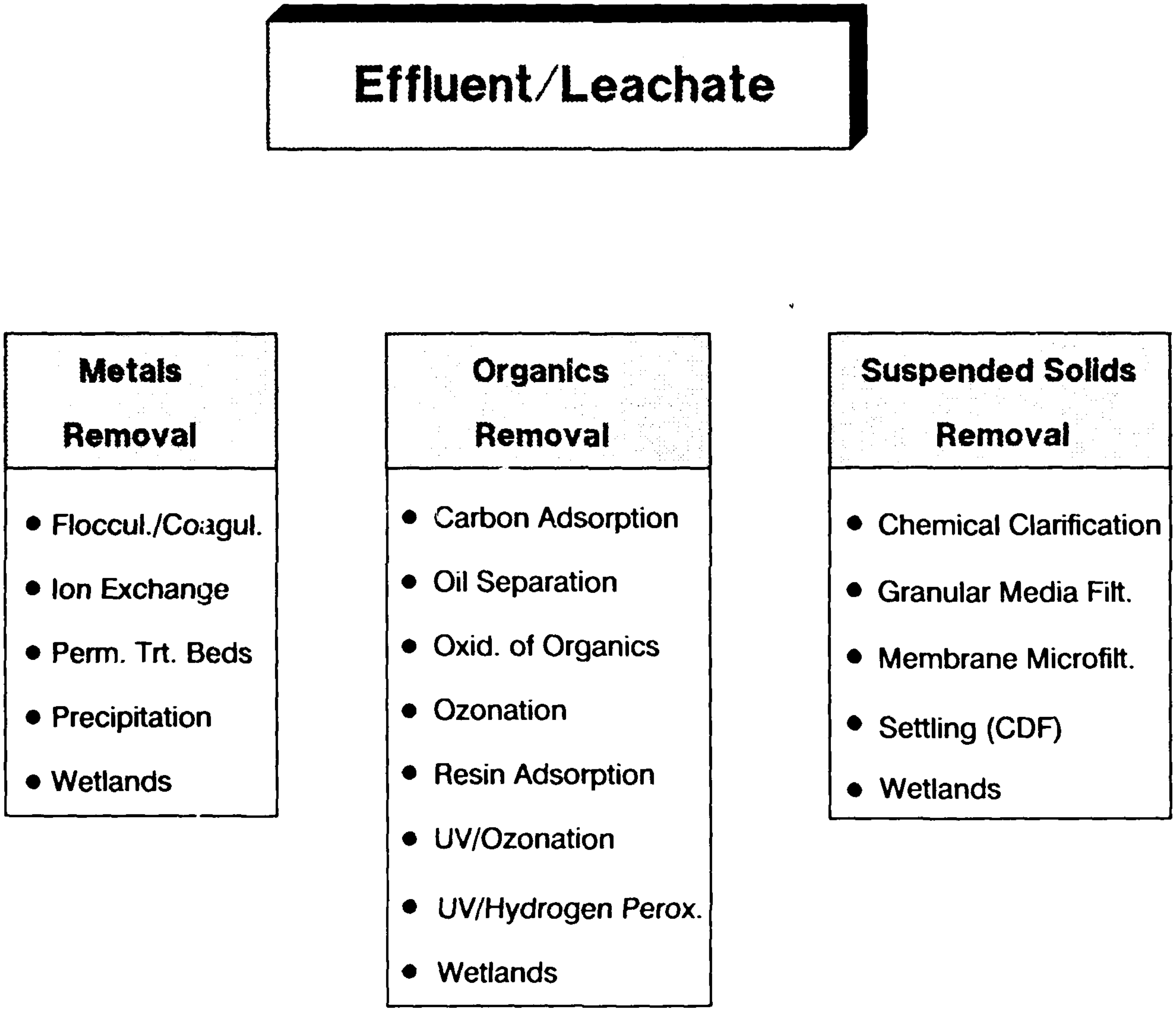
Confined Disposal

- Covers and Capping
- Ground Water Pump.
- Liners
- Oper. Techniques
- Sheet Piling
- Slurry Walls
- Subsurface Drain.
- Surface Drainage
- Wick Drains
- Sanitary Landfills
- RCRA Landfills (II)
- TSCA Landfills (II)

Open Water Disposal

- Capping
- Site Selection
- Submerged Disch.

Figure 7. Disposal options recommended for evaluation/demonstration by the ARCS program



Effluent/Leachate

Metals Removal

- Floccul./Coagul.
- Ion Exchange
- Perm. Trt. Beds
- Precipitation
- Wetlands

Organics Removal

- Carbon Adsorption
- Oil Separation
- Oxid. of Organics
- Ozonation
- Resin Adsorption
- UV/Ozonation
- UV/Hydrogen Perox.
- Wetlands

Suspended Solids Removal

- Chemical Clarification
- Granular Media Filt.
- Membrane Microfilt.
- Settling (CDF)
- Wetlands

Figure 8. Effluent/leachate options recommended for evaluation/demonstration by the ARCS program

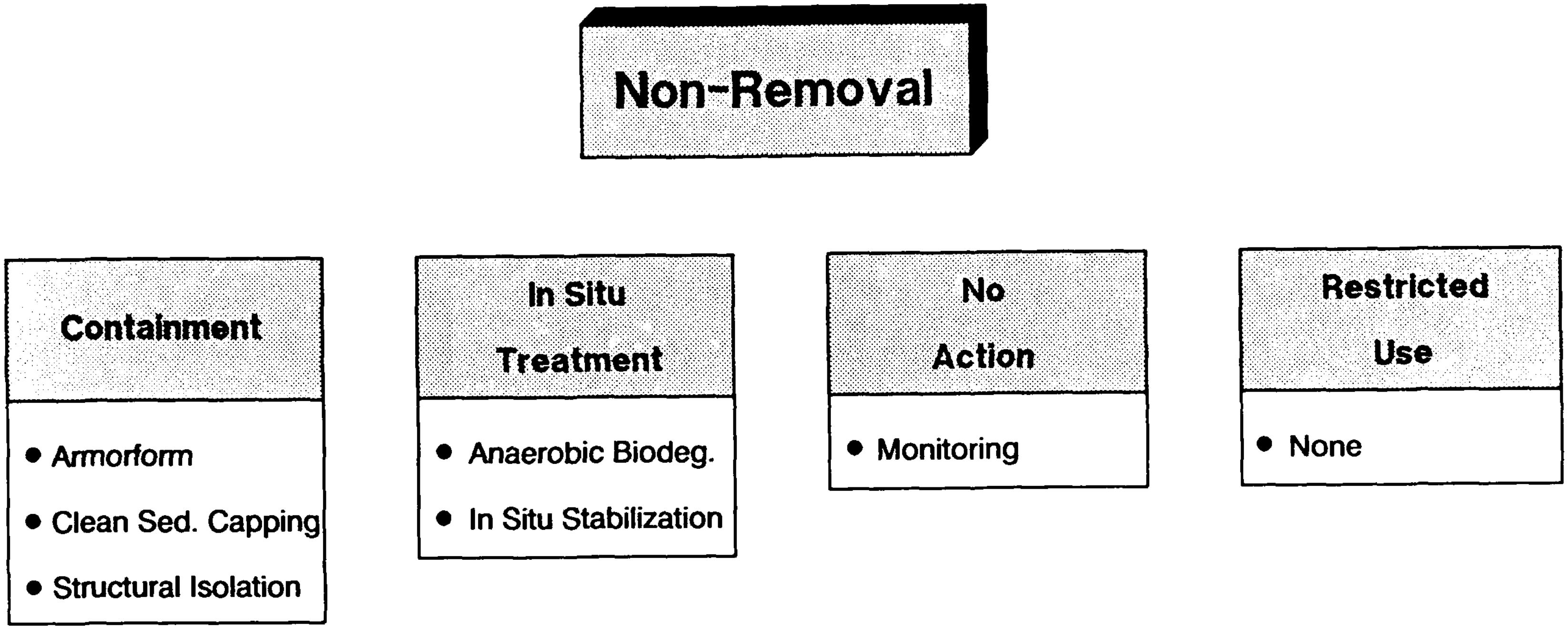


Figure 9. Nonremoval options recommended for evaluation/demonstration by the ARCS program

APPENDIX A: TECHNOLOGY REVIEWS

CONTENTS

PART I: CONTAMINATED SEDIMENT REMOVAL TECHNOLOGIES

Hydraulic Dredge Technologies

1\. Hydraulic dredges remove and transport sediment in liquid slurry form. They are usually mounted on barges and carry diesel or electric-powered centrifugal pumps with discharge pipes ranging from 6 to 48 in.* in diameter. Several different types of hydraulic dredges are discussed in the following sections.

Airlift dredge

2\. Airlift dredges use compressed air for dislodging and transporting sediment, sand, coarse-grained material, and free-flowing unconsolidated material. Airlift dredges are supported by cranes and can be mounted dockside as well as on a barge (Hand et al. 1978).** Compressed air flows from the bottom of an open, vertical pipe that is controlled by a crane. The air expands and rises, causing the creation of upward currents that force water and sediment up the pipe. For effective and reliable operation, the following operating parameters are required: (a) small compressed air bubbles must be uniformly released around the conveyance pipe, (b) a rotating cutter attachment assisting in dislodging solids prior to lifting must be used, and (c) water jets may be attached to the rotating heads for maximum suspension of fine materials (Ikalainen 1987). Typically, 33 percent solid slurries can be achieved using the airlift dredge (d'Angremond, de Jong, and de Waard 1984). The minimum depth the airlift dredge will operate economically is between 20 and 30 ft (Hand et al. 1978). The airlift dredge is not suitable for moving dredged material long distances in pipelines.

3\. An increase in the air pressure increases dredge lift capabilities, while the variance of air pressure combined with the utilization of rotating attachment heads enables the operator to reliably dredge a wide range of sediment types. The primary advantage of the airlift dredge is its continuous transportation of material that maximizes the production rate. The primary limitation is that sufficient water depth must be available for adequate

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3 of the main text.

** See References at the end of the main text.

buildup of air pressure (Hand et al. 1978). Effectiveness of the airlift dredge in minimizing resuspension has not been determined, but it is expected to be similar to other hydraulic dredges.

Clean-Up system

4. To avoid resuspension of sediment, TOA Harbor Works of Japan developed a unique Clean-Up system for dredging highly contaminated sediment (Sato 1976). The Clean-Up head consists of an auger that collects sediment as the dredge swings back and forth, and a shield that guides the sediment toward the suction of a submerged centrifugal pump. To minimize sediment resuspension, the auger is covered, and a movable wing covers the sediment as it is collected by the auger. Sonar devices indicate the elevation of the bottom. An underwater television camera is used to allow observation of the material that is resuspended during a dredging operation. Suspended sediment concentrations around the Clean-Up system ranged from 1.7 to 3.5 mg/ℓ at the surface and from 1.1 to 7.0 mg/ℓ 10 ft above the suction equipment, relative to the background near-surface levels of less than 4.0 mg/ℓ (Herbich and Brahme, in press).

Cutterhead dredges

5. The hydraulic pipeline cutterhead suction dredge is the most commonly used dredging plant, with approximately 300 operating nationwide, and is generally the most efficient and versatile. It performs the major portion of the dredging workload in the United States and can efficiently dredge all types of materials including clay, silt, sand, compacted deposits, hardpan, gravel, and rock. This dredge has the capability of pumping dredged material long distances to upland disposal areas. The cutterhead dredge is suitable for maintaining harbors, canals, and outlet channels where wave heights are not excessive. These dredges are generally classified by size in accordance with the diameter of the discharge pipeline; small class pipeline dredges have a 4- to 14-in. discharge, medium class pipeline dredges have a 16- to 22-in. discharge, and large class pipeline dredges have a 24- to 36-in. discharge (Cullinane et al. 1986).

6. Concentrations of suspended sediments from a cutterhead dredging operation range from 200 to 300 mg/ℓ near the cutterhead to a few milligrams per liter 1,000 to 2,000 ft from the dredge. The suspended solids plume is usually contained in the lower portion of the water column. Field evaluations have shown that suspended solids concentrations in plumes generated by cutterhead dredges range from 1.8 to 2.5 times background concentrations (McLellan et al. 1989).

7. The cutterhead dredge was evaluated for removing contaminated sediment during the New Bedford Superfund Pilot Study. Compared to two other dredge types, the cutterhead was superior for minimizing sediment resuspension. Suspended solids concentrations 1 to 3 ft. above the dredgehead averaged 80 mg/ℓ (USAE Division, New England 1989). Havis (1988) reviewed various dredging options and concluded that "the cutterhead is a logical selection for controlling sediment resuspension while maintaining efficient production."

Delta dredge

8. The Delta dredge was developed as a small portable dredge that removes material at a high solids concentration using a submerged 12-in. pump coupled with two counter-rotating, low-speed reversible cutters. According to the manufacturer, this equipment is capable of making a relatively shallow 7.5-ft-wide cut without disturbing the surrounding material. For this reason, turbidity levels in the vicinity of the cutterhead are low (Delta Dredge 1977, as cited in Cullinane et al. 1986).

Dustpan dredge

9. The dustpan dredge is a hydraulic suction dredge that uses a widely flared dredge head containing high-pressure water jets. The jets loosen and agitate sediment, and sediment is captured in the dustpan head as the dredge is winched forward into the excavation. This dredge is designed to operate in shallow water and have enough capacity to excavate a navigation channel in a reasonably short period of time. The dustpan dredge operates with a low-head, high-capacity centrifugal pump so that the material can be raised only a few feet above the water surface and pumped a short distance. Dustpan dredges generate suspended solids plumes similar to (or of greater concentration than) those generated by cutterhead dredges. A dustpan dredge was used in the James River to remove kepone-contaminated sediment in 1982. Plume suspended solids concentrations averaged 3.8 times background concentrations (McLellan et al. 1989).

Eddy pump

10. The Eddy pump is a new technology that is being marketed as an innovative replacement for the centrifugal pump in dredging operations. The Eddy pump uses hydraulic eddy current principles to create a swirling column of fluid in the center of the intake pipe that agitates the material to be dredged, causing the material to flow upward by reverse flow in the eddy current. This swirling material travels up the intake pipe, into the body of the

pump, and out the discharge line. The manufacturer claims that the Eddy pump, with an 8-in. suction line and a 20-in. casing, will outperform any pump with a 14-in. suction line and a 60-in. casing. The weight of an Eddy pump is one eighth that of conventional centrifugal pumps and uses less horsepower (Ikalainen 1987).

11. An Eddy pump with a cutterhead built around it has been built and is currently operating in the United States. This pump is capable of pumping 38 percent solids with the cutterhead operating and 50 percent solids with the cutterhead disengaged (Ikalainen 1987). No operating data have been reported for resuspension of sediment in the vicinity of an Eddy pump.

Hand-held hydraulic dredges

12. Hand-held hydraulic dredges can be used underwater by divers, above water by operators wading in shallow waterways, or by operators using the dredge from a boat. The dredge equipment varies from a hose/collector arrangement to a skid-mounted, high-production machine. The major use of hand-held dredges is for projects with small volumes of hazardous material in calm waters. Above-water units are limited to shallow water (USEPA 1985).

13. Hand-held dredges were used in the South Branch of the Shiawassee River in Michigan for the removal of PCB-contaminated sediment. Vacuum trucks operated as the vacuum source as well as a temporary storage and transportation vehicle for the dredged material, while the hose was controlled by wading operators. Another unit employing diaphragm sludge pumps was used by the EPA Region X Inland Response Team in the removal of PCB-contaminated sediment from the Duwamish River Waterway in Seattle, WA (Hand et al. 1978). Because there are no moving parts, sediment resuspension rates are expected to be low, but production rates are reduced.

Hopper dredges

14. Hopper dredges are designed to operate in open waters and are best suited to dredging deep harbors and rough-water shipping channels. The hopper dredge is self propelled and can be mobilized to initiate dredging in a relatively short period of time. Hopper dredges have excellent maneuverability and can work effectively in congested harbors (Cullinane et al. 1986).

15. Materials are excavated and pumped through the drag arm into hoppers located in the vessel hull. Hoppers are sometimes allowed to overflow supernatant until the contents are of a high enough density to achieve an "economic load." Hopper overflow may be quite turbid when dredging fine-grained materials that do not settle rapidly in the hopper bins. Aside from

possibly requiring rehandling if currents do not move sediments away from the dredging site, overflow of fine materials into the top portion of the water column is highly visible and aesthetically displeasing. If sediments are contaminated, pollution of the water column may be a problem. Sediment plumes caused by a hopper/drag arm dredge (with overflow) were evaluated at Grays Harbor, Washington. Sample boats anchored behind the passing hopper/drag arm dredge measured the dispersal of the sediment plume as a function of time or distance behind the dredge. During dredging with overflow, high total suspended solids (TSS) concentrations resulted near the top of the column and TSS levels of around 700 mg/ℓ developed near the bottom as the plume settled. The resuspended plume caused by the hopper/drag arm dredge without overflow produced plume TSS concentrations that were negligible in the upper water column and only 40 to 50 mg/ℓ near the bottom (Havis 1988).

Horizontal auger dredge

16. The horizontal auger dredge is a relatively small portable hydraulic dredge designed for projects where a 50- to 120-yd^3/hr discharge rate is sufficient. Instead of the conventional cutter, the horizontal auger dredge has a horizontal cutterhead equipped with cutter knives and a spiral auger that cuts the material and moves it laterally toward the center of the auger where it is picked up by the suction. This cutter can remove a layer of material 8 ft wide and 1.5 ft thick from water depths of 2.0 to 15 ft, leaving the dredged bottom flat and free of the windrows that are characteristic of the typical cutterhead dredging operation (Barnard 1978). By covering the cutter/auger combination with a retractable mud shield, the amount of turbidity generated by the horizontal auger dredge's operation may be reduced. Movement of the dredge through the water is controlled by conveying along a cable in a direction perpendicular to the auger.

17. More than 500 horizontal auger dredges are in operation. During a monitored operation, near-bottom suspended solids concentrations 5.0 ft from the auger were slightly greater than 1,000 mg/ℓ, relative to near-bottom background concentrations of 500 mg/ℓ. Surface and middepth concentrations measured 5.0 to 12 ft in front of the auger were typically less than 200 mg/ℓ above background values of 40 to 65 mg/ℓ. In general, the turbidity plume was confined to within 20 ft of the dredge (Nawrocki 1974).

18. A Mudcat horizontal auger dredge was tested during the New Bedford Superfund Pilot Study in 1988. Sediment containing approximately 200 ppm PCB was removed and pumped to a confined disposal facility. Suspended solids

concentrations 1 to 3 ft above the dredgehead averaged 1,600 mg/ℓ. However, minimal increases in suspended solids were observed in the water column surrounding the dredge (USAE Division, New England 1989).

Matchbox suction head dredge

19. To dredge highly contaminated sediments in Rotterdam Harbor, Volker Stavin Dredging developed the matchbox suction head dredge (d'Angremond, deJong, deWaard 1984). This dredge is designed to remove fine-grained sediment at near in situ density and keep resuspension to a minimum. The matchbox suction head is a plain suction dredge head enclosed in a housing that resembles a matchbox. The housing collects escaping air bubbles, and valved openings on each side of the suction head allow the leeward opening on each swing to be closed to avoid an influx of water. A comparison test of sediment resuspension of a matchbox suction head and a cutterhead was conducted by the Corps of Engineers in Calumet Harbor, Illinois, on Lake Michigan. The report concluded that the matchbox is capable of removing sediment with very little resuspension. The report also concluded that the cutterhead produced very little resuspension when operated properly (Hayes, McLellan, and Truitt 1988).

20. The matchbox dredge was also tested during the New Bedford Superfund Pilot Study. The dredge effectively removed contaminated sediment with a minimal loss of suspended solids and PCBs (USAE Division, New England 1989). Suspended solids concentrations 1 to 3 ft above the dredgehead averaged 300 mg/ℓ. Concentrations 500 ft from the dredge were at a background level of 10 mg/ℓ. Production efficiency was hampered by clogging of the dredge head with debris.

Oozer pump

21. The Oozer pump was developed by Toyo Construction Company, Japan. The pump operates in a manner similar to the Pneuma pump system; however, there are two cylinders (instead of three), and vacuum is applied during the cylinder-filling stage to achieve more rapid filling of the cylinders. The pump is usually mounted on a dredge ladder and is equipped with special suction and cutter heads depending on the type of material being dredged. Dredging depth is limited only by ladder depth. The conditions around the dredging system, such as the thickness of the sediment being dredged, the bottom elevation after dredging, and the amount of resuspension, are monitored by high-frequency acoustic sensors and an underwater television camera. A large Oozer

pump has a dredging capacity ranging from [illegible]00 to 650 yd^3/hr and produces a slurry of up to 80 percent of in situ density (Herbich and Brahme, in press).

22. In the 11-year period from 1974 to 1984, approximately 1 million cubic meters of contaminated sediments was removed by the Oozer dredge (Ikalainen 1987). During one dredging operation, suspended solids levels within 10 ft of the dredging head were all within background concentrations of less than 6 mg/ℓ (Herbich and Brahme, in press).

Pneuma pump

23. The Pneuma pump was the first dredging system to use compressed air instead of centrifugal motion to pump slurry through a pipeline. The Pneuma pump has been used extensively in Europe and Japan. During the dredging process, the pump is submerged, and sediment and water are forced into one of the empty cylinders through an inlet valve. After the cylinder is filled, compressed air is supplied to the cylinder, forcing the water through an outlet valve. When the cylinder is almost empty, air is released to the atmosphere, thus producing atmospheric pressure in the cylinder. A pressure difference occurs between the inside and outside of the cylinders, creating a suction that forces the sediment into the cylinder. When the cylinder is filled with sediment, compressed air is again pumped into the cylinder to expel the sediment from the cylinder. The capacity of a large Pneuma pump is 2,600 yd^3/hr. Use of the Pneuma pump in water depths of 150 to 500 ft is theoretically possible (Cullinane et al. 1986). However, the Pneuma pump will not operate satisfactorily at water depths less than approximately 12 ft.

24. Field tests on a Pneuma model 600/100 were conducted by Richardson et al. (1982). The results of turbidity monitoring, although not definitive, seemed to support the manufacturer's claim that the Pneuma pump generates a low level of turbidity when operated in loosely consolidated fine-grained sediment. Results also indicated that the Pneuma pump was able to dredge at almost in situ density in loosely compacted silty clay, typical of many estuarine sediments. The Pneuma pump, however, was not able to dredge sand at in situ density, and the efficiency of the dredge was consistently below 20 percent. Cables and pipelines used for the system may create temporary obstructions to navigation (Cullinane et al. 1986).

Refresher system

25. Another system recently developed in Japan is the Refresher system. This system is an effort to modify the cutterhead hydraulic dredge. The Refresher uses a helical-shaped head to feed the sediments into the suction

pipe. A cover over the head reduces resuspension. The Refresher also uses an articulated dredge ladder to keep the head level to the bottom over a wide range of dredging depths. During several tests in similar material, the Refresher system produced suspended sediment levels ranging from 4 to 23 mg/ℓ within 10 ft of the dredge head as compared to 200 mg/ℓ with a conventional cutterhead dredge. Production for the cutterhead (26-in. discharge) was 800 yd^3/hr while production with the Refresher system (17-in. discharge) was 350 yd^3/hr. The researchers felt that the Refresher system produced one fiftieth of the total resuspension produced by the operation of a cutterhead dredge (Kaneko, Watari, and Aritomi 1984).

Suction dredges

26. The suction dredge is a pipeline cutterhead dredge with the cutterhead removed. Skid plates may be placed under the ladder, and a vertical elbow may be constructed within the suction pipe to improve operations. With the exception of cutterhead controls, the operation and dredging depths for the suction dredge are comparable to those for the cutterhead pipeline dredge. Suction dredges generate low levels of turbidity but are limited to dredging soft, free-flowing, and unconsolidated material. Trash, logs, and other debris in the dredged material will clog the suction and greatly reduce the effectiveness of the dredge (USEPA 1985).

Waterless dredge

27. The waterless dredge is a recently developed dredging system where the cutter and a submerged centrifugal pump are enclosed within a half-cylindrical shroud. The waterless dredge was designed by Waterless Dredge Company for the removal of lagoon sludges at a minimum water content. According to the manufacturer, this system is capable of pumping slurry with a solids content of 30 to 50 percent by weight with little generation of turbidity. The Waterless dredge was used in the removal of sediment contaminated with lead from the Mill River in Connecticut. Results of the dredging process were apparently successful enough for the authorization of a second dredging (USEPA 1985).

Mechanical Dredge Technologies

28. Mechanical dredges remove bottom sediment by the direct application of mechanical force to dislodge and excavate the material at almost in situ densities. The mechanical dredges that are discussed in the following section

include the backhoe, bucket ladder, bucket wheel, bucket (such as clamshell, orange-peel, and dragline), and dipper dredges.

Backhoe

29. A backhoe is a boom or dipper arm with a bucket attached to the boom. The backhoe unit may be mounted on a crawler or barge and is hydraulically operated. The largest backhoe will excavate to a maximum depth of approximately 30 ft, but depths up to 80 ft are possible with the use of backhoes with extended dipper arms, modified engines, and counterweight frames. A small backhoe mounted on rubber tires can be used for fast excavations on stable working surfaces (USEPA 1985) or from barges. Resuspension rates for this equipment are expected to be high because the bucket is open as the dredged material is pulled through the water column.

Bucket ladder dredge

30. Bucket ladder dredges consist of an inclined submersible ladder supporting a number of buckets that rotate around the circumference of the ladder. They are most commonly used in the mining industry for sand and gravel excavation but may be utilized to load barges. The buckets, which range in volume from 2.8 to 366 ft^3, pick up sediment at the bottom of the ladder and bring the material to the top of the ladder where the sediment is removed by the dumping action produced when the bucket rotates around the top ladder pivot. Limitations of the bucket ladder dredge are bucket leakage and the increased turbidity due to the mechanical agitation of sediments. A large amount of support equipment and a complicated configuration of mooring lines are necessary for the operation of the bucket ladder dredge (Hand et al. 1978).

Bucket wheel dredge

31. The bucket wheel dredge is a bucket wheel excavator developed to improve the efficiency of the cutting operation. Because the cutting force is concentrated on a much shorter cutting edge, the bucket wheel has the capability of efficiently digging highly consolidated material. In addition, the material is force fed to the suction as the wheel turns, making it possible to control the solids content of the dredged material slurry by varying the rotation speed of the wheel. Theoretically, this bucket wheel not only accurately digs to prescribed levels, but also maximizes the pickup of the excavated material (Turner 1979).

Clamshell

32. The clamshell dredge is a conventional dredge readily available throughout the United States. Clamshell dredges are available in different sizes, boom lengths, and bucket sizes. Clamshell dredges are usually barge mounted and transported by tugs, but they can be ship mounted and self-propelled. The clamshell dredge is used primarily in the removal of soft or cohesive sediment and is exceptionally useful for excavating sediment in deep water and for dredging in locations alongside structures. Clamshell dredges are also used in the excavation of sediments in winding river channels (USAE District, Buffalo 1969). In most cases, anchors and spuds are used to position and move the barge during dredging. Clamshell dredges typically load dredged material into scows or barges that are towed to the disposal site. A minimum vessel draft of 6 ft is required for the clamshell barge and the barges to transport the sediment. The clamshell dredging process resuspends solids when the bucket impacts the sediment, is drawn from the sediment, and is pulled through the water column. Large clamshell dredges are capable of removing 400 yd^3/hr when excavating soft, lightweight sediment and using a 12-yd^3 lightweight bucket (USAE District, Buffalo 1969). Costs for clamshell dredges range from \$3 to \$11/yd^3 (USAE District, Chicago (in preparation)).

Closed-bucket clamshell

33. The closed-bucket clamshell is a conventional clamshell fitted with a special bucket designed to enclose the excavated sediment so that sediment resuspension caused by pulling the bucket through the water column and draining above the water is minimized. Various bucket designs have been considered. One has tongue-in-groove edges that seal when the bucket is closed. The top is also closed to minimize the loss of dredged material. The bucket can be used on clamshell dredges with no modification required to the dredge. Field tests concluded that sediment resuspension was confined to the lower water column although the total resuspension was the same as a conventional clamshell bucket (Hayes, McLellan, and Truitt 1988).

34. The closed-bucket clamshell has the same limitations as the conventional clamshell with respect to vessel draft. The vessel draft of the clamshell barge and of the sediment transportation barges precludes its use in water with depths less than 6 ft. An advantage is that the closed-bucket clamshell can remove the higher solids concentrations with near in situ water content of contaminated sediment.

35. The closed-bucket clamshell is more effective in the removal of contaminated sediment than a conventional bucket due to less sediment release as the bucket is drawn upward through the water column. Disadvantages of the closed-bucket clamshell bucket are that the seals are subject to damage and impact of the bucket on the bottom creates a surge that resuspends sediment (Hayes, McLellan, and Truitt 1988; McLellan et al. 1989). It is difficult to dredge areas with debris or boulders since these types of material can damage the rubber seals; this prevents a good seal, thus negating the bucket's effectiveness (Ikalainen 1987). A closed bucket clamshell was used for a 1990 cleanup of contaminated sediment from the Black River near Lorraine, OH.

Dipper dredges

36. The dipper dredge is basically a barge-mounted power shovel equipped with a power-driven ladder structure and operated from a barge-type hull. A bucket is firmly attached to the ladder structure and is forcibly thrust into the material to be removed. The dipper dredge is best suited for excavating hard compacted materials, rock, or other solid materials after blasting. Although it can be used to remove most bottom sediment, the violent action of this type of equipment may cause considerable sediment disturbance and resuspension, particularly during dredging of fine-grained material. In addition, a significant loss of the fine-grained material will occur from the bucket during the hoisting process (Cullinane et al. 1986). The rate of sediment excavation using the dipper dredge is dependent upon bucket size, type of material to be excavated, and depth of cut, but can range as high as 400 yd^3/hr (USAE District, Buffalo 1969). The dipper dredge is not recommended for use in dredging contaminated sediment or where resuspension of sediment must be controlled (Cullinane et al. 1986).

Dragline

37. The dragline is a conventional excavation technology that has been used for years in the excavation of sediments and other materials. Draglines are readily available in a variety of sizes with varying boom lengths and bucket sizes. Draglines are very reliable at removing sediment. However, sediment resuspension will be very high because the open bucket must be pulled through the sediment for filling and lifted through the water column. Draglines are inappropriate for contaminated sediment or where resuspension is an issue (Ikalainen 1987).

Operational Control Technologies

38. Operational controls are methods used to reduce the amount of sediment resuspension caused during dredging operations. Sediment resuspension during dredging operations at New Bedford, MA, Superfund Pilot site was greatly dependent on the operational mode of the dredges and on contributions by support and monitoring operations for the shallow estuary (USAE Division, New England 1989). Controls discussed include cutter/auger speed, depth of cut, management of project operations, positioning equipment, swing speed/speed of advance, and work boat controls.

Cutter/auger speed

39. Cutterhead and horizontal auger dredges use rotating blades or cutters to loosen the sediment and facilitate suction by the dredge pump. This prevents large debris from entering or plugging the intake pipe. Adjustments in cutter or auger rotation speed have been reported to affect the rate of resuspension of dredged material (Raymond 1984). The cutter/auger speed should be adjusted to match the capability of the pump to entrain most of the sediment dislodged by the cutters. In general, lower speeds produce less resuspended sediments.

Depth of cut

40. Large sets, very thick cuts, and very shallow cuts should be avoided. Thick cuts tend to bury the dredge head and may cause high levels of resuspension if the suction cannot pick up all of the dislodged material, while in shallow cuts the cutter tends to throw the sediments beyond the intake of the dredge (Hayes, Raymond, and McLellan 1984).

41. In the operation of a pipeline cutterhead suction dredge, the minimum depth of single pass excavation would be approximately the same as one half the pipeline diameter. Actual vertical precision of the cut is often limited by the mechanical control of the ladder and suction head to approximately 1 ft (Cullinane et al. 1986).

42. On some dredging projects, it may be more economical to roughly cut and remove most of the material, leaving a relatively thin layer for final cleanup. However, this remaining material may be subject to resuspension by ambient currents or prop wash from passing ship traffic. Requiring complete removal on each pass will reduce this resuspension (Cullinane et al. 1986).

43. When layer cutting is used, the dredge will remove a single layer of material over a large portion of the channel and then return to dredge

another layer. This continues down to the required depth of the project. Since loose material is often left on the bottom after each layer is dredged, this technique should only be used where resuspension of the remaining material will not create sediment resuspension problems (Cullinane et al. 1986).

Management of project operations

44. In certain situations it may be possible to reduce the spread of resuspended sediments by taking advantage of strong cyclic stratifications in the water column and/or currents. The site-specific nature of such considerations must be emphasized. However, with advanced planning, specific dredging sites within a harbor or bay could be rotated during selected hydrodynamic conditions to productively use confining current patterns. Sequencing of an entire project may require moving progressively from up-current to down-current, from more hydrodynamically active areas to naturally quiescent areas, or using a two-layer/sweep pattern or similar technique to pickup sediments disturbed earlier in a project and subsequently redeposited at other areas of the site (Cullinane et al. 1986).

45. Recent modifications to pipeline dredges such as flow and density instrumentation and underwater video and sensor equipment have improved production capabilities and reduced dredged sediment resuspension. The addition of flow gages and nuclear density gages provides the dredge operator with instant production data. This information can be used to make adjustments to optimize production, such as adjusting cut depth, cutter rotation, and ladder swing. Closed circuit underwater video cameras and water sensors can be mounted on the dredge ladder and used to monitor turbidity in the vicinity of the cutterhead. Adjustments can be made in cutter rotation speed and swing speed to minimize dredged material resuspension. Video cameras are only effective when dredging in relatively clear waters. Sensors are best used in turbid waters (Cullinane et al. 1986).

Positioning equipment

46. Removal of contaminated sediment often requires precise lateral positioning of the dredge to completely remove a contaminated layer of sediment without excessive overcutting or extreme overlapping of dredge passes. Visual controls using color-coded range poles proved to be effective during the New Bedford Superfund Pilot Study. More sophisticated equipment is available to electronically indicate the position of the dredge as it swings and passes through an area. However, specifying a dredge with such controls will significantly increase costs of the removal operation.

Swing speed/speed of advance

47. The leverman should swing the dredge so that the dredge head will cover as much of the bottom as possible. This minimizes the formation of windrows or ridges of partially disturbed material between the cuts. These windrows tend to slough into the cuts, and the material in the windrows may be susceptible to resuspension by ambient currents and turbulence caused by the cutterhead. Windrow formation can be eliminated by swinging the dredge in close concentric arcs over the dredging area (Cullinane et al. 1986).

48. Raymond (1984) indicated that a swing speed greater than 0.5 fps resulted in substantial sediment resuspension. A swing speed of 0.3 fps was indicated to be sufficient enough to reduce resuspension of sediment without seriously affecting the dredge efficiency.

Workboat controls

49. A hydraulic dredging operation requires two or more workboats to move cables and anchors, to ferry equipment from the shore to the dredge, and to perform maintenance on the dredge head. In shallow water, the prop wash of the workboats can be a major source of sediment resuspension. The size and weight of the anchors dictates the size and power of the workboats. For shallow sites, workboat size should be as small as possible. Workboat activities may be reduced by using spud barges in lieu of anchors or by using shoreline anchors where site conditions permit.

Turbidity Containment Technologies

50. Several options have been suggested to aid in the containment of resuspended solids and contaminants released during excavation or dredging operations. At sites where the layout of the harbor/waterway permits and contaminant levels are unusually high, structural barriers may be justified. Barriers to be discussed include caissons, dikes, oil booms, pneumatic barriers, sediment traps, sheet piling, silt curtains, and silt screens.

Caissons

51. Caissons, as used in the construction industry, are load-bearing enclosures that are placed into the ground to protect excavation for a foundation, to aid construction of a substructure, or to serve as part of a permanent structure. Caissons can be used to form a seawall or an impervious core wall for an earthen dam, or to enclose a subsurface space to be used as a pump well. They can be built of common structural materials and can have any

cross-sectional shape. The caisson ranges in size from approximately that of a sheet pile to 100 ft in length and width (Merritt 1976).

52. Caissons are often installed by sinking them under their own weight or surcharging them with the assistance of jacking, setting, excavating, jetting, and undercutting. The concept of caisson employment to contain resuspended sediment in a dredging operation is to allow the caisson to sink under its own weight with minimal disturbance of the bottom sediment. Sediment within the caisson can then be excavated or treated in situ while isolated from the surrounding water. The caisson can be removed after the excavation/treatment operation. Side-by-side placement of the caissons expands coverage of an area. A series of caissons could form a structural barrier, such as a cofferdam, encircling or blocking off a segment of the waterway or harbor. Caissons were used in the Yokohama Harbor in Japan for in situ solidification and stabilization of bottom sediments (Otsuki and Shima 1984).

Dikes

53. Retaining dikes are earthen-filled embankments that may be constructed in shallow waterways to minimize transport of contaminated sediment from a dredging area into natural waters. A retaining dike is similar to a flood protection levee in size and shape. The height and geometric configuration of a retaining dike depend upon the capacity requirements, construction materials, and foundation conditions. Dikes can be constructed perpendicular to streamflow or downstream from a dredging operation to form a holding pond or reservoir and promote settling. Retaining dikes are limited to low-flow streams and harbors with slow currents. Provisions must be made for ingress and egress of dredging equipment and for removal of the dike after removal of the contaminated sediment.

Oil booms

54. Removal of sediment containing high oil concentrations may produce a floating oil layer in the vicinity of the dredging operation. Containment of the oil layer can be achieved by oil containment booms. Such booms are typically a synthetic foam float covered by a flexible urethane or polyvinyl chloride (PVC) fabric. The fabric extends as a skirt 4 to 24 in. below the surface with a steel cable or chain at the top of the float and at the bottom of the skirt. Oil booms provide an effective option for the control of floating contaminants or oil on the surface of the water. They either remove the contaminants and oil by skimming the surface of the water or they contain them

until they can be removed by other means (Palermo and Pankow 1988). Cost of oil booms varies depending on the strength required to withstand site conditions. Typical cost of the boom material ranges from $6 to $55/ft.

Pneumatic barriers

55. Pneumatic barriers such as a pneumatic bubble screen can create a barrier to floating or suspended solids and oil (Boyd et al. 1972). Pneumatic barriers have been used as an option for containing surface oil in areas where oil booms would hinder normal ship navigation. The Dock and Harbor Authority (1986), as cited in Palermo and Pankow (1988), stated that pneumatic barriers have been used around the intakes of water treatment plants to prevent oil pollution from entering the power plant and to reduce intake screen loading by deflecting subsurface debris. Power requirements for pneumatic barriers are very costly, and this technique for creating a barrier seems impractical (Herbich and Brahme, in press). Pneumatic barriers were tested as part of a demonstration conducted by the Corps of Engineers at Great Lakes harbors between 1967 and 1969 (USAE District, Buffalo 1969). At Indiana Harbor, Indiana, a pneumatic barrier was used to prevent migration of solids through a gap in the Inland Steel lakefill. The lakefill was used for disposal of contaminated dredged material, and the gap was necessary to allow access to the lakefill by bottom dump scows. This experiment indicated that the pneumatic barrier was not fully successful in this application.

Sediment traps

56. A predredged sedimentation basin or trap down-current from a removal operation can also be an effective sink or barrier. The basin or trap may be constructed or may simply take advantage of a natural depression in the stream bed. This technique is effective primarily for coarser material and will not allow sufficient settling time for clay fines or organic particles that often transport the greater part of the contaminant load. However, historical dredging data from the Indiana Harbor Canal indicate that the canal, if dredged, would act as a sediment trap to retain contaminated sediment that would have otherwise been transported to Lake Michigan (Brannon et al. 1989). A system of dikes, channel rerouting, and in-stream sedimentation basins was recently employed at Hamilton Harbor, Ohio (McFarlane and Fairn 1989).

Sheet piling

57. General. A sheet pile cutoff wall is a physical barrier driven into the ground to cut off a contaminated area (such as an uncontrolled landfill or chemical spill) from groundwater during remediation. The wall is a

prefabricated structure usually made of steel with sections ranging up to 40 ft long joined by interlocking joints. The walls may also be constructed with wood or reinforced concrete, but these walls are less common than the steel walls. The sheet pile walls are driven into the ground by pneumatic or steam pile drivers. Sheet piling cannot be driven into rocky or granular soils. Since it is subject to an increased possibility of corrosion and breakage of interlocking, sheet piling is generally used as a temporary barrier (USEPA 1985). However, sheet piling is a proven method with experience in industry (Ammon 1983) and has been used in the Great Lakes to contain limestone fill. Sheet piling has not been used solely for containing resuspended sediment, and no evaluation data were found. When the need for the cutoff wall dissipates, the sections can be removed and reused.

58. Cofferdams. Cofferdams are sheet pile structures that could isolate a contaminated area from streamflow during dredging, dewatering, or capping activities. The cofferdam is primarily used in shallow ports, streams, rivers, and low-velocity waters. The cofferdam may be single-walled or double walled with earth fill between the piles. The singular wall is suitable only for shallow water, while double-walled structures may be used for deeper water (greater than 5 ft). Stable cellular cofferdams require a diameter-to height ratio of 0.85 (Ikalainen 1987). Sheet pile cofferdams may be installed in offset pairs across a stream to isolate areas of contaminated sediment and to allow access for dewatering and excavation. If an entire segment of a stream is blocked off, streamflow can be diverted through a bypass channel and/or piping. Costs for sheet pile cutoff walls range from $\$8.02/\text{ft}^2$ to $\$17.03/\text{ft}^2$ (Yang et al. 1987)

Silt curtains

59. Another method for physically controlling the dispersion of near-surface suspended sediment in the vicinity of dredging (and some disposal) operations in quiescent environments involves placing a silt curtain or turbidity barrier either down current from or around the operation. Silt curtains are impervious barriers that extend vertically from the water surface to a specified water depth. The flexible nylon-reinforced PVC fabric (or similar material) forming the barrier is maintained in a vertical position by flotation segments at the top and a ballast chain along the bottom. A tension cable is often built into the curtain immediately above or below the flotation segments (top tension) or some distance below the flotation (center tension) to absorb stress imposed by currents and other hydrodynamic forces. The

curtains are manufactured in sections that can be joined together to provide a curtain of specified length. Anchored lines hold the curtain in a deployed configuration that is usually U-shaped or circular.

60. While using silt curtains, contaminated sediments are trapped inside the barrier and accumulate against it. This accumulation must be carefully controlled before the barrier is removed. Silt curtains are not recommended for operations in the open ocean, in areas where currents exceed 1 knot, in areas frequently exposed to high winds and large breaking waves, or around hopper dredges and some cutterhead dredges where frequent curtain movement would be necessary (JBF Scientific Corporation 1978).

61. In studying a typical pipeline disposal operation surrounded by a silt curtain, results indicated that the vast majority (95 to 99 percent) of the fine-grained material descended rapidly to the bottom where it formed a low-gradient fluid mud mound (JBF Scientific Corporation 1978). While the curtain provides an enclosure where some of the remaining fine-grained suspended material may flocculate and/or settle, most of the suspended sediment and fluid mud flow under or around the curtain. The silt curtain does not indefinitely contain suspended sediment, but instead diverts its flow under the curtain, thereby minimizing the turbidity in the upper water column outside the silt curtain.

62. Silt curtain effectiveness, defined as the degree of turbidity reduction outside the curtain relative to the turbidity levels inside, depends on several factors: the nature of the operation; the quantity and type of material in suspension within or upstream of the curtain; the characteristics, construction, and condition of the silt curtain as well as the area and configuration of the curtain enclosure; the method of mooring; and the hydrodynamic conditions (i.e., currents, tides, waves, etc.) present at the site. Because of the high degree of variability in these factors, the effectiveness of different silt curtain operations is highly variable. Considerable additional detail on silt curtains is provided by JBF Scientific Corporation (1978).

63. A silt curtain was used during the New Bedford Superfund Pilot Study (USAE Division, New England 1989) in an attempt to minimize sediment transport from a dredging operation and an open-water disposal operation. Performance of the curtain was adversely impacted by tidal fluctuations and high winds. For this project, 1,000 ft of curtain 5 ft deep cost approximately $14,000.

Silt screens

64. Silt screens are an alternative to impermeable silt curtains. They are synthetic geotextile fabrics that allow water to flow through small openings, typically 70 to 100 mesh (US standard sieve), but contain the suspended solids. The silt screen is advantageous in that it extends from the water surface to the bottom sediment with a float on the top and an anchor on the bottom of the screen. As the water level rises and falls, the silt screen is alternately folded and extended, maintaining the screen's effectiveness without allowing suspended solids to flow through gaps underneath or above the screen (Palermo and Pankow 1988). Effectiveness in retaining fine-grained particles is limited by the pore size of the screen, which must be large enough to allow for water flow and to not easily be blinded by particulates trapped on the screen.

PART II: DREDGED MATERIAL TRANSPORT TECHNOLOGIES

Controls for Barge/Scow Transport

65. Barges and scows have been one of the most widely used methods of transporting large quantities of bulk material over long distances. Barge movement of material is reasonably cost effective and is adaptable to most dredging operations (Souder et al. 1978). Primary controls to prevent spread of contaminated materials when utilizing barge transport include decontamination of equipment, loading/unloading procedures, and selection of appropriate routes and navigation controls.

Barge selection

66. A number of types of barges have been used on the Great Lakes to transport dredged materials: split hull, bottom dump, side dump, open, and flat. The first three are typically used to transport materials to the open lake or near shore and will open along one or more seams for material release. These barges/scows can be used to transport contaminated sediments if the seams are sealed or controlled. Hay has been used to block the seam with split hull barges. An open barge is basically a box with an open top and is most readily applicable to transporting contaminated sediments. A flat barge has a flat surface and might be used to transport dry materials or debris. Barges are available in capacities ranging from a few hundred to several thousand cubic yards. Size selection depends not only on production rate of the dredge, but physical constraints for the site, including channel width, depth, and accessibility.

Route/navigation controls

67. Route selection for barge transport of dredged material (regardless of material conditions) is very important with regard to control and prevention of potential spill situations. Routes should avoid, as much as possible, public use areas and areas where there is a sensitive environmental resource. The route selected should be carefully surveyed for possible underwater navigation hazards and obstructions above the water line. A study of river conditions must be conducted to determine optimum operational conditions and situations when barge towing would be most susceptible to accidents. Also, a worst-case study should be performed to determine effects of a significant spill or leak of the dredged material. Results of these reviews should then be incorporated into spill-response plans.

Loading/unloading controls

68. The greatest potential for uncontrolled release of contaminated materials associated with barge transport is presented in the loading and unloading operations. All options for material transfer should be considered. Loading and unloading can be accomplished by hydraulic or mechanical means. With hydraulic dredging, flexible connection from the dredge to the barge reduces the possibility of pipe damage due to wave action. With clamshell dredging, movement of the crane boom between the dredge and barge must be carefully controlled to minimize material spilled into the waterway. Loading controls include restrictions to prevent material "free-falling" into a barge and maintaining a minimum freeboard in the barge to avoid overflow.

69. Barges can be unloaded directly into a disposal facility or into other vehicles for secondary transport. At barge unloading points, material can be removed hydraulically with a pump mounted on the barge or on land. Mechanically dredged sediments can be slurried with water pumped from the river for hydraulic unloading. Controls for hydraulic unloading of barges are the same as those discussed for pipeline transport.

70. Mechanically dredged sediment can be unloaded mechanically by a crane and clamshell or other means. Controls to minimize spillage during mechanical unloading used at Great Lakes CDFs include drip pans or aprons, hoppers with chutes, and various types of slides. Additional control measures that should be considered for unloading areas required with secondary transport include site drainage, spill collection sumps, and decontamination systems (Souder et al. 1978).

71. Proper design and selection of pumps for dredged material transport are critical for smooth operation. Pumps should be selected on the basis of flows and material content expected during the dredging operation. Correct sizing, installation, and construction of protective shelters will significantly reduce maintenance and likelihood of pump failure.

Decontamination

72. Decontamination of the barge after shipment is complete is particularly important since the barge may be used in different operations. Also, the decontamination operation will have to be carefully planned to prevent runoff from entering clean areas. High-pressure water sprays to remove contaminated material will suffice in most cases, and water residue collection will have to be considered.

Controls for Hopper Dredge Transport

73. Controls for hopper dredge transport are the same as for barge/scow transport.

Controls for Pipeline Transport

74. Pipelines are commonly used to transport bulk materials over relatively short distances. Hydraulic pipeline transport has been used for industrial transport of many types of ores and minerals, coal, limestone, and fertilizers. However, the most extensive use of hydraulic transport is in the dredging field. For navigation dredging, pipelines with booster pumps are up to 3 miles in length; whereas commercial land reclamation/fill operations may have pipelines as long as 15 miles. Pipelines may be longer depending on distance from excavation point to the disposal site. The cost and real estate requirements for lengthy or fixed pipelines may be feasible for sites with long-term maintenance dredging needs, but prohibitive for one-time sediment remediation projects. Temporary pipelines, extending along the waterway or some public access may be more feasible for such actions. Such pipelines would be furnished by the contractor hired for a specific dredging increment, removed after the dredging was completed, and would not require permanent easements or rights-of-way (Souder et al. 1978).

75. During the design stage, engineers should carefully consider pipeline routes, expected climatic conditions, corrosion resistance, redundancy of safety devices (i.e., additional shutoff valves, loop/bypasses, pressure relief valves), coupling methods, and systems to detect leaks. Souder et al. (1978) outline specific pump and pipeline design procedures.

Pipeline selection

76. Because pipelines for dredges are usually in place for a relatively short period of time, pipeline systems generally use piping and connections that can be easily installed and dismantled for reuse. Movement of the dredge also requires flexibility in bending of the pipeline and ease of adding/removing sections of pipe to accommodate progression of the dredging operation. Steel or iron pipe with flanged joints has traditionally been used in the dredging industry, but use of high-density polyethylene (HDPE) pipe for dredging applications is increasing in popularity. HDPE can be joined by flanges or compression couplings, but the recommended joining technique is by

a heat fusion technique. HDPE offer the advantages of lower hydraulic friction losses, more flexibility in bending, lighter weight, improved resistance to abrasion, and slightly lower costs compared to steel pipe. HDPE should not be used for extremely sharp, granular material (Pankow 1987). Steel pipe is more rigid than HDPE, allowing longer unsupported spans and reducing susceptibility to damage during handling with construction equipment.

Pipeline routing

77. Selection of the best pipeline route should not be overlooked as a control measure for transporting contaminated dredged material. However, since sediment remediation projects are relatively short term, pipelines for such projects are generally temporary and have limited flexibility in route selection. The pipeline system almost always includes a section of floating pipeline extending from the dredge to the shore and may include a shoreline section from the water's edge to the disposal site. While the shortest distance from the dredge to the disposal site is usually the most economical route, it may not offer the best protection against breaks in the pipeline. The floating section of the pipe should be routed to minimize interference with boats or ships. In some cases the line may be submerged to avoid frequently moving the line to clear the way for boat or ship traffic. The in-water section of the pipeline should also avoid strong currents or other forces that increase the chance for a break in the line. Routing the pipeline over an area that is included in the remediation project is preferable to transporting the contaminated material across an area that is clean or an area that is environmentally sensitive. The land portion of the pipeline route should be selected to avoid areas where it might be damaged by traffic or construction activities and to take advantage of topographic features that would assist in containing material released if the pipe should rupture.

Pump controls

78. Proper design and selection of pumps for dredged material transport are critical for smooth operation of a pipeline system. Pumps should be selected on the basis of flow and material content expected during the dredging operation. Correct sizing, installation, and construction of protective shelters will significantly reduce maintenance and the likelihood of pump failure.

79. Three basic pump types are used in pumping dredged materials: positive displacement, centrifugal, and compressed air pumps. Positive displacement pumps are used in long-distance pipelines, as fewer pumps are

required due to their higher pumping pressure. However, since the valve system of the positive displacement pump can be impeded or damaged by foreign material (nuts, bolts, wire, or rocks), it is recommended that the material undergo careful screening or that the positive displacement pump not be used (Souder et al. 1978).

80. Centrifugal and compressed air pumps are better able to pump dredged material owing to their ability to accept variable-sized materials. In terms of contaminant control during pumping operations, special consideration should be given for mitigating corrosion and cavitation of pump impellers. The abrasive nature of sediment as well as contaminants within the dredged material may quickly corrode internal mechanisms of pumps. The impact of solid particles on impellers and interior housing will reduce effectiveness of the pump as well as cause (or contribute to) leakage (Souder et al. 1978). Souder et al. (1978) provide detailed example design procedures for determining pump size and estimates for cost factors.

Leak detection

81. Placement of leak-detection instrumentation at critical locations along the pipeline route should be considered since early detection of leaks may prevent major contamination from occurring. Detection devices should be located where frequent inspection, maintenance, and calibration can be performed. Devices such as flow or pressure indicators should be situated between pump stations so the loss of pressure or flow would activate a leak alarm. Such devices should also be available to the dredge operator so the dredge can be shut down immediately if a pressure change indicates a leak (Cullinane et al. 1986). If a leak in the pipeline should occur during pumping, the pumps should be shut down and the contaminated area contained with booms or absorbent materials to prevent spreading. Absorbent materials could be placed on the liquid, and shovels could then be used to place the contaminated liquid and soil that absorbed the liquid into barrels for treatment and disposal.

Redundancy of safety devices

82. Most safety devices employed for a pipeline transport system are subject to failure. Even though pipe, pipe connections, and pumps are carefully selected and assembled, reliability is less than 100 percent. Therefore, key components of the system should be replicated where failure of a component can produce major spills of contaminated material. For extreme conditions, duplex booster pumps and leak detection devices may be necessary.

Decontamination

83. The decontamination of a hydraulic pipeline system would involve purging the pipeline with water or a clean sand slurry to scrub the inner lining of the pipe. The use of sand would improve removal of contaminated dredged material clinging to the inside of the pipe and pumps. The sand exiting the pipeline after decontamination would have to be disposed of as contaminated material or treated to remove the contaminants.

Controls for Rail Transport

84. Rail haul using the unit train concept is technically feasible and economically competitive with other transport modes for hauling dredged material distances ranging from 10 to 100 miles. A unit train is one reserved to carry one commodity from specific points on a tightly regulated schedule (Souder et al. 1978). Facilities are required for rapid loading and unloading to make the unit train concept work and to enable benefits from reduced rates on large volumes of bulk movement. Bottom dump cars or rotary car dumpers are needed to meet the rapid loading and unloading requirement. Control of dust by using covers is important since the dredged material may remain in the rail car for extended periods of time, dry out, and possibly become a dust problem. Economic feasibility demands the utilization of existing railroad tracks. However, the building of short intermediate spurs may be required to reach disposal areas.

85. The concept of a unit train has significantly increased efficiency and utilization of rail transport of dredged material. With regard to rail haul, mechanically dredged material or sediments that have been dewatered are most suitable. The transport of a dredged material slurry is not recommended since the increased moisture content increases the volume of material to be transported. As of 1978 there were over 100 unit train bulk hauling operations for hauling coal primarily, but other materials could feasibly be transported.

86. The following items should be taken into consideration in planning for rail haul transport to a CDF or treatment site:

a. Scheduling and length of unit trains are often strictly regulated.

b. State regulations may require open hopper cars to be covered.

c. Dual use of hopper cars may require washing of cars between use and treatment of wash water to prevent contaminant transfer.

87. Rail transport has a lower energy cost per unit volume of dredged material than truck hauling. Rail transport may require a large unrecoverable capital expenditure. In addition, it has some of the same problems associated with trucking, such as an ongoing administrative burden, vulnerability to labor disputes and strikes, risk of spills, and because of the labor requirements, an operational cost that will rise continually. However, special circumstances may favor rail hauling. For example, if dredged material is to be used to rehabilitate strip-mined lands, a rail line may have been built for hauling out the coal. That line would still be available for the transport of dredged material (Souder et al. 1978).

88. Rail transport was considered during the Craney Island, Virginia, Disposal Study. Unit trains returning empty to West Virginia after transporting coal were considered as possible carriers of dredged material. If implemented, this plan would have required washing the cars after unloading the dredged material in order to avoid contaminating the coal being transported on the return trip. Another problem with this plan would have been the disposal of the residue after washing the rail cars (Souder et al. 1978).

Car selection

89. Three methods of ensuring the adequacy of rail car equipment are available: by leasing, by outright purchase, or through placement of the required number of cars in "assigned service" by the carrier under the terms of the haul contract. Generally, an assigned service option is available only for a solid (dry) or semisolid (mechanically dewatered) material that can be transported in hopper cars. As a generalization, the amortization of the purchase of a hopper car (at approximately $90,000 to $120,000 new) will be at a higher cost than the rental or lease fee (USEPA 1979). Open-top rail cars in a unit train concept would have a capacity of 78 yd^3 (Souder et al. 1978).

90. Railroad hopper car use is subject to minimum shipment fees per car and certain demurrage criteria. For example, a single hopper car minimum shipment is 180,000 lb, and demurrage criteria are that the car must be loaded within 48 hr and unloaded within 24 hr. Typical hopper car capacities are 96, 119, and 152 yd^3, with the smallest size being typically the most readily available (USEPA 1979).

91. Transporting contaminated dredged materials over long distances requires control of potential emissions from the rail car, such as dust or

water leaking from the bed. Placing a cover over the dredged material will substantially reduce windblown dust. This is particularly necessary when using railways where the reduction of public exposure to contaminated dust is desired. To prevent water leaking from the railcar bed, use of heavy polyethylene liners is recommended. Lining the railcar bed will also aid in decontamination after the car has dumped its load (USEPA 1979).

Route selection

92. Selecting a rail route for transporting contaminated dredged material has similar factors as barge/scow transport. Local traffic patterns and volumes should be carefully analyzed so as to avoid congested routes or routes that may offer increased risk of accidents. In addition, routes should avoid public use areas, environmentally sensitive areas, and major residential areas.

Loading/unloading controls

93. The loading/unloading controls for rail transport are generally the same as those discussed for barge transport. Since rail transport of a slurry is not recommended, controls for mechanical transfer from a barge to rail cars should be considered. Rails cars could be unloaded inside a disposal site, storage area, or transfer station mechanically or hydraulically (if additional water is available to form a slurry). If the unloading area was not inside a disposal site or secure storage area, the following controls should be considered:

- a. Drainage of water from the unloading area into a central sump for periodic removal.
- b. Daily removal of spilled material.
- c. Specially designed unloading ramps to collect spilled material.

Decontamination

94. Decontamination of rail car undercarriages may be necessary to control contaminated materials from falling onto public roadways when leaving loading/unloading areas. High-pressure water sprays to remove contaminated material will suffice in most cases. Water residue collection will have to be considered. If the dredging operation is to be of long duration, a semipermanent wash stand may be constructed to more efficiently remove material and control runoff. Whenever rail cars are to be used for other purposes, beds should be decontaminated prior to reuse.

Controls for Truck Transport

95. Trucking provides flexibility not found in other modes of transport since terminal points and route can be changed readily at low cost. Provided trucks are leased rather than purchased, the truck hauling option is not capital-intensive and allows more flexibility than pumping or other transport modes. This flexibility is valuable where more than one location for treatment or disposal may be used (USEPA 1979).

96. Trucks have been used for transport of mechanically dredged materials over distances up to 5 to 10 miles. Rail transport becomes more cost effective at greater distances. Controls associated with transporting dredged material by truck parallel those for barge/scow and rail transport.

Truck selection

97. Transporting contaminated materials over long distances requires control of potential emissions from the truck, such as dust or water leaking from the bed. Placing a cover over the dredged material will substantially reduce windblown dust. This is particularly necessary when using roadways with heavy traffic, where reducing public exposure to contaminated dust is desired. To prevent water leaking from the truck bed, use of heavy polyethylene liners and special gaskets for gates can be used. Also, sand or clay could be used to seal the bottom of the gate. Lining the truck bed will also aid in decontamination after the truck has dumped its load.

98. Sediment hauling trucks are similar to standard highway trucks because both types of trucks must use public roads and comply with vehicle width, height, and gross weight restrictions. For the majority of cases, which involve comparatively short distances with one-way travel times less than 1 hr, ease and speed of loading and unloading are of paramount importance. The larger trucks with a capacity of 18.5 yd^3 are the most economical except for one-way haul distances less than 10 miles and annual sediment volumes less than 3,000 yd^3 for dewatered dredged material (USEPA 1979).

Route selection

99. Selecting a truck route for transporting contaminated dredged material has similar factors as barge/scow transport. The primary factor is the availability of roads between the loading and unloading points. Local traffic patterns and volumes should be carefully analyzed so as to avoid congested routes or routes that may offer increased risk of accidents. In addition,

routes should avoid public use areas, environmentally sensitive areas, and major urban/residential areas. The following factors should be reviewed:

- a. Bridge/tunnel/underpass restrictions.
- b. Roadway capacity (size and weight).
- c. Grades and curves on the proposed route.

100. Restrictions may be placed on any significant truck operations, such as requiring specific routes or limiting operations to daylight hours. Such haul scheduling may require the provision of some form of temporary storage of the dredged material in a confined disposal facility. Using trucks or trailer bodies as temporary storage may not be the most economical method when drivers' work hours and overtime pay are considered.

Loading/unloading controls

101. The simplicity of loading and unloading requirements and the relative abundance of available roadways make truck hauling technically the most attractive transport mode. The economic feasibility of truck hauling is based on rates established by negotiation with trucking companies and includes all associated driver and fuel costs.

102. Federal, state, and local regulations will govern the maximum size and weight a truck can attain for the hauling of dredged material. During loading operations the truck must not be overloaded. A primary factor affecting weight of the dredged material is its moisture content. Dredged material high in moisture content will weigh more than dewatered dredged material, thus increasing the weight and volume of dredged material for transport as well as transportation costs. Therefore, the feasibility of dewatering the dredged material before transport should be considered (Souder et al. 1978).

103. The loading/unloading controls for trucks are similar to those for barge/scow and rail transport. Since truck transport of slurries is not recommended, the controls for mechanical transfer from barges should be considered. Unloading wet sediments at a disposal facility or a storage or rehandling area can pose a number of problems. Depending on the moisture content, mechanically dredged sediment may be quite fluid or dry enough to pile. Specially designed unloading ramps may be necessary for truck access. Earthmoving equipment may be needed to move the wet sediments and maintain truck access.

Decontamination

104. Decontamination of truck undercarriages may be necessary to control contaminated materials from falling onto public roadways when leaving

loading/unloading areas. High-pressure water sprays to remove contaminated material will suffice in most cases. Water residue collection will have to be considered. If the dredging operation is to be of long duration, a semipermanent wash stand may be constructed to more efficiently remove material and control runoff. Whenever trucks are to be used for other purposes, beds should be decontaminated prior to reuse.

PART III: PRETREATMENT TECHNOLOGIES

Dewatering Technologies

105. Dewatering technologies are used to drain water associated with excavated sediments and carriage water used to slurry sediments with hydraulic dredging or pipeline transport. Mechanically dredged sediments typically have a water content comparable to in situ sediments (roughly 50 percent water by weight for most fine-grained sediments). Hydraulically dredged or transported sediments may be 90 percent or more water. Many treatment technologies have rigid requirements on the amount of water in feed materials, and dewatering may be necessary to prepare sediment for subsequent treatment. Water removed from dredged sediments or slurries must receive further treatment before discharge. Effluent/leachate treatment technologies are discussed in Part VI.

106. Dewatering technologies include passive systems and mechanical systems. Passive systems are those which are used at confined disposal facilities. These include settling, surface and subsurface drainage, wick drains, and related CDF management practices to promote drying and cracking. The Corps of Engineers has developed a number of guidance documents on the dewatering and densification of dredged materials at CDFs (US Army Corps of Engineers 1987, Haliburton 1978).

107. Mechanical dewatering systems have been extensively used for conditioning municipal and industrial sludges and slurries. These systems usually require the input of energy to squeeze, press, or evaporate water from the feed. Relatively few applications to soils or sediments are known. Most mechanical dewatering technologies can reduce water content to about 50 percent by weight. Since this is the starting water content for mechanically dredged sediments, the applicability of these technologies may be limited to hydraulic slurries.

Primary settling

108. Within a CDF, a hydraulic slurry will be dewatered by several processes, including settling, drainage, and evaporative drying. With hydraulic dredging/transport, the CDF functions as a large settling pond. Coarse sediments will deposit rapidly near the discharge, while finer particles may require detention times of several hours to several days to settle. The settling efficiency of a CDF is controlled by the hydraulic characteristics of the settling pond and the drainage mechanism. With most CDFs designed for

hydraulic dredges, an overflow weir is used to drain surface water. Weir overflow is controlled by the static head and the effective weir length provided. The depth of the pond water is controlled by the weir crest elevation. The ponded surface area of the site is less than the total surface area enclosed by the dikes because of the mounding of the coarse-grained solids and the minimum freeboard requirements. Effective settling area is reduced by wind, turbulence, and short-circuiting. Internal dikes can be built to improve the settling efficiency by altering flow patterns, modifying currents, and allowing longer periods for settling (Cullinane et al. 1986).

109. The solids that accumulate in the pond will decrease the effective size and settling effectiveness of the pond. The treatment requirements for the water drained from the CDF (effluent) may therefore increase as filling progresses. Alternately, accumulated solids might be removed for treatment either continuously or periodically to maintain the settling efficiency.

110. Once active disposal operations are completed, the dredged material solids continue to consolidate, expelling water from the sediment. Lowering the weir elevation allows for drainage of the surface water. Evaporation and transpiration of water from the surface remove water and further promote consolidation. Over a period of months, a solids concentration competitive with mechanical dewatering effectiveness can be achieved.

Surface drainage

111. Surface water conditions within a CDF will depend on the type of facility and method for dredging/disposal. In-water CDFs will have a permanent pond until sediments have been deposited to an elevation above ambient lake levels. Once filled to this level, the surface water conditions in an in-water CDF will be similar to an upland facility. Upland CDFs will have ponded conditions during hydraulic dredge/disposal operations. With mechanical dredge/disposal operations, limited amounts of free water are released from the sediments and may pond. Heavy rains can also cause localized ponding.

112. Drainage of surface water can be accomplished through a number of mechanisms. Most existing in-water CDFs on the Great Lakes have dikes constructed of stone and granular material and remain permeable for part of their filling life. As dredged materials are disposed to the CDF pond, the water level rises from displacement. This static head drives water through permeable sections of the dikes. Suspended sediments become entrapped by dike materials and, when dredged materials are placed on the dike face, their

permeability is greatly diminished. When dikes are no longer permeable enough to pass flows equivalent to the dredge disposal, surface water is drained using overflow weirs or filter cells, or is pumped from secondary basins.

113. With hydraulic dredging/disposal to upland CDFs (or in-water CDFs filled above the lake level), overflow weirs are most commonly used for surface drainage. At the beginning of disposal operations, the outlet weir is set at a predetermined elevation to ensure that the ponded water will be deep enough for settling as the containment area is being filled. As the disposal operation begins, slurry is pumped into the area. No effluent is released until the water level reaches the weir crest elevation. Effluent is then released from the area at about the same rate as slurry is pumped into the area. Thereafter, the ponding depth decreases as the thickness of the dredged material deposit increases. After completion of the disposal operation and the activities requiring water, the ponded water is removed as quickly as effluent water quality standards will allow (USACE 1987).

114. The removal of water following the dredging operation can be expedited by managing inlets and weirs during the disposal operation to place a dredged material deposit so that it slopes continually and as steeply as practical toward the outlets. Once the dredging operation has been completed and the ponded water has been decanted, site management efforts should be concentrated on maximizing the containment storage capacity gained from continued drying and consolidation of dredged material and foundation soils. To ensure that precipitation does not pond water, the weir crest elevation must be kept at levels allowing efficient release of runoff water. This will require periodic lowering of the weir crest elevation as the dredged material surface settles.

115. A method employed to aid in drainage and evaporation of the water present in dredged material placed in CDFs is progressive trenching. Evaporation is accelerated in this method by rapid removal of any precipitation by trench construction and by prevention of surface water ponding. As drying occurs, these trenches are progressively deepened (Haliburton 1978). Progressive trenching must be applied on a substantial amount of land (tens to hundreds of acres), and the drying times to achieve solids content may be hundreds of days to years and may still be inadequate for destruction or detoxification treatment technologies (Haliburton 1978).

Subsurface drainage

116. A subsurface drainage system may be used at a CDF for dewatering of dredged material and/or leachate collection. These systems usually consist of a network of perforated pipes placed under or around the perimeter of a CDF. These pipes drain to a series of sumps where water is withdrawn. Spacing between the pipes and sizing of the pipes depends on the static head that is allowable in the CDF and the rate at which water must be removed (Cullinane et al. 1986).

117. An underdrainage system or subsurface drain aids in dewatering dredged material placed in a CDF by collection of leachate and by promotion of consolidation of the solids. Underdrainage filter material must be free draining and free of fines (<5 percent passing the US sieve No. 200). The material must also minimize penetration and piping of the fine-grained dredged material. Well-graded concrete sand, fine uniform sand, or filter fabric are good filter materials (Haliburton 1978). The feasibility of subsurface drainage as a sediment dewatering technology may be limited where several lifts or layers of fine-grained sediment are to be disposed. These fine sediments may clog the drainage materials. In addition, the permeability of fine-grained sediments following compaction may be so low as to limit drainage to the system.

118. Several variations of underdrainage systems exist. These different systems are the gravity underdrain, vacuum-assisted underdrain, vacuum-assisted drying beds, and electro-osmosis. The gravity underdrain provides free drainage at the base of dredged material by downward flow of water by gravity. Downward seepage and weight gradients act as a force to produce dredged material densification. The system is slow, may require more land area, and is subject to clogging. Haliburton (1978) reported that vacuum-assisted underdrain is the same as the previous system, except for the use of an induced partial vacuum in the underdrainage layer. Dewatering is improved by 50 percent over the efficiency of the gravity system with the use of the partial vacuum in the underdrainage layer. Vacuum-assisted drying beds use a porous media filter plate above an aggregate-filled support plenum that drains to a sump. A small vacuum pump that is connected to the sump becomes operational when the volume of slurry is reduced 50 percent by gravity drainage. This small vacuum pump remains operational until solids crack and air filters through.

119. Underdrainage is similar to trenching in respect to land requirements and extended drying times. Underdrains provide the benefits of collecting contaminated leachate or managing the water content and oxidation/reduction characteristics of the dredged material, which may aid in managing mobility of metals or maintaining aerobic or anaerobic biodegradation. Subsurface drainage has been implemented at the Lucas-Berg CDF in Illinois.

Wick drains

120. Wick drains have been used to promote dewatering and consolidation of fine-grained wet materials in confined disposal sites. Though commonly referred to as wicks, the polymeric vertical strips provide a conduit for upward transport of the pore water, which is under pressure from the overlying weight of the material. By placing the vertical strips on 5-ft centers to depths of 40 ft, both radial and vertical drainage are promoted. At the Maryland Port Authority's Seagrit Project, the surface of the dredged material was covered with a geotextile fabric and surcharged with a layer of sand to provide the pressure to drive the dewatering process. Wick drains reduce consolidation time by a factor of 10 compared to natural consolidation (Koerner, Fowler, and Lawrence 1986).

Belt filter press

121. Belt filter presses operating continuously have been successfully demonstrated on river sediments and on industrial and municipal wastewater treatment facility sludges (Rexnord 1986). Sediment slurries varying from 1 to 40 percent solids by weight can be processed by the belt filter press. However, the higher the sediment solids feed concentration is, the drier the resulting sediment cake is.

122. Belt filter presses use single or double moving belts to dewater sludges. The belt filter press process involves three stages: (a) conditioning by either the addition of a flocculant or by a thickening drum section, (b) gravity drainage of free water, and (c) the compression zone. A flocculant is injected to facilitate solids separation, or a thickener drum screen section removes some of the filtrate by gravity. The slurry then flows to a gravity drain section consisting of a conveyor belt where more filtrate is removed. The slurry leaving this stage should have a solids content of approximately 30 percent, depending on the slurry feed concentration (USEPA 1980; Rexnord 1986). The belt filtration section consists of two filter belts operating on drive and guide rollers at each end like conveyor belts, with the upper belt operating as the press belt and the lower belt operating as the

filter belt. The upper side of the filter belt is supported by two rollers pressed against the press belt, which run in the same direction and speed as the filter belt. The two drive rollers of the press and filter belts are coupled. An adjustable-pressure roller system maximizes the static and shear pressure applied to the filter belt by the press belt. Slurry flowing from the gravity drain section is pressed between the two belts and dewatered. After passing through this pressure zone, static pressure along with shear forces are applied for further dewatering. Shear forces are applied by the adjustment of the supporting rollers of the filter belt and the pressure rollers of the press belt so that the belts and the slurry between them form an S-shaped curve. The dewatered sediment cake is then removed by a scraper (USEPA 1980, as cited in Ikalainen 1987).

123. A belt filter press was demonstrated to obtain 50 to 60 percent solids by weight while processing river sediment from Ashtabula River. The throughput was approximately 25 tons/hr of solids feed for a 8.2-ft-wide (2.5 m) full-size belt filter press. The typical solids capture rates were 95 to 98 percent for this sediment, with the majority of the lost solids captured in the belt wash water. The combined effluents from the belt filter press (gravity drain and belt filter press filtrates and belt wash water) typically contained 2 to 3 percent solids by weight (Rexnord 1986). A belt filtration system for a 500,000-yd^3 facility was estimated to cost $6 million in capital cost and $3/ton of dry solids for operation and maintenance costs.

Carver-Greenfield evaporation process

124. An unconventional evaporation technology that can be applied to sediment or wastes containing oil-soluble contaminants including PCBs and dioxins is the Carver-Greenfield process developed by DehydroTech Corporation. In this process, a food-grade carrier oil is injected into the waste as a fluidizing agent to maintain the liquid phase as solids content increases. The oil also minimizes scale formation and corrosion of the heat exchange surfaces. This oil/waste slurry is pumped through a grinder to prevent obstructions in the evaporator tubes, to optimize evaporation, and to simplify control. The oil-soluble contaminants are extracted from the waste by the carrier oil, and volatile compounds are stripped out and condensed with the carrier oil or water. Water is evaporated and removed as the slurry flows down the evaporator tubes. The resulting waterless slurry then flows to a centrifuging vessel to remove most of the carrier oil. After centrifugation, residual oil remaining in the waste is removed by hydroextraction. The

carrier oil is recovered by evaporation and steam stripping, and the contaminants are removed from the carrier oil by distillation (USEPA 1989d).

125. Oil is subsequently recaptured by centrifugation and recycled. The condensate from the evaporation system results in a sidestream containing ammonia and dissolved organics. Subsequent treatment may be required for this sidestream. Gaseous emissions from the system must be sent to a boiler or incinerator for destruction of volatile compounds (USEPA 1989d).

126. The Carver-Greenfield evaporation process has been successfully tested in a pilot plant. The treated waste was a refinery "slop oil" consisting of 72 percent water, dissolved flotation sludge, American Petroleum Institute (API) separator bottoms, tank bottoms, and biological sludge. The USEPA is in the process of locating a site for demonstration of this process (USEPA 1989d).

Centrifugation

127. Centrifugation is a dewatering technology that uses rapid rotation of a fluid mixture inside a rigid vessel to separate the components based on their mass. Centrifuges are generally used in conjunction with flocculants and can be used to dewater or concentrate soils and sediments ranging in size from fine gravel down to silt. They are capable of removing particles as small as 1 μ, but removal efficiencies are drastically reduced for particles smaller than 10 μ (Krizek, Fitzpatrick, and Atmatzidis 1976). The forces in centrifugation are similar to the gravitational forces in sedimentation with the exception that centrifugal forces are thousands of times stronger. Centrifugation is a clean, simple, and reliable option for sludge and solids dewatering. They are less effective than filtration processes and dewatering lagoons, but more effective than gravity thickeners. Centrifuges are generally more appropriate for dewatering sticky or gelatinous sludges than vacuum filtration (USEPA 1987). Advantages of centrifugation include limited space requirements, fast setup and shutdown, and generation of little or no air emissions since the process is essentially enclosed. Limitations include a possibility of unacceptable levels of contaminants in the concentrate overflow since heavier particles settle first and inorganic waste constituents tend to sorb to fine clay and silt (USEPA 1985). Improvements of recovery and removal efficiencies may be made by the incorporation of a paper or cloth filter into the centrifuge or the injection of flocculants. Types of centrifuges available are the solid bowl, basket, and disc centrifuge.

128. Data from municipal sludge dewatering operations indicate that 15 to 40 percent solids concentrations are possible with the solid bowl centrifuge. Approximately 85 to 97 percent of the solids are captured with chemical conditioning for both the solid bowl and basket centrifuge. The solids cake concentration for the basket centrifuge ranges from approximately 9 to 25 percent. Disk centrifuges can concentrate a 1 percent sludge to 6 percent solids (USEPA 1978 and 1982a, as cited in USEPA 1985).

129. The cost for a fixed centrifuge unit with a throughput capacity of 50 lb/hr (dry) are $500,000 for capital and $84,000/year for operation and maintenance (Jacobs Engineering 1986, as cited in Camp, Dresser, and McKee, Inc. 1986).

Chamber filtration

130. Chamber filtration utilizes rigid individual filtration chambers operated in parallel under high pressure to dewater a slurry. The most common chamber filtration unit is the plate and frame filter press; the diaphragm filtration unit is also used.

131. Plate and frame filter press. The plate and frame filter press is a semicontinuous conventional dewatering technology that effectively dewaters wastewater sludges, sediment, and hard-to-handle slurries. The plate and frame filter press can be used in situations requiring a large area of filtration in minimal area. The unit consists of parallel vertical plates placed in a series and covered on both sides with a monofilament filter. The plates are held firmly in a frame and are pressed together between a fixed and moving end. The slurry is pumped under pressure into the filter press and passes through feed pores in trays that lie along the length of the filter press. Water in the slurry flows through filter media covering the plates while solids form a cake on the filter's surface. When filtrate ceases draining through the filter, feed of material into the press ceases and dewatering is complete. The filter press is then opened, and the individual vertical plates are moved sequentially over a gap between the plates and the moving end in order to allow the solids cake to fall off the filters. After the solids cakes have been removed, the plates are pushed back into place by the moving end, and the press is closed for the next dewatering cycle (Weber 1972). Pressure plate warpage and deterioration of the plate gasket, which may sometimes be caused by plate warpage, have been problems associated with the plate and frame filter press (USEPA 1980, as cited in Ikalainen 1987).

132. Plate and frame filter press units have been proven effective, successful, and dependable for years in the dewatering of industrial and municipal wastewater treatment facility sludges. They have been improved by advances with the working pressures associated with the press Filter cake solids content have been improved to greater than 50 percent because of these advances. Filter presses offer solids concentrations of greater than 50 percent, improved solids capture rates, improved clarity of the filtrate, and reduced chemical consumption (USEPA 1980, as cited in Ikalainen 1987).

133. Diaphragm filter press. Diaphragm filter units are specially designed filter units that combine an initial pumping cycle followed by a squeezing cycle, which reduce process time and cost. The largest diaphragm filter unit manufactured is approximately 6,000 ft^2. Multiple-diaphragm filter units are required for larger press areas (USEPA 1985).

Evaporation

134. Evaporation is a commercially available mobile or fixed dewatering process that employs heat energy for the vaporization of a liquid or the more volatile components from viscous liquid solutions, slurries, suspended solids mixtures, sludges contaminated with oil, grease, paint solids, polymeric resins (USEPA 1987), and soils contaminated with volatile compounds, organics, or metals (Camp, Dresser, and McKee, Inc. 1986). A concentrated solid or semisolid that can be more effectively handled and treated is formed, and the vapor stream released is either condensed and collected or released into the atmosphere depending on the volatilized components. (USEPA 1987).

135. Evaporation processes are categorized either as conventional or unconventional technologies. Conventional evaporation technologies include thin-film evaporation, kettle evaporation, tubular evaporation, scraped surface evaporation, and solar evaporation; an unconventional evaporation technology is the Carver-Greenfield process. Solar evaporation and the Carver-Greenfield evaporation process are discussed separately as pretreatment options.

136. The most common conventional evaporation process used for waste recycling is agitated thin-film evaporation. This process is utilized on wastes with high solids content, viscous liquids, and slurries. The thin-film unit consists of a large surface on which a thin film of waste material is continuously applied and heated. The volatiles in the waste are vaporized while a concentrated semisolid remains for further treatment.

137. Costs for a mobile evaporation technology are not currently available, but costs for a fixed evaporation system with a throughput of 50,000 gallons per day are $145,000 for capital cost and $150,000 for annual operation and maintenance (Jacobs Engineering 1986, as cited in Camp, Dresser, and McKee, Inc. 1987).

Gravity thickening

138. Gravity thickening is a dewatering technology that operates on differences in specific gravity between solids and water to accomplish separation. An effluent with a reduced concentration of suspended solids is produced and removed while a thickened mass of solids remains in a smaller slurry volume. Effluent removal reduces the amount of slurry requiring treatment and disposal.

139. Gravity thickening usually occurs in a circular vessel constructed of concrete or steel designed similar to a conventional clarifier. Slurry influent is pumped into a feed well in the center of the thickener. The feed well dissipates the velocity and stabilizes the currents of the pumped sludge influent. The sludge is allowed to thicken and compact due to gravity settling. Clarified liquid overflows an effluent weir and leaves through an effluent pipe while the concentrated sludge is raked to the center of the vessel and is discharged by gravity or pumping. Flocculants may be injected in order to enhance agglomeration of solids and to promote a quicker or more effective settling (Dorr-Oliver 1981, as cited in USEPA 1985). The size and specifications of the gravity thickener depend on several factors, including maximum flow, waste type, volume of solids per day, percent solids, specific gravity, surface chemistry, maximum particle size, and percent solids required in the underflow.

140. Conventional gravity thickeners require large areas for operation and are not applicable where space is restricted or for large dredged material flow rates. High-rate gravity thickeners providing up to 15 times the throughput of conventional thickeners, reducing area requirements, are available (Dorr-Oliver 1981 as cited in USEPA 1985). These are suitable for operations where operator supervision cannot be provided. Gravity thickening units have proven effective and dependable for years in the dewatering of industrial and municipal wastewater treatment facility sludges, but they have not been used for dredged material slurries.

Solar evaporation

141. Solar evaporation, a technology widely used in arid climates, can be used on dredged material in a lined pond or lagoon. The water is evaporated by solar energy, leaving a concentrated mass of solids behind (Camp, Dresser, and McKee, Inc. 1987). Solar heating contributes to the dewatering of dredged material in a CDF, but is not the only mechanism. Consolidation and surface drainage also contribute to dewatering in humid climates.

Vacuum filtration

142. Vacuum filtration is a continuous process with self-cleaning filter media (Long and Grana 1978). The vacuum filter unit consists of a rotating cylindrical drum mounted horizontally and partially submerged in a trough containing a slurry. A continuous belt filter made of fabric or wire mesh covers the drum. A vacuum supply applies negative pressure to the inside of the drum, causing liquid to flow through the filter and into the center of the drum while the moist solids adhere to the filter. The filtrate exits the drum through the vacuum hose into a separator where the effluent exits the unit for further treatment or disposal. The solids cake adhering to the filter is either removed by knives that scrape against the drum as it rotates or is blown off with compressed air in blow cycle. The solids are then removed, treated, and disposed of properly. Several operating parameters within the vacuum filtration system can be altered to affect the performance of the filtration unit. These parameters include (Long and Grana 1978): (a) vacuum drawn during cake formation and dewatering phases; (b) degree of drum submergence--high drum submergence may increase the filter yield, but the moisture content in the discharged filter cake may also be increased; (c) drum speed; and (d) filter media porosity.

143. Vacuum filtration units have been proven effective, successful, and dependable for years in dewatering industrial and municipal wastewater treatment facility sludges. The solids capture rate of the vacuum filter usually ranges from 85 to 99.5 percent and cake solids content usually ranges from 20 to 40 percent depending upon various factors including feed type, solids concentration, chemical conditioning, machine operation, and management. Solids loadings are a function of feed solids concentrations and chemical preconditioning. Subsequent processing requirements usually range from 5 to 15 lb of dry solids/hr/ft^2. Limitations include sensitivity to slurry type and conditioning procedures, and increased costs of conditioning if a

slurry is difficult to dewater (Ikalainen 1987). Krizek, Fitzpatrick, and Atmatzidis (1976) concluded that vacuum filtration appears to be feasible for dredged material slurries of 10 to 20 percent solids by weight.

144. A vacuum filtration unit was used on dredged material from Toledo Harbor and a Toledo Harbor, Ohio, land disposal site. Solids content prior to conditioning with lime ranged from 15 to 23 percent. After treatment the solids content of the cake solids obtained were consistently above 43 percent (Long and Grana 1978). Unfortunately, vacuum filtration for most dredged material applications is not economical. For example, the processing of 25,000 yd^3/day would require approximately 25 rotary drum filters, with a total surface area of 2,075 yd^2. The capital cost for the rotary drums would be more than $6 million (1978 dollars) with operating and maintenance costs ranging from $5 to $30/ton of dry solids (1978 dollars). However, there may be instances when the use of this process may be justified (Barnard and Hand 1978).

Particle Classification Technologies

145. Several particle classification or separation technologies are available to classify contaminated soils or slurries according to particle size. Separation by grain size is important in the management of contaminated soils and sediments since the contaminants tend to sorb primarily onto fine-grained clay and organic matter. Particle classification technologies are discussed in the following section.

Flotation

146. Froth flotation is a physicochemical process used primarily in the ore and mineral industry to form a concentrated ore stream that has been adapted for use in other industries. In the ore industry, froth flotation is used for almost all sulfide materials, nonsulfide metallic minerals, industrial minerals, and coal in the size range of 0.1 to 0.01 mm (USEPA 1988e).

147. Flotation is dependent upon surface chemistry, particle size, and shape distribution of the feed, contaminant distribution with particle size, characteristics of the soil, specific gravity and chemical analysis of the soil, mineralogical analysis, solids-to-liquids ratio, and the nature of the pretreatment. The pH is also a very important parameter, and can be regulated by the addition of lime, caustic soda, soda ash and sulfuric acid (USEPA 1988e).

148. For treatment, metallic ores are ground finer than 48 to 65 mesh, but coal is naturally produced in the washing process at 10 to 28 mesh (USEPA 1988e). The particle sizes must be reduced so the minerals or contaminants will be able to be floated by the air bubbles (Kiang and Metry 1982). After grinding, the suspended particles are treated with chemicals called conditioners to cause the particles to be air-avid and water-repellent. The mixture is agitated with air, and the ore or contaminants attach to the air bubbles that are generated and float to the surface, forming a froth. This concentrated froth is skimmed off leaving a cleaned product. Typical conditioners used in the flotation of sulfides and natural metals are alkyl xanthates and dithiophosphates. Mineral oxides, silicates, and aluminosilicates are floated using anionic and cationic reagents such as fatty acids and amines. Commonly used frothing compounds, or conditioners, include pine oil, cresylic acid, polypropylene glycol ether, and 5 to 8 carbon aliphatic alcohols (i.e., methyl amyl alcohol). Approximately 0.01 to 0.2 lb/ton of conditioner is required. Conditioners used for fluorspar, phosphate rock, iron ore, and nonmetallics flotation include crude or refined fatty acids, petroleum sulfonates, and sulfonated fatty acids. Cationic conditioners used for floating quartz, potash, and silicate minerals include fatty amines and amine salts. Modifying agents, such as sodium or calcium cyanide, can be injected into the waste to repress unwanted minerals, such as pyrite, in complex sulfide systems (USEPA 1988e).

149. Several types of equipment are available for the froth flotation technology. The most commonly used froth flotation device is the mechanical flotation device that uses a rotating impeller on an upright shaft for agitation and aeration. In a cell-type mechanical flotation system, froth product discharge is obtained by overflow with or without mechanical paddles. Pneumatic flotation machines are the least frequently used froth flotation devices. They employ a blower's injection nozzles to mix air and pulp. In the flotation column a counter current flow is created in the lower section. Electroflotation is a process that uses ultrafine gas bubbles formed by electrolysis (USEPA 1988e). Another mechanism is dissolved-air flotation that uses high-pressure air saturation of waste followed by a decrease in pressure to remove suspended solids or oils by enhancing their "flotation" characteristics. The suspended solids or oils accumulate at the air-water interface that has formed and are skimmed off. These units are used for a more complete oil

removal than can be obtained by coalescence (Camp, Dresser, and McKee, Inc. 1986).

150. Flotation has been adapted for use on microorganisms, waste paper, and particular ions in a solution. In the case of microorganisms, sodium chloride has been used to float the microbes, concentrate them, and remove them from the liquid phase. Flotation has been used in the paper industry to remove ink, pigments, and coatings from the cellulose fiber. The cellulose fiber can be reused to make additional paper products. In the case of ion flotation, a surfactant ion of opposite charge is injected as a conditioner to remove particular ions present in a liquid. Ion exchange resins could be used, but the resins are more easily removed by screening than by flotation (Kiang and Metry 1982).

151. Costs for a 100,000-gpd dissolved air flotation unit are $190,000 for capital costs and $64,000 for annual operation and maintenance (Jacobs Engineering 1986, as cited in Camp, Dresser, and McKee, Inc. 1986). Kiang and Metry (1982) indicate that costs depend on the size of the operation and nature of the contaminants to be floated. Operating costs for the flotation and recovery of sulfide ores range from $4/ton of ore processed in a 500 ton/day system to $1.50/ton of ore processed for a 10,000 ton/day system (Kiang and Metry 1982).

152. Flotation cells have been used on mill tailings to separate radioactive minerals. Canada has extracted radium from uranium mill tailings and uranium from Elliot Lake ore. The US Bureau of Mines has confirmed that 95 percent of the uranium can be extracted from sandstone ore containing 25 percent uranium oxide (USEPA 1988e). Test results indicate that a ferrous iron conditioner can be used to treat a cyanide-contaminated solution. A ferro-cyanide precipitate was formed and floated and, in one case, resulted in the removal of approximately 95 percent of the cyanide present in the solution (Kiang and Metry 1982).

Grizzlies

153. Grizzlies are vibrating or fixed separation units used to remove oversized material and reduce slurry velocity for subsequent processing technologies. Grizzlies consist of parallel, framemounted bars spaced 1 to 5 in. apart that promote the flow and separation of oversized materials from the dredged slurry. They are generally 6 to 9 ft wide and 12 to 18 ft long (Mallory and Nawrocki 1974).

154. Grizzlies significantly improve the reliability and efficiency of subsequent solids separation technologies and also reduce maintenance costs by reducing the amount of abrasive material that comes into contact with downstream treatment processes. Maintenance requirements are minimal since grizzlies contain no moving parts and are abrasion resistant. These units require little area and can be arranged in series or parallel to achieve classification of materials and to accommodate very high flows.

Heavy media separation

155. According to USEPA (1987), heavy media separation is a pretreatment process that is most commonly used in the mining industry to separate oils from tailings and to separate solid materials with different absolute densities. Mixed solids are placed into a fluid (heavy media) with a specific gravity so that the lighter solid floats while the heavier solid sinks. The heavy media is usually a suspension of magnetite in water with adjustment in specific gravity relying upon the amount of magnetite powder. Limitations include the possibility of dissolving solids and the presence of solids with similar densities, while an advantage is the low cost involved to efficiently separate magnetic materials (magnetite recovery).

Hydraulic classifiers

156. Hydraulic classifiers are physical separation units used in the removal of sand and gravel from dredged material slurries and in the classification of the sand and gravel according to grain size. Hydraulic classifiers have the capability of removing and classifying solids ranging in size from 3/8 in. to approximately 105 to 74 μ (Mallory and Nawrocki 1974). Hydraulic classifiers may be used in conjunction with hydrocyclones or spiral classifiers in the separation of fine-grained materials such as clay and silt. Settled solids are fed from the hydraulic classifier into the spiral classifier by a rotating screw up an incline. Low-mass fines are separated from the sand and gravel by agitation and the abrading and washing action of the screw. Hydraulic classifiers consist of rectangular vessels ranging in size from 8 to 12 ft wide and 20 to 48 ft long (Mallory and Nawrocki 1974) with v-shaped bottoms where material is collected. Discharge valves located along the bottom of the vessel are activated by motor-driven vanes that sense the solids level (USEPA 1985). Slurry is injected into the tank at a rate limited to 250 to 350 tons/hr (Mallory and Nawrocki 1974), and as the slurry flows to the opposite end, solids settle according to size and settling velocity. Coarse solids settle out initially, and as the slurry progresses through the

classifier, finer solids progressively settle. Solids that have settled can be selectively directed by manually adjusted gates below the discharge valves for subsequent handling and treatment (Mallory and Nawrocki 1974).

157. Settling cone. The simplest form of a hydraulic classifier is the settling cone that operates similar to an overflowing funnel with the coarse, solid-laden material discharged through a weight-activated discharge valve in the bottom of the unit while liquid and fine-grained solids flow radially over the upper lip of the cone (USEPA 1988e).

158. Single-compartment hydraulic classifier. The D-O Siphon Sizer is a single-compartment hydraulic classifier built by Dorr-Oliver in which sands are discharged by siphons controlled by hydrostatically actuated valves extending to the bottom of the hindered settling zone (USEPA 1988e).

159. Multi-compartmental hydraulic classifiers. More complex hydraulic classifiers include the Jet Sizer by Dorr-Oliver and the Super Sorter by Deister Concentrator Company. These classifiers operate on a basis of hindered settling and are multicompartmental. Each compartment contains a low-pressure hydraulic water inlet that is controlled such that the coarser materials are maintained in a hindered settling condition while fine-grained materials are passed into successive compartments. Hydraulic water consumption for multicompartmental hydraulic classifiers is higher than that of single-compartment hydraulic classifiers (USEPA 1988e).

160. Hydraulic classifiers are an effective method for the classification of particles ranging from fine gravel to fine sands. They are generally designed for mobile system applications with quick startup and shutdown time and have fairly simple maintenance requirements. Hydraulic classifiers are easily integrated with other separation technologies and are advisable in situations where large flows are involved or classification of fine-grained materials is required. The effectiveness of hydraulic classification can be improved with the addition of a spiral classifier or hydrocyclone in order to remove the fine-grained materials (USEPA 1985). Limitations of the hydraulic classifier include the requirement for other separation technologies for materials less than 200 mesh. Also, some fines will be removed with the sand and gravel that is discharged.

161. Costs for hydraulic classifiers vary with size and capacity. For a hydraulic classifier ranging in size from 24 to 49 ft long, 8 to 12 ft wide, and 10 ft deep with a feed rate of 200 to 350 tons/hr, initial costs range from $30,000 to $76,000 (Mallory and Nawrocki 1974).

Hydrocyclones

162. Hydrocyclones represent a widely used technology that separates solids from water by centrifugal force. In applications where contaminated dredged materials are involved, hydrocyclones would be used in the removal of smaller particles from slurries and in situations requiring a distinct particle size separation. Hydrocyclones can be used in conjunction with hydraulic classifiers in the separation of fine-grained materials such as clay and silt. Hydrocyclones are especially applicable to sites where there is limited space (USEPA 1987). Hydrocyclones consist of a cone-shaped vessel with an underflow discharge outlet connected to a cylindrical pipe that functions as a tangential feed inlet. The top of the hydrocyclone is connected to an axially mounted overflow pipe that extends a short distance into the conical vessel to form the vortex finder that prevents newly introduced feed from flowing directly out the overflow pipe (USEPA 1988e). Dredged material in slurry form is injected into the conical vessel with sufficient velocity to create a vortex action. This vortex forces the slurry into a spiral motion that forces some of the rotating slurry out the overflow pipe. Smaller particles are discharged with this slurry while larger, heavier solids particles are forced against the wall of the cone by the vortex's centrifugal force and exit through the apical underflow discharge outlet (Dorr-Oliver 1984, as cited in USEPA 1985). The hydrocyclone operates as an effective treatment for dredged material, potentially separating the fine-grained particles containing contaminants such as heavy metals and organics from the relatively clean coarser, heavier solids.

163. Hydrocyclones are available in a wide range of sizes (from units separating a few gallons per minute to units handling 2,000 to 7,000 gpm) (Dorr-Oliver 1984 and Krebs Engineers, undated, as cited in USEPA 1985) and can be operated in series or parallel. In general, the larger the diameter and inlet of the hydrocyclone, the greater the capacity and coarser the separation. With a smaller diameter and inlet, the capacity decreases and the separation becomes finer. Hydrocyclones can be used in series with decreasing size to achieve high degrees of particle separation or can be utilized in stages to achieve a higher underflow concentration and a more clarified overflow. The first stage could be used as a classification stage, while the second stage overflow hydrocyclone could be used as a clarifier with the underflow cyclone functioning as the concentrator. The maximum underflow

concentration is approximately 60 percent since some liquid is required for solids discharged (Dorr-Oliver, undated, as cited in USEPA 1985).

164. Hydrocyclones are not effective in the separation of highly viscous slurries, slurries with a solids concentration greater than 30 percent, or particles with specific gravity of approximately 2.5 to 3.2 (Krebs Engineers, undated, as cited in USEPA 1985). Slurries with high clay content cannot be separated effectively with hydrocyclones (Oklahoma State University 1973, as cited in USEPA 1985) unless dispersants are injected or the slurry is diluted.

165. Tiederman and Reischman (1973) performed a feasibility study on hydrocyclones for dredge systems that concluded in the recovery of sand from dredged materials. The applicability of hydrocyclones to contaminated sediments was evaluated by Van Der Burgt (1985), as cited in Cullinane et al. (1986), who proposed a field demonstration of a hydrocyclone.

166. Costs for hydrocyclones vary widely according to the size and number of hydrocyclones placed in a series or in stages. Initial costs can range from $5,000 to an indefinite amount, depending on the size and number of hydrocyclones used (Hoffman Muntor Corporation 1978 and Krebs Engineers, undated, as cited in USEPA 1985).

Impoundment basins

167. The impoundment basin is a diked area or CDF with an adjustable weir for effluent overflow control. Multiple basins can be used in parallel to allow continuous sediment separation from water while accumulated solids are removed from individual basins or in a series to separate solids according to decreasing grain sizes. Impoundment basins are used in the removal of gravel down to fine silt (10 to 20 μ with the aid of flocculants) (Mallory and Nawrocki 1974). They have been used in the temporary storage of dredged material and in the classification of sediment by grain size. They are well suited for large-scale dredging operations but require a large area. The major limitation is the absence of a solids removal system and minimal control for performance as a particle separation process. Therefore, a mechanical dredge such as a backhoe or a clamshell dredge must be used, which increases the operation costs of impoundment basins.

Magnetic and electrostatic separation

168. Magnetic and electrostatic separation exploit the difference in magnetic and conductive properties between contaminants and the soil to effect separation. Soils treated by magnetic and electrostatic separation may be dry

or in a water slurry form. If the contaminants are finely disseminated throughout the soil, these separation technologies are not likely to work (USEPA 1988e).

169. High gradient magnetic separation (HGMS) was commercialized in 1974 for the removal of mineral impurities in clay slurries. This process separates weakly paramagnetic particles and suspended solids having no magnetic properties from gas or liquids. Steel wool containing 95 percent void space and a magnetic field are used to collect impurities as the liquid passes through the magnetized steel wool. The intensity of the magnetic field can range from 1 to 20 kilogauss for conventional HGMS, but superconductors can produce a magnetic field ranging from 20 to 100 kilogauss. The liquid stream to be treated by HGMS must be sieved to 100 μ or less, limiting application to dredged material. HGMS can be operated either as a continuous or batch process. A batch operation would be ideal if the impurities removed are a small percentage of the volume of waste passing through the unit or if high operating pressures are necessary. A continuous-feed operation would be ideal if impurities removed make up a large percentage of the waste passing through the system or if high operating pressures are not necessary. Capital costs vary depending on the size of magnetic field necessary and the type of material to be treated. Operation costs for large volumes are estimated to range from $1 to $5/1,000 gal of weakly paramagnetic liquid waste and approximately $10 to $50/1,000 gal for removal of ferromagnetic material from liquid waste (Kiang and Metry 1982).

170. Open gradient magnetic separation (OGMS) removes particles by imposing a high gradient magnetic field across a free-flowing material without a magnetic matrix. This continuous process has been tested on a bench scale. Preliminary results of a joint Departments of Energy and Defense/USEPA project for separating metals from waste sludges, slurries, and granular mixtures by HGMS and OGMS indicate that these two processes are limited to solid particles that can be separated into contaminated and noncontaminated particles when dried. Since treatment leaves a high percentage of contaminants in the treated material, magnetic separation may best be used in metallurgical applications. Magnetic separation may be considered as a pretreatment step since it does reduce the amounts of contaminants and suspended solids (Kesari et al. 1987).

Moving screens

171. Three types of moving screens used for fine particle separation are the vibrating, revolving, and gyrating screens. Vibrating screens are the most widely used of the screening processes because of their larger capacity per unit of screen area and their higher efficiency (Perry and Chilton 1973). The vibrating screen consists of a plain screening surface in a rectangular frame ranging in size from approximately 3 to 10 ft wide and 6 to 30 ft long with a capacity ranging from 300 to 950 tons/hr. They may be arranged with one, two, or three screening decks, allowing for progressively finer separation with less area requirements. Although the screen may be placed horizontally, they are usually placed at a 20-deg slope to allow for a cascading effect, thus increasing the probability of fine-grained particle separation (Allis Chalmers, undated, as cited in USEPA 1985). Once vibration begins, fine-grained particles sift through the screen. Vibrating screens are typically used to separate materials ranging from 1/8 in. up to 6 in. However, high-speed vibrating screens are available for the separation of finer material ranging from 4 to 325 mesh (Perry and Chilton 1973). Vibrating screens are best suited for dry materials or materials with a high water content since materials with a low water content that are not dry tend to obstruct the screen pores. Vibrating screens with a heated deck are available to reduce moisture content of material, but are not cost effective for high-moisture content material. Because of these limitations, vibrating screens have limited applicability to dredged material slurries. Water sprays can be used when the screen pores are obstructed by high moisture material. The water spray operating at 3 to 6 gpm/ton at a minimum of 20 psi is used to discourage clogging (Allis Chalmers, undated, as cited in USEPA 1985). Vibrating screens are also sensitive to abrasive particles in the feed material, resulting in the frequent replacement of screens. Vibrating screens are relatively compact and are well suited for use in mobile treatment systems. The cost of the vibrating screen varies with size and capacity. Capital cost for a screen that is 10 ft long, 5 ft wide, and 5 ft deep with a capacity of 200 tons/hr is approximately $25,000. Operation and maintenance costs of the vibrating screen are relatively low compared to other types of moving screens (Allis Chalmers, undated, and Derrick Manufacturing Corporation, undated, as cited in USEPA 1985).

Shaking tables

172. The shaking table is one of the more versatile gravity separation options that, in one pass, can produce a high-grade concentrate over a wide range of particle sizes. The shaking table can be used in a wide array of functions: (a) from roughing to cleaning, (b) from the treatment of sands to slimes, and (c) from the separation of two heavy minerals to coal preparation (USEPA 1988e).

173. In this separation procedure, feed enters through a distribution box along part of the upper edge. The wash water and shaking action spread the feed over the table. Product discharge occurs along the opposite edge and the end of the table. The essentially rectangular table has an adjustable slope of about 0 to 6 deg from the feed edge to the discharge edge. The surface is a suitably smooth material (e.g., rubber or fiberglass) and has an arrangement of riffles that decrease in height along their length toward the discharge end. Different duties may require a different deck size or riffle pattern, and a range of decks are offered by most manufacturers. Modifications on the basic shaking table design include the Bartles-Mozley separator, the Holman slime table, and the Bartles crossbelt concentrator (USEPA 1988e).

Spiral classifiers

174. The spiral classifier is a size, gravity, or mass separation process utilizing rotating screws mounted in an inclined rectangular vessel to wash, dewater, and classify sand and gravels up to 3/8 in. in diameter. Spiral classifiers may be used in conjunction with hydraulic classifiers in the separation of fine-grained materials such as clay and silt. Settled solids are fed from the hydraulic classifier into the spiral classifier by a rotating screw up an incline. Low-specific gravity fines are separated from the sand and gravel by agitation and the abrading and washing action of the screw. The actions of the continuously rotating screw grinds particles together, removing the clay and silt adhering to the sand and gravel and aiding in the dewatering process by breaking the film of moisture on the sand and gravel (Eagle Iron Works 1982, as cited in USEPA 1985). The fines and wastewater are removed at the overflow at the bottom of the vessel while the dewatered sand and gravel are discharged through the top of the vessel.

175. In general, a greater tub length indicates a higher degree of dewatering while greater screw diameter indicates a larger capacity (Eagle Iron Works 1982, as cited in USEPA 1985). Spiral classifiers are designed for use with mobile systems and have the capability of processing up to

950 tons/hour. Maintenance requirements are simple, and startup and shutdown procedures are accomplished quickly.

176. Costs vary with size and configuration of the spiral classifier. Classifiers ranging from 22 to 34 ft long, 8 to 19 ft wide, and 8 to 12 ft deep initially cost $14,000 to $77,000 for a single-screw type and $37,000 to $150,000 for a double-screw type. Operation and maintenance costs vary depending on power used (electricity, gas, or diesel fuel) (Mallory and Nawrocki 1974).

Stationary screens

177. Stationary or fixed screens differ from moving screens in that they have no moving parts. The screen surface is continuously curved on a sharp positive slope; therefore, the velocity of the slurry across the surface must provide enough centrifugal force to keep the slurry in contact with the screen to allow for separation. One fixed screen that has potential application to solids separation at contaminated sites is the wedge-bar screen, which is similar to the grizzly in that it consists of frame-mounted parallel bars on a curved deck but the bars are spaced closer together for a finer particle separation (USEPA 1985).

178. Slurry is evenly fed across the width of the screen and flows tangentially down the screen. The sharp edges of the wedge-bar slice off small particles and direct them through the slots along with most of the liquid. The dewatered, oversized material slides down the screen and is discharged. Wedge-bar screens range in size from 2 to 6 ft in width with a 30- to 200-gpm/ft^2 capacity.

179. A modification of the wedge-bar screen, the hydrosieve, uses a pressurized water spray to encourage more efficient separation by removing fine-grained material adhering to coarser material and by breaking up clumps of material that tend to obstruct the screen. Hydrosieves are available with capacities up to 1,500 gpm (USEPA 1985).

180. Wedge-bar screens are less efficient than the vibrating screen since the oversized materials that are discharged contain a considerable amount of fines. The hydrosieve serves as a solution to this problem by washing the fines from the coarse material. Wedge-bar screens may be operated preceding the vibrating screen to provide for a more efficient solids separation than either process alone (Allis Chalmers, undated, as cited in USEPA 1985). The wedge-bar screen is more resistant to abrasion than the vibrating screen and offers a relatively low-cost method for solids separation. The

wedge-bar screen contains no moving parts, is easily operated and maintained, and requires only a small operating area (USEPA 1985).

Slurry Injection Technologies

181. Slurry injection is identified as a technology type that is applicable to hydraulic dredging projects. Turbulence in the pipeline transporting the slurry is used to mix chemicals, microorganisms, or other additives with the dredged material.

Chemical clarification

182. Chemical clarification is defined as the use of conditioners to promote coagulation or flocculation of the smaller colloidal-size particles in dredged material. These particles settle very slowly and often have high contaminant concentrations compared to the bulk sediment. Coagulation causes these particles to agglomerate into larger particles with sufficient size and density to settle more rapidly (Jones, Williams, and Moore 1978). Coagulants include inorganic chemicals, such as the salts of iron and aluminum widely used in the water treatment industry, and organic polyelectrolytes. Wang and Chen (1977) evaluated inorganic and organic coagulants for application to dredged material and recommended organic polyelectrolytes for dredging operations because they are less dependent on pH and require lower dosages compared to inorganic coagulants. Treatment of dredged material slurry was demonstrated in pilot studies by Jones, Williams, and Moore (1978) and by Schroeder (1983). Simple processes of mixing concentrated polyelectrolyte and water by pumping the solution into a port in the pipeline are readily available. Turbulence in the pipeline provides energy and mixing for the polyelectrolyte and solids. However, high sheer or prolonged periods of mixing can decrease the effectiveness of the flocculant. A settling process must follow polyelectrolyte mixing to complete the chemical clarification process. Large polymer loadings can achieve near 100-percent reduction in turbidity and suspended solids in the slurry based on small column tests of treated pipeline slurry. Full-scale field conditions would likely be less efficient because of inefficiencies in the settling process.

Microbe addition

183. A concept for biological treatment of organic contaminants in sediment is to seed the material with microorganisms that have been either acclimated to or developed specifically for the contaminants of concern. A

number of commercial firms market "super bugs" that are acclimated to degrade toxic materials. Injection of the biomass into the pipeline is potentially the best opportunity for mixing the microorganisms throughout the sediment mass.

Nutrient addition

184. Biological treatment processes require a sufficient supply of nutrients for growth of beneficial microorganisms. Nitrogen and phosphorus, an organic carbon source, oxygen, and micronutrients are possible deficiencies that may have to be supplemented to enhance biodegradation of sediment contaminants. An initial deficit could be met by injection of these materials into a slurry pipeline. However, sediment in the Great Lakes has a sufficient supply of nutrients. Therefore, nutrient addition will not be discussed any further.

PART IV: CONTAMINATED SEDIMENT TREATMENT TECHNOLOGIES

Biological Technologies

185. Biological technologies can be used to treat contaminated sediment when the use of microorganisms to remediate a site is appropriate. Several aerobic and anaerobic biodegradation technologies are available.

Aerobic bioreclamation

186. Aerobic bioreclamation is a demonstrated technology used to treat soils or groundwater contaminated with organic materials. An aerobic bioreclamation system must be engineered to create favorable aerobic conditions in the treated medium. A sufficient supply of nutrients for the growth of aerobic microorganisms must be available. Nitrogen and phosphate are the most common nutrient sources for microbes involved in biodegradation while oxygen may be provided to soil or sediment by the use of air, pure oxygen, hydrogen peroxide, or ozone. Other potential nutrients include iron, trace metals, magnesium, potassium, calcium, sodium, sulfur, and manganese. An organic carbon source such as citrate or glucose may be added if the compound to be treated is only degraded by cometabolism and a primary carbon source is required (USEPA 1985).

187. Aerobic biodegradation is usually carried out in processes in which control of the environment is feasible since aerobic biodegradation requires stable operating conditions such as temperature, soil moisture, and pH (USEPA 1987). If microorganisms present in the soil are not adequate for timely degradation, a mobile bioreactor can be used to produce supplemental microbes that can be injected into the soil. One concept for aerobic bioreclamation of contaminated sediment is to optimize conditions for aerobic organisms in a CDF by adding supplemental nutrients and/or oxygen or managing the CDF to maintain aerobic conditions.

188. Radian Corporation (1989) conducted a bench-scale biodegradation study for PCB removal on New Bedford Harbor Superfund site (Massachusetts) sediment. The study, designed to simulate conditions that may be expected in a full-scale biological treatment system to remediate New Bedford Harbor sediments, consisted of a biphenyl-degrading culture development phase and a PCB culture development phase. Results indicated that there was an overall PCB reduction, but preferential reduction occurred in the concentrations of

di- and tri-isomer groups in the active reactors compared to the uniform concentration reduction of all groups in the control reactors.

Anaerobic bioreclamation

189. Anaerobic bioreclamation uses anaerobic metabolism that includes anaerobic respiration using nitrate or sulfate as a terminal electron acceptor and fermenting/methanogenic processes using a methanogenic consortium (strictly anaerobic bacteria). Destruction of certain organic contaminants, such as halogenated compounds, various aromatics, and some pesticides is possible (USEPA 1985). Research indicates that xenobiotic compounds may be dehalogenated or completely destroyed under anaerobic conditions (Sulflita et al. 1982 and Pfaender and Alexander 1972, as cited in USEPA 1984). Methanogenic consortiums are capable of degrading trichloroethylene, tetrachloroethene, and other lower molecular weight halogenated organics that are not generally amenable to aerobic or other respiratory processes (USEPA 1985).

190. Temperature plays an important role in the biodegradation of contaminants, affecting both the composition of the active community and the enzyme-catalyzed reaction. The effects on the active community become more pronounced when two or more organisms are involved in the reaction since different organisms may catalyze the rate-determining step at a different temperature (Rogers, Kohring, and Wiegel 1989). Microbial activity generally decreases with decreasing temperature and is near zero at temperatures below 4° C.

191. 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 sulfates can be present. Most sediments are anaerobic in situ with ample opportunity for contaminant biodegradation under ambient conditions. A CDF could be treated by anaerobic bioreclamation by implementing ponded conditions necessary to maintain anaerobic conditions.

192. Rogers, Kohring, nad Wiegel (1989) conducted tests on freshwater lake sediments from two sites near Athens, GA, to determine the effect of temperature and redox conditions on the anaerobic biodegradation of 2,4-dichlorophenol. Under methanogenic conditions, dechlorination of 2,4-dichlorophenol occurred at temperatures between 5° and 50° C. The product formed, 4-chlorophenol, was further degraded after several weeks to phenol and then to carbon dioxide and methane. Reductive dechlorination was observed under sulfate-reducing conditions only at temperatures between 18° and 40° C after

365 days of incubation. A large portion (>30 percent) of the sulfate remained following complete 2,4-dichlorophenol degradation. Inhibition of methanogenic activity was reported during this period. The rates of degradation under sulfate-reducing conditions varied from 2 to 19 percent of the rates observed during methanogenic conditions. After 127 days of incubation under conditions favorable for denitrification, no reductive dechlorination was observed.

193. Applications of this technology are conceptual. Anaerobic bioreclamation is slower, and fewer compounds can be degraded in comparison to aerobic bioreclamation.

Anaerobic digestion

194. Anaerobic digestion is a widely used technology that uses the following microbes to achieve the degradation of low to moderate levels of organic contaminants in wastewater: (a) hydrolytic bacteria that catabolize saccharides, proteins, and lipids; (b) acetogenic bacteria that catabolize the products of hydrolytic bacteria such as fatty acids and neutral end products; (c) homolactic bacteria that catabolize multicarbon compounds to acetic acid; and (d) methanogenic bacteria that metabolize acetic and higher fatty acids to methane and carbon dioxide. These strictly anaerobic bacteria are commonly referred to as methanogenic consortia and are found in anaerobic sediments or sewer sludge digesters. Anaerobic digesters are usually airtight reactor vessels with provisions for venting or collecting methane and carbon dioxide (USEPA 1987).

195. USAE District, Buffalo (1969), examined bench-scale tests of anaerobic digestion. The tests indicated that anaerobic digestion of the dredged material was not as efficient as the anaerobic digestion of wastewater sludge. The dredged material produced only 1 ft^3 of gas/lb of volatile solids whereas the wastewater sludge produces approximately 10 ft^3 of gas/lb of volatile solids. The reactor volumes required and the low efficiency of the technology limit the feasibility of anaerobic digestion for dredged material.

Bioreactor

196. The bioreactor is an aerobic biodegradation technology that functions to increase the availability of contaminants and nutrients to microbes within a tank. The slurry, which may contain 5 to 50 percent solids by weight, is constantly agitated in a reactor to maintain an even mixture and proper environmental conditions. Nutrients, oxygen, or pH controllers may be added to maintain these conditions. Microbes may be added, if necessary, to maintain the proper biomass concentration. Residence time varies depending on

the sediment, contaminant concentration, and biodegradability. Once biodegradation is complete, the slurry is dewatered with the residual water, possibly requiring further treatment. The bioreactor may be enclosed to prevent air emission into the atmosphere. Limitations of the technology include inhibition of microbial metabolism by chloride substitution and heavy metals and temperatures that are outside the optimum range of 15° to 70° C (USEPA 1988d).

197. Bioreactors are available from several firms. Ecova Corporation operates a system that treats soils contaminated with high concentrations of organics (up to 14,000 ppm pesticides) and can be combined with other processes to treat vapors and heavy metals. The Ecova treatment system will be demonstrated on a wide range of toxic organic compounds at the Goose Farm Superfund site in Plumstead Township, NJ. Detox has a submerged fixed-film reactor that biodegrades chlorinated hydrocarbons such as PCBs in soil and sludges with naturally occurring microbes. Mo Tec operates a liquid-solid contact digestion bioreactor that can treat soil and sludge contaminated with creosote and pentachlorophenol. Cometabolites such as polynuclear aromatic hydrocarbons (PAHs), chlorinated hydrocarbons, or chlorinated aromatics are required in order for the microbes to acclimate to metabolizing waste molecules resembling the cometabolites (USEPA 1988d). A demonstration project (planned for spring 1990) has been proposed for the Mo Tec liquid/solid contact digester. In this demonstration, 50 to 100 yd^3 of contaminated soil from a wood preserving facility will be processed over a 3-month period. TNO of the Netherlands has developed a wet and a dry bioreactor to treat contaminated soils and dredged material containing mineral oils, polychlorinated aromatics and other non-chlorinated hydrocarbons. The dry bioreactor is similar to composting while the wet bioreactor is similar to an aerobic activated sludge system. The Netherlands Organization for Applied Scientific Research (TNO) is operating its bioreactor on a laboratory scale on a batch basis. Pilot-scale experiments with a throughput of 11 tons/day are being developed. Heidemij Uitvoering has the rights to the TNO bioreactor technology, and prices are expected to be approximately $45/ton although they vary depending on treatment time required (USEPA 1988b).

Composting

198. Composting is a biological technology that can be applied to biodegradable waste in aerobic or anaerobic environments. This technology involves the 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.

199. The three basic types of composting are (a) open windrow systems, which consist of stacking the compost bed into elongated piles and aerating the compost by tearing down and rebuilding the piles; (b) static windrow systems that also involve piling the compost in elongated rows, but aeration is accomplished by a forced-air system consisting of a grid of perforated pipes underneath the compost; and (c) in-vessel systems that aerate the compost by tumbling, stirring, and forced aeration.

200. In anaerobic composting, the composts are placed in a vessel flushed with nitrogen initially to remove any oxygen and then every 3 to 4 days afterward. Laboratory-scale tests by Isbister, Anspach, and Kitchens (1984), as cited in Wilson (1987), used this process to treat a compost mixture containing 2,000 mg/kg of Aroclor 1242. After 4 weeks the removal efficiency was estimated to be between 27 and 47 percent with an estimated residual of 825 to 1,120 ppm (Wilson 1987). Tests on the same material using aerobic composting achieved 62 percent degradation of Aroclor 1242.

201. Composting requires considerable work-site space, and a lack of control of weather and other conditions renders the process uncertain with regard to time and effort required. Difficulties that would be encountered in composing dredged materials include the high water content of dredged material and the need for a high organics content. Additional difficulties that would be encountered are the requirements to turn or aerate the material and to control the leachate and runoff. Cost for a West German composting process was estimated to range from $82 to $136/ton (USEPA 1988b).

Enzyme processes (including bacteria and white rot fungus)

202. The degradation of organic compounds such as aliphatic, aromatic, and heterocyclics by enzymes is a biodegradation process that utilizes hydroxylation of the vicinal carbon atoms prior to ring cleavage to obtain degradation. Enzymes may be applied as a free-flowing solution or bonded to a solid substance. Thirty-four bacterial strains and five fungal strains have degraded PCBs to varying degrees using enzymes (Unterman et al. 1985, McCormick 1985, Rochkind et al. 1985, and Isbister et al. 1984, as cited in Carpenter 1986). Since most enzymes are substrate specific, different enzymes catalyze reactions to degrade different compounds.

203. Mixed cultures might be used to mineralize (totally degrade to CO_2, H_2O, and HCl) a compound that cannot be degraded completely by one enzyme culture. Most bacterial isolates that degrade PCBs use a 2,3-dioxygenase system that hydroxylates and cleaves the aromatic ring between the 2 and 3 positions (Ikalainen 1987), whereas fungal systems use this hydroxylation and cleavage and, in addition, form monohydroxy PCB derivatives. The white rot fungus produces an enzyme system capable of degrading organopollutants including chlorinated lignin-derived by-products of the Kraft pulping process, and aliphatic, aromatic, and heterocyclic compounds (USEPA 1987).

204. Research with ^{14}C-labeled 3,4,3'4'-tetrachlorobiphenyl and 2,4,5,2',4',5'-hexachlorobiphenyl revealed only 2 percent degradation to $^{14}CO_2$ after 60 days (Bumpus et al. 1985, as cited in Ikalainen 1987). In another report, the degradation of ^{14}C-labeled Aroclor 1242 and 1254 to $^{14}CO2$ was 18 to 20 percent after 60 days (Bumpus and Aust 1986, as cited in Ikalainen 1987). Results of tests conducted for PCB destruction revealed that *Alcaligenes eutrophus* H850 and *Pseudomonus putida* LB 400 degraded 13 test congeners from 80 to 100 percent (Wilson 1987).

205. Enzymes produced by microbes could possibly be harvested from cells and applied to contaminated soils. Munnecke et al. (1982), as cited in USEPA (1984), stated that a cell-free enzyme system has been used in the detoxification of containers containing organophosphate pesticide waste (Munnecke 1980, as cited in USEPA 1984) and that 1 percent diazinon in soil was hydrolyzed within 24 hr by parathion hydrolase.

206. Enzyme activity can remain viable in harsher environments than can microorganisms. Such environments include pH and temperature extremes, high salinity, and high solvent concentrations (Munnecke et al. 1982, as cited in USEPA 1984). Cell free enzymes must be able to function without cofactors or coenzymes. 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. Conceptually the cell-free enzyme system would quickly transform hazardous compounds in soil if they remained active. White rot fungus and parathion hydrolase have been demonstrated on a laboratory-scale basis for soils.

Chemical Technologies

207. Chemical technologies can be used to treat contaminated sediment when the use of chemical agents at a site is appropriate. Several of these technologies are discussed below.

Chelation

208. Chelation is a chemical process in which a chelating molecule (ligand) forms multiple bonds with metal ions, resulting in a ringed structure that incorporates the metal ion. The metal ions are bound and restrained from forming ionic salts that might precipitate out (USEPA 1987). Chelating agents must be used according to their affinity for particular metals (USEPA 1985). Many agents, such as EDTA (ethylenediaminetetraacetic acid) increase metal mobility and may be used in a solution-mining removal system for heavy metals. Conversely, tetraethylenepentamine (Tetren) is an effective chelating agent for immobilization. The reaction product (containing such metals as copper, zinc, nickel, and cadmium) sorbs into high clay content soils and is effective in this sorption due to Tetren's maximization of amino groups for metal complexing. Heavy metal wastes are also submissive to sorption by Tetren. One of the most important parameters involved in chelation is pH. Hydrogen ions influence both the metal cation and the chelating agent. Thus, any change in pH affects the equilibrium of the system.

209. Recent studies on the effectiveness of chelating agents indicate that chelating agents have a wide range of efficiency depending on chelate dosage and chelating agent. Ellis and Fogg (undated), as cited in Raghavan, Coles, and Dietz (1989), reported reductions of 96, 22, 100, 75, and 52 percent on lead, nickel, cadmium, copper, and chromium, respectively, while using an EDTA/hydroxylamine/citric acid sequential extraction for in situ remediation of Western Processing, Inc. A 13 to 16 percent EDTA solution was used by the USEPA Releases Control Branch at the Church of God in Leeds, AL. Removal efficiencies for lead were 94 to 97 percent using a 4 to 5 ton/hr-capacity screw extractor to inject and mix the EDTA solution with the soil. USEPA, Region V, used EDTA in laboratory-scale tests on soils from Lee Farm in Woodville, WI, to reduce gross lead contamination to below 5 ppm leachable lead (Castle 1986 and USEPA 1986, as cited in Raghavan, Coles, and Dietz 1989). Chelation has not been demonstrated for remediation of contaminated sediments.

Chemical hydrolysis

210. Hydrolysis is the reaction of any substance with water. Hydrolysis occurs when a compound undergoes bond breakage and dissolves into a water-ionic solution mixture. Breakage can be achieved when chemicals are added, when irradiation (photolysis) occurs, or when enzymatic bond cleavage takes place (USEPA 1987). 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 nitriles (Metry 1980), but is not applicable for the treatment of inorganic contaminants. Temperature, solvent composition, catalysis, and pH are environmental factors affecting the rate of hydrolysis.

211. Organic hydrolysis is the reaction of an alkali with a solution of an alkali salt and an organic acid. Water can cause organic hydrolysis by itself, but modern commercial methods use temperature and pressure to cause the reaction. An acid, alkali, or enzyme can be used as a catalyst to aid in the process (Metry 1980).

212. Some toxic by-products may form according to the materials being used in the reaction (Metry 1980). Chemical hydrolysis is a common industrial method that must be carefully implemented to avoid mobilizing heavy metals. Mobility precautions are required, especially for acid hydrolysis (USEPA 1987). Applicability of this process to contaminated sediment is limited.

Nucleophilic substitution

213. Nucleophilic substitution can be used in waste treatment to chemically remove chlorine from organic (aromatic) compounds using the electron donating principle under mild conditions. Since nucleophilic substitution depends upon a high pH level, the reaction should proceed in alkaline conditions. Chlorine can be removed by a benzyne mechanism that takes place on aryl halides (PCBs) lacking activity groups and containing one ortho group. Perhaps the most effective removal by substitution is the use of alkali metal hydroxides in polyethylene glycol (APEG) or in polyethylene glycol methyl ether (APEGM).

214. The process using APEG as a reagent, sodium or potassium based, involves the displacement of chlorine by polyethylene glycol (PEG) to form an alkali metal chloride and a substituted organic polymer (PEG ether). The reaction occurs effectively and quickly due to the alkali metal being held in solution by the PEG anion. The halogenated molecule becomes soluble and forms a single phase for displacement (USEPA 1987). The reaction should be carried

out in a nitrogen atmosphere since most APEG reagents are air and water sensitive (Camp, Dresser, and McKee, Inc. 1986). Substitution takes place between 120° and 180° C (Carpenter 1986), but excess heat and reagent are required if the medium containing contaminants has more than 7 percent moisture (USEPA 1987). Temperature, reaction time, and reagent dose can be adjusted to optimize the effectiveness of the process.

215. The APEG process is accomplished on dewatered soils. Solid-liquid separation equipment with a slurry reactor for heating is required. The reaction can be carried out in a reactor or in situ. Although APEG cannot treat nonorganochlorine contaminants (USAE District, Chicago 1989), it can treat contaminants such as PCBs, acids, oils, thiols, and dioxins. By-products include chloride salts, polymers, and heavy metals (Camp, Dresser, and McKee, Inc. 1986). Potential problems that have been identified and must be worked out before APEG is feasible for dredged material on a large scale include: (a) problems with mixer design related to mass transfer, reaction kinetics, and solids separation; (b) reagent recovery and disposal; (c) solids disposal; and (d) treatment of the organic reaction products remaining in the solids after APEG dechlorination (USAE District, Chicago 1989).

216. Potassium-polyethylene glycol (KPEG) dechlorinates PCBs, leaving a less toxic, water-soluble biphenyl ether residual. Specific KPEG reagents exist for solids, liquids, and sludges. 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 wastes. Further treatment must be supplied by oxidation, biodegradation, carbon adsorption, or incineration (USEPA 1988d).

217. The Galson Research Corporation has completed studies to provide a suitable KPEG dechlorination process. The Terraclean Cl process uses a mixture of potassium hydroxide, PEG, and dimethyl sulfoxide (DMSO). The DMSO serves as a phase transfer catalyst to promote PCB extraction. A hot volume of this reagent (150° C reaction temperature) is mixed with the soil using a rotating mixer (preferably a converted cement mixer). After reaction, most of the reagent is decanted from the soil, and the soil is washed 2 to 3 times to remove residual reagent and dechlorinated by-products. The wash fluid flows through an activated carbon treatment bed with the contaminated carbon later being incinerated (Carpenter 1986). Reagent recovery is >99 percent with residuals less than 1 ppm. Reaction time is between 30 and 120 minutes (Carusone and Hickman 1988).

218. In a December 1988 report by Galson Research Corporation on KPEG treatment of New Bedford Harbor sediment, bench-scale test results indicated a reduction from 6,000 to 7,500 ppm PCBs to 4 ppm in 12 hr at 165° C and residual recovery of 98 percent. Cost for treatment of 50,000 yd^3 of sediment including labor, maintenance, and equipment was $7,349,979 at $147/yd^3 sediment (Galson Research Corporation 1988). Costs generally range from $146 to $175/yd^3 (Carusone and Hickman 1988).

219. A field-scale evaluation by PEI in Guam, USA, using KPEG concluded that removal of DMSO and TMH (triethylene glycol methyl ether) did not hinder dechlorination. The APEG system consisted of a steam-jacketed mixer, steam generating plant, and condensate collection system. The mixer had a total capacity of 793 gal with a working capacity of 490 gal. Fifteen cubic yards of soil contaminated with Aroclor 1260 (3,430 ppm) was treated in batches of 1.5 to 2 yd^3. The efficiency of PCB reduction was 99.999 percent at a cost of $200/ton (Chan, Kornel, and Rogers 1989).

220. General Electric also has provided a very similar process using glycol reagent in equal portions with contaminated soil to carry out the reaction (USEPA 1988d).

221. Sodium-based PEG reagents may also be used. The Goodyear Tire Company in 1980 used sodium naphthalene and tetrahydrofuran dechlorination of PCBs to form a salt and to polymerize biphenyls into a sludge. Sun Ohio and Acurex modified this noncommercialized process. The Sun Ohio PCBX process uses mobile units for reduction of PCB concentrations in transformer oils. These units can reduce PCB concentrations to less than 2 ppm and recycle the oil back into the transformer. The PCBX can be applied to pesticides and other wastes with high concentrations of PCBs. However, no published numerical data were found. Acurex claims to have treated oil with PCB concentrations of 7,000 ppm. Battelle Columbus Laboratories reduced dioxin concentrations from 380 parts per trillion to 40 ± 20 parts per trillion. Sun Ohio has at least five units in operation, and Acurex has at least four units (Congress of the United States 1983).

Oxidation of inorganics

222. Oxidation of inorganics in soils 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 arsenite (As(III)) to less soluble arsenate (As(V)). As(V) may be further immobilized by precipitation with ferrous sulfate to form ferrous arsenate. Other compounds may

become more mobile under oxidized conditions, limiting application of this process to many contaminated sediment problems. Oxidation may be accomplished in sediments by providing for natural aeration of the sediment or by adding oxidizing agents such as ozone, hydrogen peroxide, chlorine dioxide, or potassium permanganate. Aeration of the sediment is not practicable for long periods of time, and the addition of oxidation has potential for producing toxic by-products.

223. The in situ oxidation of arsenic-contaminated groundwater with potassium permanganate has been demonstrated in Cologne, Germany. The permanganate was injected through wells over a 2-year period. Arsenic concentrations in water samples were reduced from 13.6 to 0.06 mg/ℓ. The SITE program includes a chemical oxidation process using chlorine dioxide. The process, marketed by Exxon Chemicals and Rio Linda Chemical Company, is reported to have applications to sludges containing cyanides or organics (USEPA 1989d).

Oxidation of organics

224. Chemical oxidation of organics is a technology in which the oxidation state of an atom is increased by removal of electrons. Oxidation readily transforms, degrades, or immobilizes contaminants in the soil system. Complete degradation (to carbon dioxide and water) is dependent upon oxidant concentration, pH, oxidation potential, and formation of a stable intermediate (USEPA 1984). Necessary equipment includes contact vessels with agitators, storage vessels, and metering equipment. Toxic products may form if the reaction is not completed (USEPA 1985).

225. Oxidation is not applicable for high-strength complex waste systems (USEPA 1985), nor is oxidation applicable to highly halogenated organics. Natural organic compounds in the soil complex might be consumed along with the organic contaminants (USEPA 1984).

226. Oxidation is an applicable pretreatment technology for use prior to biological treatment and is used primarily for treatment of dilute waste streams containing oxidizable organics such as aldehydes, phenols, and benzydine (USEPA 1985). Oxidation of organics has limited application for slurries, tars, and sludges (Kiang and Metry 1982).

227. Organic contaminants in soil and groundwater can be oxidixed in situ by using strong reagents like ozone and hydrogen peroxide. Other reagents include calcium hypochlorite, potassium permanganate, sodium hypochlorite, fluorine, and chlorine gas. These oxidants can be applied in water solution, by spreading directly onto the soil surface, injecting into the

subsurface, or placing them into injection wells (USEPA 1984). These options are adaptable to dredged material in a CDF.

228. Exxon Chemicals, Inc., in conjunction with Rio Linda Chemical Company, have developed a chemical oxidation/cyanide removal system applicable to soils, aqueous wastes, or any leachable solid waste contaminated with organic compounds. This process will be demonstrated in the Superfund Innovative Technology Evaluation (SITE) program in two separate demonstrations, one for organics and one for cyanide treatment (USEPA 1989d).

Reduction of metals

229. Chemical reduction of metals is the lowering of the oxidation state of a metal by addition of electrons to the atom. Reducing conditions and selectivity can depend on pH adjustment. Reducing agents include alkali metals, sulfur dioxide, sulfite salts, and ferrous sulfate (USEPA 1988d). Metal reduction is more commonly applied than organic reduction and is used primarily for reduction of hexavalent chromium, mercury, hexavalent selenium, and lead (USEPA 1984).

230. According to Camp, Dresser, and McKee, Inc. (1986), equipment required for reduction includes mixers with agitators, meters, and storage tanks. Slurries and soils may need larger reaction vessels and longer retention times than aqueous wastes. If a waste is treated in situ, surface injection of reagents and water is necessary to subdue possible violent reactions. The reduction process may be monitored by the Oxidation-Reduction Potential Electrode. Laboratory and pilot-scale tests are required to determine feed rates and reactor retention times (Cullinane et al. 1986).

Reduction of organics

231. Chemical reduction of organics involves decreasing the oxidation state by the addition of electrons to the atom to reduce toxicity or solubility, or to transform organic contaminants to an easily handled form. Reducing conditions and contaminant selectivity can depend on pH adjustment (Camp, Dresser, and McKee, Inc. 1986). Currently, no practical application for reduction of organic compounds exists, but reduction can occur with the use of catalyzed metal powders (aluminum, iron, and zinc) and sodium borohydride as reagents (USEPA 1985). Other reducting agents that may work include alkali metals (sodium and potassium), sulfur dioxide, sulfite salts (e.g., sodium bisulfate), and ferrous sulfate (USEPA 1988d). All of these reagents have been shown to degrade toxic organic constituents by electron donation (USEPA 1984). Treatable wastes include chlorinated organics, unsaturated

hydrocarbons (Camp, Dresser, and McKee, Inc. 1986), unsaturated aromatics, and aliphatics (USEPA 1988c).

Thionation

232. Thionation is a process in which sulfur displaces chlorine in an organic molecule. This method is in the elementary stages of study (Wilson 1987). However, thionation reactions will degrade organic pollutants. Sulfur and sodium carbonate react with p-dichlorobenzene between 150° and 170° C to remove chlorine, leaving an insoluble polymer, sodium chloride, and carbon dioxide (Carpenter 1986). This process has limited applicability to sediment.

Extraction Technologies

233. Extraction is the removal of an undesired contaminant from soils or sediment by dissolution in a fluid that is later recovered and treated. Extraction involves elutriation of organic/inorganic constituents from soil or sediment for recovery or treatment by placing the soil in contact with the solvent. The elutriate is then collected, treated, and/or recycled (Cullinane et al. 1986). Extraction is often used to remove volatile organics from permeable soils and may be used to treat soils or sludges contaminated with metals, inorganics, and organics including PCBs, gasoline, fuel oil, halogenated solvents (TCE and trichloroethane), aromatics (benzene, toluene, cresol, and chlorinated phenols) (Camp, Dresser, and McKee, Inc. 1986), amines, ethers, and anilines (USEPA 1984). Extracting agents vary according to the contaminants to be treated. They include water, acids, bases, complexing and chelating agents, surfactants, and certain reducing agents (USEPA 1985) as well as water/chelating and water/surfactant combinations (Camp, Dresser, and McKee, Inc. 1986).

234. In containerized extraction processes, soil is excavated and placed in a contactor vessel or an extraction unit. An aqueous washing solution as described above is injected into the soil, and contaminants are extracted from the soil and concentrated in the washing solution. The washing solution leaches out of the soil and is collected and recycled by a specific treatment technology appropriate for the type of contaminants involved.

235. For in situ extraction processes, the contaminated site is flooded with an appropriate extraction solution and the elutriate leaching from the site is collected in a series of shallow well points or subsurface drains. The elutriate/leachate is then treated and recycled back into the site. Soils

may require multiple washing and flushing cycles for effective contaminant removal.

Acid leaching

236. Weak acids such as aqueous solutions of sulfuric, hydrochloric, nitric, phosphoric, and carbonic acid are used as dissolving agents for basic metal salts such as hydroxides, oxides, and carbonates in industrial waste. Acid solutions are also used in the flushing of amines, anilines, and ethers. Because of the toxicity of many acids, weak acid solutions such as sodium dihydrogen phosphate and acetic acid are used for in situ treatment because of their stability and low toxicity (USEPA 1984). Basic solutions such as NaOH are used as flushing agents for soils contaminated with metals such as zinc, tin, lead, and phenols.

237. The TAUW Infra Consult B.V. has completed full-scale testing of 30,000 m^3 of wet soil with a cadmium-only leaching technique using in situ ion exchange. Hydrochloric acid was used as a reagent to leach cadmium into horizontal drains. The solution was pumped to a water treatment system containing Rohm and Haas IMAC GT-73 resins for ion exchange. Cadmium concentration in the soil after treatment was <1 mg/kg. Cost for the project was $2.5 million for the 30,000 m^3, or $83/$m^3$ ($63/$yd^3$) (USEPA 1988b).

238. Epoc Water, Inc., has developed a mobile acid leaching and microfiltration process that uses low-cost mineral acids, alkalis, or in special situations, chelating agents to remove metals from soils. The process consists of five basic steps: (a) chemical leaching to solubilize metals, (b) solids separation using a tubular filter press, (c) washing the waste in situ, (d) metals precipitation using a proprietary microfiltration method, and (e) dewatering to a low-volume concentrate. Residual organic contaminants in the precipitate can be removed using activated carbon. The process is relatively insensitive to metal content and can process solids with metal concentrations of up to 10,000 mg/kg. Epoc's acid leaching process was accepted into the SITE Demonstration Program in October 1989 (USEPA 1989d).

239. An acid leaching process developed by IT Corporation can be used to treat soils contaminated with organics and heavy metals. This process claims to produce no hazardous combustion products. Volatiles are extracted from the soils by steam injection. The soil is then transferred to a vessel where extraction of metals takes place using hydrochloric acid. Most metals are converted into chloride salts. The acid solution containing the metals is pumped to a batch distillation system where the acid is recovered. The still

bottoms containing the metals are drawn off and disposed offsite or recovered. This process was accepted into the SITE Emerging Program in October 1989 and has been tested in the laboratory on a limited basis. The process has been effective in the removal of volatile and semivolatile organics from sludges. In a separate bench-scale study on soils, some heavy metals were removed as chlorine salts (USEPA 1989d).

Acurex solvent wash process

240. The Acurex solvent wash process is based upon solid/liquid extraction using a proprietary solvent mixture to extract PCBs from soils or sediments. The appropriate solvent is selected by comparing of adsorption isotherms and PCB diffusion rates into several fluids such as pure hexane, pure FC-113 (1,1,2,- trichlorotrifluoroethane) and FC-113/hexane blend (Carpenter 1986). No information on the solvent's toxicity or residual in treated sediment is available (Ikalainen 1987).

241. Weitzman (1985), as cited in Ikalainen (1987), reported that up to 50 percent of polychlorinated biphenyls present in soil can be removed independent soil type. A maximum of 40 percent water is acceptable for efficient process operation. A pure freon and topsoil combination causes favorable equilibrium conditions, but other combinations may cause the equi librium time to increase to an unfavorable 18 hr. Other solvent combinations have achieved practical equilibrium after only 30 to 40 min, though equilibrium is less choice. Fine-grained materials may cause problems with handling and with fines carryover.

242. A pilot test on soils containing 1,983 ppm PCBs produced final concentrations of <2 ppm. The pilot test provided a design for a full-scale test prototype system consisting of a soil contactor, steam generator, reclamation system, dirty and clean solvent storage tanks, and ancillary piping equipment. Vent condensers and an activated carbon adsorption system for emissions control were also included in this prototype system. Costs for Acurex treatment range from \$130 to \$390/m^3 of soil (Carpenter 1986). Wilson (1987) reported that Acurex recommended their process not be considered for Hudson River sediments.

B.E.S.T. process (TEA)

243. The basic extraction sludge treatment (B.E.S.T.) treats soils or sludges contaminated with PCBs, oils, and creosote. The RCRA wastes amenable to treatment are dissolved air flotation float, slop oil emulsion solids, API separator sludge, and leaded tank bottoms (USEPA 1989d). The process starts

with the mixture of one part free water sediment and one to seven parts amine-based solvent, usually triethylamine (TEA). Since TEA is flammable in the presence of oxygen, the treatment system must be sealed from the atmosphere and operated under a nitrogen blanket (USEPA 1989d). The temperature must be below critical solution temperature (CST) (approximately 60° C) (USEPA 1988d), and alkaline conditions (pH 10) are required (USEPA 1988c). A single liquid phase forms, and solid matter is removed by centrifugation (generally by solid-bowl centrifugation) (USEPA 1988c) and dried to remove residual TEA. The solution is heated to above CST to separate the liquid into amine and water phases. The top fraction, consisting of TEA and oils, is decanted. Volatile organics, acetone, toluene, and methyl ethyl ketone may be removed by distillation before the TEA is recycled as feed (USEPA 1988d). The remaining lower layer of water is sent to a stripping column before discharge. This first extraction yields approximately 79.3 percent removal with subsequent extractions removing up to 98.7 percent (Carusone and Hickman 1988).

244. According to the USEPA (1988d), the B.E.S.T. process produces an effluent stream of dry solids, water, waste oil, and solvent. Solvent is separated from the oil and recycled in the process. Biological treatment or carbon adsorption may be required to remove residual organics. If soluble metals are present, precipitation or other metals removal processes must be applied. Oils are incinerated if they are not suitable for recycling.

245. The first full-scale testing of this technology occurred at the General Refining Superfund site in Garden City, GA (USEPA 1989d). In July 1988, the Resources Conservation Company (RCC) (which has patented the B.E.S.T. process) conducted a study for EBASCO/E. C. Jordan using B.E.S.T. on New Bedford, MA, harbor sediment (Allen and Ikalainen 1988). Based on bench testing, estimated costs for treatment were \$57 to \$73/yd^3 of sediment (USEPA 1988b). The result of PCB removal on low-level contaminated sediments (400 ppm PCB) was 99.1 percent. The RCC assumed efficient dredging to minimize entrainment, decantation, and filtration. The company also used centrifugation to minimize the volume of feed material for the B.E.S.T. system, thereby lowering costs. B.E.S.T. is also being considered for the Hudson River cleanup (Sanders 1989).

246. In June 1988 the USAE District, Chicago, contracted the RCC to demonstrate the B.E.S.T. process on sediment samples from the Indiana Harbor and Canal. In bench-scale testing, 7.6 ppm PCBs yielded 0.5 ppm solid fraction, <0.03 ppm water fraction, and 200 ppm oil fraction. The TEA parameter

finalized with 50 ppm solid fraction, 120 ppm water fraction, and 2,500 ppm oil fraction (USAE District, Chicago (in preparation)). Carusone and Hickman (1988) report that a system designed to treat an average of 520 m^3/day, with a peak capacity of 675 m^3/day, should cost $133.30/$m^3$ to operate.

Biotrol soil washing process

247. Biotrol, Inc., has developed a continuous unit that uses water as the washing agent to clean soils contaminated with oil, pentachlorophenol, and polyaromatic hydrocarbons such as creosote from wood-preserving sites. This unit, which is also expected to be applicable for the removal of PCBs, fuel oil, and metals, is most effective on soils containing a high percentage of sand with a majority of soil particles coarser than 200 mesh (USEPA 1988c). This limits applicability to contaminated sediments, which are more often fine-grained.

248. In the Biotrol soil washing process, contaminated soil is excavated and screened to remove large debris (0.5 to 1 in. in diameter). Once the large debris is removed, the contaminated soil is fed into the soil washing unit where water is injected and mixed with the soil. The slurry is screened again and fed into a froth flotation unit where hydrophobic components (oil and certain clay minerals) are removed. The soil slurry then flows into a countercurrent attrition/classification system consisting of scrubbing units, hydrocyclones, and spiral classifiers. Most of the soil is then discharged as the washed product, while the process water containing highly contaminated fine-grained particles and dissolved contaminants is retained for further treatment. The fine solids are dewatered and along with the clarified process water are treated biologically (if applicable). The fine solid slurry is treated by a contaminant-specific microorganism in a low-energy reactor consisting of three continuous-stirring tanks in a series. The clarified water, if applicable, is treated using a fixed-film bioreactor system (USEPA 1989d).

249. This soil washing system was operated successfully as a pilot-scale unit at the McGillis and Gibbs Superfund site in New Brighton, MN, from September to October 1989. The unit was operated continuously with a treatment capacity of 500 to 1,000 lb/hr (USEPA 1989d).

C.F. Systems extraction
process (carbon dioxide)

250. C.F. Systems has developed a continuous system that uses compressed gases, such as carbon dioxide at its critical point, to extract

contaminants (such as carbon tetrachloride, chloroform, benzene, naphthalene, gasoline, vinyl acetate, furfural, butyric acid, higher organic acids, dichloroethane, oil and grease, xylene, toluene, methyl acetate, acetone, higher alcohols, butanol, propanol, phenol, heptane, PCBs, and other complex organics) (USEPA 1989d) existing in aqueous solutions, sediments, soils, and sludges. The design of the extractor is different for contaminated wastewater when compared to the extractor for contaminated semisolids. A trayed tower contactor is used with wastewater, while a series of extractor/decanter vessels operating countercurrently is used for semisolids (USEPA 1989d). The solids must be slurried before treatment. Heavy metals and inorganics are not amenable to treatment. Carbon dioxide is primarily paired with aqueous solutions containing hazardous solvents and oxygenated compounds. Ideal pressure is 950 psi for carbon dioxide extraction (USEPA 1988d). (See also propane extraction, discussed below.)

C.F. Systems extraction process (propane)

251. C.F. Systems has also developed a continuous system that uses compressed propane at its critical point to extract contaminants. Propane works best for sediments, soils, and sludges containing PCBs and organics. These organics include carbon tetrachloride, chloroform, benzene, naphthalene, gasoline, grease, xylene, toluene, acetone, butanol, phenol, heptane, and higher order alcohols (USEPA 1988c). Ideal pressure is 250 psi for propane extraction (USEPA 1988d).

252. Propane at ambient temperature and 200 psi extracts PCBs with other organics from water, slurry, or sediment (Wilson 1987). Contaminated sediment is fed to the top of the extractor and makes non-reactive contact with condensed solvent flowing up through the extractor. Eighty percent is dissolved after each step, and 99 percent is dissolved by the third step (USEPA 1988d). The clean material is removed from the extraction, and the contaminated propane is fed to a separator where it is vaporized and recycled by recompression. Contaminants are taken away as concentrate.

253. A pilot-scale test was conducted by C.F. Systems in September 1988 on PCB-laden harbor sediment at the New Bedford Harbor, Massachusetts, Superfund site. Harbor sediments containing 350 ppm PCB were extracted to 10 ppm after 10 passes through the unit. This solvent extraction unit was demonstrated concurrently with USACE dredging studies. Extraction efficiencies of 90 to 98 percent were achieved on sediments containing PCB concentrations between 350 and 2,575 ppm. Laboratory tests indicate 99.9 percent removal for

volatile and semivolatile organics in aqueous and semisolid wastes (USEPA 1989d). Treatment cost for 800,000 yd^3 treated over an 8-year period, reducing PCB concentrations from 580 to 50 ppm, was estimated to be $48/ton (USEPA 1989a). Treatment costs should generally range from $150 to $450/ton (USEPA 1989d).

CROW process

254. The contained recovery of oily wastes (CROW) process transports oily wastes and water in shallow or deep contaminated soil above ground by using steam and hot water displacement. The CROW process is presently used for secondary petroleum recovery and for primary production of heavy oil and tar sand bitumen. Sites with soils containing coal tars, pentachlorophenol solutions, and creosote are amenable to treatment. Although no single process contains and cleans dense organic liquids, the CROW process provides in situ removal of large oily waste portions; reduces volume, mobility, and toxicity; immobilizes residual saturations of oily wastes; and stops the downward migration of organic contaminants (USEPA 1988c).

255. Injection and production wells are drilled into contaminated soils. Steam is then injected and condensed, causing organic liquids to dislodge and flow upward into the more permeable soil regions. Organic liquid saturations in the subsurface increase, and an the oil bank forms. Oil saturation is reduced to an immobile residual behind the oil bank. Hot water is injected to heat and mobilize all oily wastes. The oily wastes are recovered and the oil bank is displaced into a production well (USEPA 1988c). Further treatment is required for the recovered wastes. Application of the CROW process to contaminated soils is included in USEPA's Emerging Technologies program. Bench- and pilot-scale testing are planned (USEPA 1988c). This process has limited applicability to contaminated sediment.

Electroacoustic soil decontamination

256. The USEPA (1988c) defines electroacoustic soil decontamination (ESD) as the application of a direct current electric field and an acoustic field to allow transport of liquids through solids (fine-grained soils). Components of this system developed by Battelle Memorial Institute include electrodes and an acoustic source. Contaminants that may be treated by electroacoustic soil decontamination include cadmium, chromium, lead, cyanide, chromate, and dichromate.

257. A double-layer boundary is required for the electric potential to treat soils. The two layers consist of a fixed layer of negative ions in the

solid phase and an evenly dispersed layer of loosely held positive and negative ions. The addition of the electric potential results in the displacement of the loosely held ions and their movement to their respective electrodes. The ions drag water with them as they move through the soil (USEPA 1988c).

258. Other effects that may occur during ion movement are ion exchange, development of pH gradients, electrolysis, gas generation, oxidation and reduction reactions, and heat generation. Heavy metals can be leached or precipitated out of the soil by electrolysis, oxidation and reduction, or ionic migration. Application of the electric field increases the rate of leaching. Precipitation of the respective heavy metals is controlled by appropriate pH and osmotic gradients (USEPA 1988c).

259. The acoustic field is added to the electric field to enhance dewatering or leaching of contaminants. It may also clear the scale inside recovery wells when their pores become clogged with the contaminated particles (USEPA 1988c). The operation of this process without the acoustic field is defined as electro-osmosis (Acar et al., undated).

260. USEPA (1988c) stated that electroaccoustic soil decontamination is under evaluation and will eventually be applied to in situ cleanup of contaminated soils. This technology could prove cost effective for site remediation if proven practical on a pilot-scale basis. To date, this process has not been applied to in situ site remediation (USEPA 1989c) or to contaminated sediment.

EPA mobile soil washing unit

261. The USEPA operates a mobile soil washing unit that uses water as the extracting fluid. A coarse screen or a water knife is used in the process design to remove oversized debris. This unit uses a four-stage countercurrent extraction process that employs hydrocyclones between each extraction to separate the soil and the extracting fluid. Contaminated soil fed to the first extraction vessel is washed by extraction fluid from the first hydrocyclone. Froth flotation produces maximum mixing between the soil and the extraction fluid. This slurry exits the bottom of the extracting vessel and enters the first hydrocyclone where solids are separated from the extraction fluid. The solids then enter the second extractor vessel, and extraction fluid from the second hydrocyclone is injected. This process of washing and dewatering continues until the cleaned solids are removed from the fourth hydrocyclone (Raghavan, Coles, and Dietz 1989).

262. Scholz and Milanowski (1983) performed laboratory tests on sand/gravel/silt/clay mixtures and organic loam contaminated with phenol, arsenic trioxide, and PCBs in separate tests. The tests indicated that contaminants were washed free of the soil, but the effectiveness depended upon the solvent mixture used (water + sulfuric acid to pH 1, water + NaOH to pH 11, water + 5 percent sodium hypochlorite, water + 1 percent TWEEN 80, water + 1 percent MYRJ 52, and water + 5 percent methanol). For the inorganic soil mixture contaminated with phenol, all extractions were highly effective, with DREs greater than 87 percent. For the organic loam, the sodium hydroxide solution was most effective.

Harbauer semibatch soil washing system

263. The Harbauer semibatch soil washing system uses a low-frequency vibration step to improve cleaning by mechanical action. This system is currently considered to be among the best soil washing units developed in the Federal Republic of Germany. In this pilot-scale process, the soil is prepared by separating cut particles greater than 60 mm by a vibrating sieve and washing these particles with a blade washer before the main soil stream. The soil is then subjected to the vibration unit that dislodges contaminated fines from the soil. A soil washing solution is injected and mixed into the soil, which undergoes further vibration. After conveyance through the vibration unit, the washed soil is separated by sedimentation for particle sizes from 10 μ down to 200 μ, by a series of hydrocyclones for particles down to 20 μ and by a flocculation step followed by a belt filter press for particles down to 15 μ. Dewatering, which reduces the residual volume to be landfilled, is accomplished by the belt filter press (USEPA 1988d).

264. The Harbauer semibatch soil washing system contains a full-scale groundwater treatment system operating at 1,584 gpm that includes operations for dissolved air flotation, countercurrent stripping, air stripping, sand filtration, and/or discharge into a receiving stream. Limitations for this unit include the disposal of PCB-laden or polyaromatic-laden carbon (from activated carbon treatment) and problems that may arise with the efficiency of hydrocyclones. This unit has had limited success in treating heavy metals but has been able to treat organic-laden soils. This unit was built at a fixed site in Berlin, but three units that may be either mobile or fixed are currently in the planning stages (USEPA 1988d).

265. A test run on contaminated soils at the Berlin-Mariendorf gas works indicated DREs of 99.7, 100, and 98.9 percent for PAHs, phenol, and

total cyanide, respectively. This unit has an average throughput of 40 tons of contaminated soil/hour with recovery of 95 percent of the input soil by volume (Raghavan, Coles, and Dietz 1989).

266. The Harbauer system, which is considered semibatch because some of the steps are batch while others are continuous, costs approximately $136/ton of soil for O&M not including disposal of residue, with capital costs ranging from $4.3 to $6.1 million (USEPA 1988d).

Harmon Environmental Services, Inc., solvent wash process

267. An emerging proprietary process developed by Envirite Field Services, Inc., uses a patented solvent blend that has successfully removed PCBs in soil to levels less than 2 ppm. This process uses solvent washing with agitation for mixing purposes. Once the desired decontamination level is reached, the soil is steam stripped for residual solvent removal. This technology has successfully treated metal foil, paper, sands, clays, soils with a high organic content, and soils mixed with organic matter. It also can be applied to soils containing PCBs, dioxins, chlorodibenzofurans, and most types of petroleum products and oil. Testing of this process began in 1988 on a laboratory- and pilot-scale basis (USEPA 1988c).

Heidemij mobile soil washing system

268. The Heidemij mobile soil washing system is a pilot-scale technology that uses froth flotation to clean soils at a throughput of 30 tons/hr. Coarse rubble greater than 4 mm is removed from the soil by a wet screening process that results in a slurry containing a 1- to 3-ratio of solids to water. Soil washing agents (a Heidemij trade secret) are injected before the slurry enters the froth flotation tanks. The slurry is retained in these tanks for a retention time dependent upon the type of contaminant. The contaminated floating froth is skimmed from the slurry and pumped to wet scouring tanks for a final washing in clean water. The cleaned slurry is dewatered in a filtration process and is then returned to its original site. Soil contaminants treated by this process include oil products, heavy metals, inorganics, aromatics, polycyclic hydrocarbons, chlorinated hydrocarbons, pesticides, herbicides, and fungicides. The Heidemij mobile soil washing process is not applicable for soils containing a fine fraction (particle size less than 50 μ) over 20 percent. The end volume of cleaned soil is usually 85 to 90 percent of the treated volume. The cost of this unit varies from $90 to $155/ton not including disposal, with a capital cost of $2.8 to $3.4 million (USEPA 1988b).

In situ vacuum and steam extraction and air stripping of volatile organic compounds

269. In situ extraction removes volatile organic compounds (VOCs) from ambient temperature soils and groundwater and conceptually could be applied to a confined disposal facility (CDF). It works best for sites possessing liquids of high vapor pressure. The more volatile the compound, the faster the process. Typical recovery rates are between 20 and 2,500 lb (VOCs)/day. According to USEPA (1988d), basic equipment components include high-vacuum pumps, a connecting pipe system leading to injection wells drilled to just above the water table, and monitoring wells that measure interstitial air pressure around the production wells. Spacing of these wells is determined by models and pilot testing. The system operates by applying a vacuum through the production wells to pull up VOC vapors from soil pores and to draw fresh air from the soil surface down into the soil. Collected liquid volatiles flow through a liquid/vapor separator, and the acquired vapors are treated by an activated carbon filter, a catalytic converter, or an afterburner. The remaining liquid is treated in a closed aeration unit to volatilize any remaining VOCs.

270. Commercial applications of this general concept for groundwater treatment are marketed by Hanover Univeltechnik, Solvent Services, Terra Vac, Inc., and Toxic Treatment, Inc. The steam injection and vacuum extraction unit developed by Solvent Services, Inc., is being demonstrated at a site in San Jose, CA, to remediate 1.2 acres of land. The Terra Vac, Inc., in situ vacuum extraction unit was first applied at a Superfund site in Puerto Rico to clean up a carbon tetrachloride spill. This unit has also been used at a field demonstration at the Groveland Wells Superfund site in Groveland, MA. During this demonstration, 1,300 lb of VOCs, primarily trichloroethylene, was extracted during a 56-day period. The Toxic Treatment, Inc., unit was demonstrated at a SITE demonstration the week of 18 September 1989 for the remediation of 12 soil blocks. Demonstration results are expected in early 1990. Treatment costs for the Terra Vac unit range from $10/ton of soil at larger sites not requiring off-gas or wastewater treatment to $150/ton of soil at a small site (USEPA 1989d).

Integrated vapor extraction and steam vacuum stripping

271. This modification of the steam extraction process was developed by AWD Technologies, Inc., for the treatment of soils and groundwater

contaminated with VOCs. This integrated system combines an AquaDetox moderate-vacuum stripping tower developed by Dow Chemical for the treatment of groundwater and a soil gas vapor extraction/reinjection (SVE) process to treat contaminated soil. These processes form a closed-loop system that provides simultaneous in situ remediation of contaminated groundwater and soil with no air emissions. The system occupies approximately 4,000 ft^2.

272. AquaDetox is a high-efficiency, countercurrent stripping technology that will typically reduce up to 99.99 percent of VOCs present in groundwater. This system is capable of effectively removing over 90 of the 110 volatile compounds listed in 40 CFR Part 261, Appendix VIII. The SVE system uses a vacuum pump to induce airflow through the soil, removing vapor-phase VOCs with the extracted soil gas. This gas is treated in activated carbon treatment beds to remove additional VOCs and is then reinjected into the ground. Noncondensable vapor from the AquaDetox system is combined with the vapor from the SVE system and passed through a granulated activated carbon unit. A key component of this system is a vent header unit designed to collect the noncondensable gases or air that may leak into the portion of the unit operating below atmospheric pressure. The steam used to regenerate the activated carbon treatment beds is condensed and treated by the AquaDetox system (USEPA 1989d). By-products of this process are a free-phase recyclable product and treated water. The regenerated carbon can be reused for approximately 3 years, after which it must be disposed (USEPA 1989d).

273. This process is currently being used at the Lockheed Aeronautical Systems Company in Burbank, CA. Groundwater to be treated at this site contains as much as 2,200 ppb of trichloroethylene and 11,000 ppb perchloroethylene. The soil gases to be treated at this site have a total VOC concentration of 6,000 ppm. The rates of treatment are up to 1,200 gpm for groundwater and 300 ft^3/min for soil gas (USEPA 1989d). Because VOCs are not often a problem for contaminated sediment, this process has limited applicability to sediment remediation.

Low-energy acetone-kerosene extraction (Steiner extraction)

274. The low-energy acetone-kerosene extraction process, developed by the Applied Science Department of New York University, extracts PCBs and some other organic contaminants from soils and sediments and concentrates the extract in a manner appropriate for chemical destruction. This process separates the sediment into a liquid and a solid, then leaches the solid portion

with a hydrophilic solvent (acetone). The acetone is steam stripped from the sediment. The PCBs are treated with a hydrophobic solvent (kerosene) (Carusone and Hickman 1988).

275. For full-scale removal operations, a large countercurrent extraction vessel is necessary. Conceptually, the process can handle up to 50 percent water content. Theoretically, the acetone is removed from the soil by steam stripping. However, unknown amounts of acetone may remain in the soil after treatment. Efficiencies of up to 85 percent contaminant removal per extraction step can be achieved.

276. Studies on PCB-contaminated sediment from Waukegan Harbor, Illinois, confirmed the validity of the basic low-energy process. However, field testing was not attempted (Wilson 1987). The capacity of low-energy acetone-kerosene extraction equipment ranges from 260 to 750 yd^3 of sediment/day. The cost of the treatment process is estimated to be $\$41/yd^3$ of sediment (Carusone and Hickman 1988).

277. The low-energy solvent extraction process currently available from ART International, Inc., uses common solvents, including acetone and kerosene, in the extraction of organic contaminants, including PCBs, from soils and sediments. The organic contaminants are removed from the soil with a water leaching solvent and are then concentrated in a water immiscible stripping solvent. The leaching solvent is recycled while the stripping solvent, containing most of the contaminants, leaves the unit for final destruction. This technology was accepted into the SITE Emerging Program in October 1989 and is currently available for bench-scale treatability studies (USEPA 1989d).

Mechanical aeration/extraction

278. Camp, Dresser, and McKee, Inc. (1986) defines mechanical aeration/extraction as the contact between clean air and contaminated soils to transfer volatile organics into the airstream. Mechanical aeration/extraction strips volatiles such as benzenes, toluenes, xylenes, trichloroethylene, ketones, and alcohols from soils. Heating of the soil accelerates stripping and enhances removal of less volatile organics. Posttreatment of the volatiles can be accomplished through activated carbon canisters, water scrubbers, or incineration in an afterburner. Equipment employed for the process include closed mechanical aeration systems, pneumatic conveyor systems, vacuum extraction systems, and low-temperature thermal stripping systems.

279. In the closed mechanical aeration process, contaminated soil is mixed in a pug mill or rotary drum system. Volatile organics are released by

churning the soil, captured by induced air within the chamber, and passed to an air pollution control device (water scrubber, afterburner, or vapor-phase carbon adsorption system). Air emissions are discharged through a stack (Camp, Dresser, and McKee, Inc. 1986).

280. The pneumatic conveyor system includes a long tube carrying high-velocity air, an induced draft fan, a feeder for dispersion of particles into the air stream, and a cyclone collector for final recovery of solids. The unit heats inlet air to 300° F to induce volatilization. Air velocity is estimated at 75 ft^3/sec for high air-to-soil ratios. Pneumatic conveyors are used in manufacturing for drying 90 percent moisture solids (Camp, Dresser, and McKee, Inc. 1986). These processes will be difficult to implement for contaminated sediment.

MTA Remedial Resources, Inc., soil washing process

281. A commercially available soil washing process developed by MTA Remedial Resources, Inc., uses existing mining and oil recovery technology to concentrate and remove contaminants from soils using an alkaline and surfactant addition. The treatment residues consisting of detoxified soils can be returned to the site while the by-products consisting of concentrated organics will require incineration, landfilling, or other treatment for ultimate contaminant removal. This technology has also been demonstrated for the removal of metallic compounds of lead, cadmium, copper, chromium, and nickel (USEPA 1988d).

O. H. Materials extraction process (methanol)

282. The O. H. Materials Company provides a method of extraction by addition of methanol to PCB-contaminated soil. Soil previously dried to 5 percent moisture is slurried with methanol, separated, and redried. Solvent cleanup for reuse is attainable by addition of activated carbon and complete incineration as a RCRA waste. The clean soil may be treated with light land farming for biological degradation or evaporation of residual methanol. Wastewaters are treated in a holding pond (Carusone and Hickman 1988).

283. In 1985, the O. H. Materials Company used this process to extract PCBs from soils at a Superfund site in Minden, WV. The PCB concentration in the soil was reduced to <25 mg/kg before being land farmed. An assumption was made that further stages of extraction would remove more PCBs. In another test in EPA Region III, extraction provided 75 percent contaminant removal per extraction step (Carpenter 1986), though estimated total efficiency of the O. H. Materials extraction process is 97 percent contaminant removal (Carusone

and Hickman 1988). Fine particles in soil were dispersed to create colloids. When methanol was injected, large volumes of sludge were generated. This sludge is not easily treated (Ikalainen 1987). The cost of the O. H. Materials extraction process is approximately \$334/m^3 of soil (Carpenter 1986).

Oil CREP soil washing system

284. The Oil CREP System developed by TBSG Industrievertretungen GmbH of the Federal Republic of Germany (FRG) is a simple operation that uses Oil CREP, a proprietary combination of surfactants, solvents, and aromatic hydrocarbons, to extract oil products from soil and sand while preserving the structure of the oil for recycling. Oil CREP I was developed as a biodegradable version of Oil CREP and is less efficient than its predecessor. Oil CREP II is being developed for use on soil types other than sand. In this process, oil-contaminated sand or gravel is fed by a hopper into the unit. Oil CREP I is injected into the feed material and is mixed by a screw mixer. The sand travels to a rotating separator vessel where oil is disengaged from the sand by freshwater or seawater. The oily mixture flows into an oil collection tank while the clean sand is reused onsite. Equipment associated with the Oil CREP system include hydrocyclones, mixers, crushers, flotation tanks and, in the case of contaminants that form an emulsion when mixed with Oil CREP I, a water treatment plant. Currently, two small-scale Oil CREP units have been developed to clean oil-contaminated sand. The first, developed in 1984, has a throughput of approximately 10 m^3/hr (44 gpm) while the second, a prototype unit that updates the first unit, has a throughput of 8 m^3/hr (35 gpm). A third system with a throughput of 20 m^3/hr (88 gpm) is in the planning stages. The Oil CREP System was successful in removing PCBs, PAHs, and various hydrocarbons in spring 1986 from a site in Flensburg, FRG, but was not effective in the removal of fluoranthene. Costs of this technology, including transport, are estimated to range from \$82 to \$109/ton.

Soilex solvent extraction process (kerosene/water)

285. The Oak Ridge National Laboratory is developing the Soilex Process that uses kerosene and water as solvents to efficiently break up soil particles (Carpenter 1986). Soil-to-water and soil-to-kerosene ratios ranging from 3 to 5 were evaluated. Afterward, kerosene retention was about 25 volume percent. The soil was land farmed to remove the remaining kerosene by evaporation. Water does not interfere, but optimum reaction occur at a water content of 60 percent.

286. Carpenter (1986) discussed a three-stage, batch pilot unit operating with a 6- to 1-volume ratio. Initial PCB concentrations of 180 to 350 mg/kg were reduced to 6 to 9 mg/kg. The pilot plant consisted of three stages of mixing equipment and was operated in a countercurrent mode. Soil and water were added to stage one, and soil and kerosene to stage three. Each mixture had an air-driven mixer and a 200-ℓ maximum capacity. An interstage solvent pump and a 120-ℓ solvent tank transferred the kerosene in a countercurrent mode. A distillation packed column 2.4 m long and 7.5 cm in diameter included an 18-ℓ steam-heated reboiler and product condenser. The distillation unit stripped kerosene from the PCB and oils for recycling. Each batch took approximately 3 days to complete.

287. The Soilex process accepts wet sludge as well as soils (Carusone and Hickman 1988). Total estimated efficiency is 95 percent, but actual removal of 52 percent per extraction resulted in only 85 percent total efficiency. At least 16 hr settling time must be allowed for separation of the kerosene-water mixture. RCRA wastes may also be generated. The Soilex extraction process cost is estimated to be approximately \$790/m^3 of soil (Carpenter 1986).

Steam stripping

288. According to Camp, Dresser, and McKee, Inc. (1986), steam stripping is the injection of steam into a liquid or slurry to evaporate organic contaminants. Steam stripping can be used to treat VOCs, phenols, ketones, phthalates (Camp, Dresser, and McKee, Inc. 1986), chlorinated hydrocarbons, xylenes, alcohols, and chlorinated aromatics (USEPA 1987). Water-immiscible organics and metals are not amenable to steam stripping.

289. Direct injection of steam and multiple-pass heat exchangers are the most reliable systems for steam stripping. Direct injection is an energy-intensive method used for aqueous and mixed waste with lower level volatile organics that cannot be stripped with air (Camp, Dresser, and McKee, Inc. 1986). Heat exchangers are innappropriate for sediments. Direct injection might be an option for a CDF where amenable contaminants are present.

Surfactants

290. Surfactants can be injected into soil to flush hydrophobic organics and emulsify nonsoluble organics including PCBs, crude oil, and tertiary oils, but may clog soil pores, preventing further flushing (USEPA 1985). A study performed by Texas Research Institute (1979), as cited in USEPA (1985), for the American Petroleum Institute concluded that a mixture of anionic and

nonanionic surfactants resulted in a contaminant recovery of up to 40 percent. In a laboratory study conducted by Ellis and Payne (1983), as cited in USEPA (1985), using an aqueous surfactant solution, crude oil recovery increased from less than 1 percent to 86 percent, and PCB recovery increased from less than 1percent to 68 percent. The USEPA conducted field and laboratory studies on the effectiveness of a 50/50 blend of two commercially available surfactants, Adsee 799 and Hyonic PE-90, on soils at the Volk Field, Wisconsin, fire training pit. Based on both gravimetric and infrared spectroscopy determinations of contaminant concentrations, there was no measurable decrease in contaminants following as many as 14 pore volumes of soil washing in the field tests (USEPA 1985).

Immobilization Technologies

Chloranan encapsulation

291. Chloranan encapsulation involves the injection of cement, water, and an additive called Chloranan into solids or sludges contaminated with organic compounds, heavy metals, oil, and grease. Chloranan encapsulates the organic contaminants to prevent their interference with the solidification process. Contaminants are immobilized from soils in a concrete-like matrix that is leach resistant. The chloranan process is available from New Environment, Inc., Hartford, OH.

292. This process was demonstrated for the SITE program in October 1987 at a former oil reprocessing plant in Douglassville, PA, that contained high levels of oil and grease along with volatile and semivolatile organics, PCBs, and heavy metals. Results of unconfined compressive strength tests for 28-day samples ranged from 220 to 1,570 psi. Durability tests consisting of wet/dry and freeze/thaw cycles resulted in no changes in the physical strength of the solidified matrix. Microstructural analysis indicated possible degradation of the sample over a period of time. The end product volume was approximately 120 percent more than the initial waste volume. Leaching test results were mixed, with TCLP results being very low (essentially all values for metals and volatile and semivolatile organics were below 1 ppm). There were no changes in the TCLP values of volatile and semivolatile organics from untreated to treated waste (USEPA 1988b). Cost estimates based on the SITE demonstration ranged from $98 to $206 per ton (USEPA 1989b).

Freezing (ground)

293. Ground freezing is a process that uses freezing loops that have been installed in the ground and a self-contained refrigeration system that pumps coolant around the freezing loop (Sullivan, Lynch, and Iskander 1984, as cited in USEPA 1985). According to USEPA (1985), ground freezing has yet to be demonstrated in actual waste operations. Freezing does not treat the waste itself, but treats the soil containing the waste by decreasing the permeability of the soil. However, the condition is only temporary because of thermal maintenance expense associated with maintaining the freezing conditions.

In situ stabilization

294. Several commercial firms offer equipment for injection and/or mixing of solidification/stabilization reagents with material contained in a disposal site or for other in situ application of S/S technology. In situ S/S tor contaminated dredged material could be accomplished in the waterway, in a CDF, or in barges or scows used to transport material to the site. Additives for a large CDF could be added to and mixed with partially dewatered dredged material using agricultural spreaders and tillers (Francingues 1985).

295. The Geo-Con/DSM deep soil mixing system is a demonstrated technology operated as a batch process that attempts to immobilize organic and inorganic compounds contaminating soils, sediments, and sludge bottoms. Two basic components of this technology are the deep soil mixing system, which has the capability of in situ mixing of the chemicals with the soil, and a batch mixing plant used to the supply proprietary treatment chemicals (USEPA 1988b). The deep soil mixing system consists of one set of cutting blades and two sets of mixing blades attached to a vertical auger rotating at approximately 15 rpm. The additive and any supplemental water are injected through two conduits in the auger with additive injection on the downstroke.

296. The Geo-Con/DSM equipment, in combination with a cement-organo clay proprietary additive offered by International Waste Technologies, was demonstrated for the SITE Program at a PCB-contaminated site in Hialeah, FL, in April and May 1988 (USEPA 1988c). Although PCBs did not leach from the solidified soil, absolute immobilization could not be confirmed because of low PCB concentrations in the untreated soil. Sufficient data for treatment of metals and other organics were not available for the evaluation of the immobilization or removal efficiency of this process. Costs estimated by the SITE evaluation were \$150 per yd^3 (USEPA 1989f).

297. S.M.W. Seiko, Inc., has developed an in situ S/S process called the "soil-cement mixing wall" that involves injection and mixing of S/S agents into contaminated soils with hollow augers. This technique has been used for 18 years for mixing soil cement or chemical grout for various construction applications, including cutoff walls and soil stabilization. The volume increase ranges from 10 to 30 percent, depending on the nature of the soil matrix and the amount of S/S agents and water required for treatment. This in situ method is applicable for the treatment of soils containing metals and organics such as pesticides, phenols, and PCBs. Site selection for demonstration of this process is currently under way (USEPA 1989d).

298. An in situ process that mixes reagent with the soil or sediment by direct injection of the S/S reagent is available from ENRECO, Inc. (Cullinane, Jones, and Malone 1986). Another alternative for in situ S/S is to use common construction machinery such as a backhoe or clamshell to mix additives with the soil. This option works well where large amounts of additive are required.

Lime-based pozzolan S/S

299. Pozzolanic materials are described as those that set to a solid mass when mixed with hydrated lime. Pozzolans all contain silicilic acid and frequently contain aluminum oxide. Solidification/stabilization of contaminated materials using lime and pozzolans requires that the material be mixed with a carefully selected reactive, pozzolanic additive to a pasty consistency and subsequently blended with hydrated lime. The resulting moist material may be packed or compressed into molds or placed into a disposal site and compacted. The pozzolanic material typically used for S/S is bituminous coal fly ash or subbituminous coal fly ash. The process is less expensive but produces a less durable product and has greater contaminant leachability when compared to cement-based processes (Cullinane, Jones, and Malone 1986). Lime/fly ash S/S of dredged material was evaluated in laboratory studies of sediment from Everett Bay, Washington (Palermo et al. 1989), and Indiana Harbor, Indiana (Environmental Laboratory 1987). Results of leachate testing for several heavy metals were mixed.

300. A lime-based technology marketed by Separation and Recovery Systems, Inc., is included in the SITE program. It uses lime and other nonhazardous minor chemicals to enhance S/S. Wastes and contaminants treated by this technology include acidic sludges containing at least 5 percent hydrocarbons and wastes containing up to 80 percent organics. This process only

tolerates low levels of mercury and moderate levels of lead although claims of metals immobilization have been made. The USEPA is currently in the process of locating a demonstration site for this technology under the SITE program (USEPA 1989d).

Macroencapsulation

301. One macroencapsulation method is the placement of solidified/ stabilized contaminated materials into overpack drums. After the waste is solidified/stabilized and placed in the drums, the lid is welded or fused on the drum to form a container that completely isolates the waste from the surrounding environment (USEPA 1989c). Although macroencapsulation is one of the most effective solidification processes, it is impractical for large volumes of material.

302. A method of surface encapsulation developed by Environmental Protection Polymers utilizes chemical stabilization and solidification with lime or cement, then microencapsulation with 1,2-polybutadiene. After microencapsulation, the material is encapsulated with polyethylene resin (USEPA 1989c). Environmental Protection Polymers has also developed a simpler approach in which contaminated soils or sludges are injected into a high-density polyethylene overpack. A lid is then spin-welded on the container by a portable welding device developed by Environmental Protection Polymer, thus forming a seam-free capsule (USEPA 1985). The cost of the polybutadiene/HDPE microencapsulation process was estimated by Environmental Protection Polymers to be approximately $90/ton, while encapsulation in the seam-free overpack is approximately $50 to $70 per 80-gal drum (USEPA 1985).

Organic polymerization

303. Organic polymerization is a S/S technology that uses a polymer to immobilize contaminants within various wastes. The most common organic polymer is urea formaldehyde. This technology has been used primarily for radioactive wastes but has been used on a limited basis for the immobilization of organic chlorides, phenols, cyanides, and arsenic. Kyles, Malinowski, and Staczyk (1987), as cited in USEPA (1989c), indicate that organic polymerization can be used in the immobilization of flue gas desulfurization sludge, electroplating sludge, nickel-cadmium battery wastes, kepone-contaminated sludge, and chlorine product wastes that have been dewatered and dried (USEPA 1988d). The addition of organic materials makes application of this process to contaminated sediments questionable.

Portland cement pozzolan S/S

304. Many S/S processes incorporate Portland cement as the binding agent. Pozzolanic products such as fly ash are frequently added to Portland cement to react with any free calcium hydroxide and thus improve the strength, handling characteristics, and chemical resistance of the concrete-like product. Cement processes reduce the mobility of heavy metals due to their conversion to insoluble hydroxides or carbonates because of the elevated pH of cement. Sorbents and other additives, such as soluble silicates, clays, emulsifiers, carbon, zeolites, cellulosic sorbents, and lime, are often mixed with cement to decrease the loss of specific contaminants and improve performance. This process is one of the more versatile and adaptable S/S methods, results in a product with exceptional strength and durability, and retains contaminated materials very effectively (Cullinane, Jones, and Malone 1986).

305. Laboratory-scale evaluations of cement-based S/S have been conducted for contaminated sediments from Everett Bay, Washington (Palermo et al. 1989), Indiana Harbor, Indiana (Environmental Laboratory 1987), and New Bedford Harbor, Massachusetts (Myers and Zappi 1989). All of these evaluations demonstrated improved immobilization for most, but not all, heavy metals. Best Demonstrated Available Technology program studies on contaminated soils indicated that cement-based S/S was effective in immobilizing arsenic, lead, zinc, copper, cadmium, and nickel (Weitzman 1988, as cited in USEPA 1989c). Leachability of organic carbon for the Everett and Indiana Harbor sediments was not affected by S/S. However, leachability of PCBs in New Bedford sediment were reduced by factors of 10 to 100. The USAE District, Chicago (in preparation) estimated the cost of S/S for Indiana Harbor sediments to be $\$55/yd^3$.

Proprietary solidification processes

306. The total number of proprietary processes for S/S of contaminated materials is unknown. The number is generally increasing, but often vendors are unsuccessful in marketing their product and drop from the list. Descriptions of all of the processes are not available in the literature because of "trade secrets" or because they have not been independently evaluated. Several proprietary processes are mentioned under other options for immobilization processes, and others are briefly described below.

307. URRICHEM. A process developed by Soliditech, Inc., uses the injection of URRICHEM, a proprietary reagent, into a mixture of waste and pozzolanic fly ash, kiln dust, or portland cement to chemically and physically

immobilize hazardous waste components within the solidified matrix. Waste types and contaminants amenable to this technology include a broad range of organic and inorganic slurries and bulk hazardous liquids. Wastes containing radioactive nucleides, explosives, and high levels of strong inorganic acids such as hydrochloric or sulfuric acids are not applicable to this solidification process (USEPA 1988c).

308. The Soliditech process using URRICHEM was demonstrated under the SITE program in December 1988 at the Imperial Oil Company/Champion Chemical Company Superfund site in Morganville, NJ. Treated wastes contained petroleum hydrocarbons, PCBs, other organic compounds, and heavy metals. Volume of the waste increased an average of 22 percent while the bulk density increased approximately 35 percent. Physical tests indicated that the solidified samples were durable, with unconfined compressive strengths ranging from 390 to 860 psi and little weight loss after 12 cycles of wet/dry and freeze/thaw tests. Tests also indicated that the treated waste had a low permeability and that density increased after treatment. Chemical analyses of leachates and extracts indicated that heavy metals present in the untreated waste were immobilized and PCBs were absent (USEPA 1989d).

309. <u>DCM shale silicate process.</u> The DCM cement shale silicate proprietary process developed by Delaware Custom Material, Inc., employs cement and an emulsifier to stabilize oily wastes. Brookhaven National Laboratories conducted tests indicating the stabilization of oily wastes with a volumetric loading of up to 30 percent (Clark et al. 1982, as cited in Cullinane, Jones, and Malone 1986). Manufacturers claim the process is also applicable to the solidification of wastes containing acids and organic solvents (Hayes and Granlund, undated, as cited in Cullinane, Jones and Malone 1986).

310. <u>FMS silicate.</u> A S/S technology developed by Silicate Technology Corporation uses silicate compounds to fix and solidify organics and inorganics in soils and sludges and remove organics contaminating groundwater. This technology uses a proprietary reagent, FMS silicate, to adsorb organic contaminants prior to cement injection to form a high-strength nonleaching monolith. The material is then stabilized using the FMS silicate reagent with granular activated carbon for removal of organics from waste streams, and solidified by reactions occurring due to the first step. This process can be used in the treatment of soils and sludges contaminated with metals, cyanides, fluorides, arsenates, ammonia, chromates, and selenium in unlimited concentrations. Higher molecular weight organics in groundwater, soils, and sludges that can

be treated include halogenated, aromatic, and aliphatic compounds. This process is not applicable for the treatment of low molecular weight organics including alcohols, ketones, and glycols (USEPA 1988c). The Silicate Technology process was evaluated by Myers and Zappi (1989) for S/S of sediment from New Bedford Harbor sediment.

311. A demonstration of the Silicate Technology Corporation silicate S/S technology was set to occur between December 1989 and August 1990 at the Kaiser Steel site in Fontana, CA (USEPA 1989d).

312. Chemfix S/S process. The Chemfix S/S process was demonstrated in March 1989 at the Portable Equipment Salvage Company in Clackamas, OR. This process was effective in reducing concentrations of copper and lead in the extracts of the Toxicity Characteristic Leaching Procedure (TCLP). Concentrations were reduced 94 to 99 percent in the treated extract in comparison with the raw waste extract. Durability tests showed little or no weight loss after 12 cycles of wet/dry and freeze/thaw tests. Permeability decreased more than one order of magnitude (USEPA 1989d).

313. Bench-scale work was performed by Chemfix Technologies and by Associated Chemical and Environment Services (ACES) to assess the feasibility of using a cement-based or pozzolanic solidification process as a component in the remediation plan for the Marathon Battery Site (Ebasco, Appendix D, 1986b, as cited in Carusone and Hickman 1988). In the case of cadmium-contaminated sediments, Chemfix tested (a) sodium silicate and portland cement, (b) sodium silicate and cement kiln dust, and (c) sodium silicate, portland cement, and a catalyst. The products were subjected to Extraction Procedure Toxicity Characteristic (EP) testing for metals and 48-hr unconfined compressive strength (UCS) tests. The UCS values for mixtures 1, 2, and 3 were 34.7, 20.8, and 17.4 psi. Only the sodium silicate and portland cement mixture passed the EP toxicity testing with a cadmium concentration in the extract of 0.709 mg/ℓ (the EP toxicity maximum is 1 mg/ℓ). Cobalt and nickel are not standard EP toxicity parameters and were not measured. The ACES conducted bench-scale studies with three mixtures composed of differing weight percentages of waste, pozzolan, and lime. The 48-hr UCS test results range from 7 to 19 psi. Cobalt and nickel were included in the EP toxicity testing. Two of the three mixtures were found to have cadmium, cobalt, and nickel levels less than 1.0 mg/ℓ (Carusone and Hickman 1988).

314. Envirosafe I process. The Envirosafe I process has used a fly ash and lime mixture for the stabilization of sludge containing oil (49 percent

oil and grease) and for the neutralization of sludges containing inorganics and metals. Unconfined compressive strength tests as well as leaching tests were used to demonstrate process effectiveness (Smith and Zenobia 1982, as cited in Cullinane et al. 1986).

315. PQ Corporation process. The PQ Corporation has developed a modification of the silicate process that involves the use of sodium silicate to successfully stabilize a sludge containing organics and heavy metals. The process has also successfully stabilized wastes containing high levels of organics and petroleum by-products as well as wastes containing organic solvents (Spencer et al. 1982, as cited in Cullinane et al. 1986).

316. Sil-B. The Silica Bonding (Sil-B) method is based on the neutralization of sodium silicate by the addition of acid to form a silicic acid liquid that has a low viscosity and good sediment-mixing properties. Small-scale testing of this technique was conducted in the River Waka in Uchikawa, Japan, that is contaminated by raw sewage discharges and heavy metals in bottom sediments (Tabuse 1982). The small field application of the Sil-B process involved placement of a bottomless-box frame (similar to a caisson) in the river bottom such that river water trapped within the frame could be pumped out. After water was pumped out, Sil-B agent was added to the exposed bottom sediment and mixed with the sediment with a grab-bucket. The thrust of Japanese implementation of S/S is to remove and "improve" (physically) bottom sediments for use as fill in creating new land. Applications of solidification techniques in Japan are quite commonplace (Tabuse 1981; Kita and Kubo 1983, Nakamura 1983, and Otsuki and Shima 1983, as cited in Carusone and Hickman 1988). However, the analyses do not sufficiently address the extent of contamination prior to treatment or the chemical stability of treated sediments (Carusone and Hickman 1988).

317. Wastech, Inc., process. Wastech, Inc., has developed a process in which a proprietary binding agent is mixed with soils, sludges, or liquids contaminated with volatile or semivolatile organic and inorganic compounds. This matrix is then mixed with cementitious materials to form a high-strength, nonleaching monolith that can be land disposed without double liners or caps. This process has been applied to soils, sludges, and raw organic streams containing lubricating oil, aromatic solvents, evaporator bottoms, chelating agents, and ion exchange resins ranging in concentration from parts per million levels to 40 percent by volume. Treatability studies are currently under

way on an oily waste and a wood preserving waste. The USEPA is in the process of site selection for a demonstration of this process (USEPA 1989d).

318. Soils from the Tacoma Tar Pits Superfund site were fixed with a proprietary product. The treated monolith was subjected to various chemical and physical tests to determine the integrity of the monolith. The TCLP tests indicated that the fixation process inhibited the release of various contaminant classes to different degrees. Lead was strongly fixed while PAHs and PCBs were leached from both raw and fixed samples in low quantities, but the fixed sample levels were below cleanup goals. All fixed soils, except the tar samples, passed UCS test limits of 50 psi and were resilient to the stresses of the wet/dry durability tests (Rupp 1989).

Soil cooling

319. Soil cooling involves the decrease of soil system temperature in order to reduce the vapor phase and volatilization rate of volatile constituents. Soil cooling may enhance later in situ treatment by retention of contaminants for longer periods of time in the soil system. USEPA (1984) described one method of lowering temperature as the application of cooling agents to the soil surface. Testing of ethyl ether vaporization from a liquid pool indicated that solid carbon dioxide (dry ice) is more effective than its liquid form, liquid nitrogen, or ice. The vapor concentration reduced from 8,300 to 96 ppm. Greer and Gross (1980), as cited in USEPA (1984), indicated that dry ice temperature was at -85° C for 80 min, and soil was fed at a rate of 250 kg/2.7 m^3.

320. Soil surface modifications also produce cool soil temperature. Agricultural soils are usually cooler in the summer and warmer in the winter due to vegetation. Most soils warm slower in the spring and, once heated, may require irrigation to cool. Tillage creates a surface barrier to reduce heat flow to the subsurface (USEPA 1984).

321. Cooling agents are more effective than soil modifications, but are much more expensive (Cullinane et al. 1986). Limited field applications using cooling agents have been conducted on liquid spills. Long-term reliability requires continuous treatment (USEPA 1984). This process is inappropriate for contaminated sediment.

Soil vapor pore volume reduction

322. If soil contaminants are volatile, suppression of volatilization may be appropriate. Retaining these compounds within the soil system allows for later application of in situ techniques. According to the USEPA (1984),

the best method for volatilization reduction other than soil cooling is the reduction of soil vapor pore volume through which soil vapors travel.

323. Reduction of soil vapor pore volume is accomplished by modification of the soil system through compaction and water addition to reduce air-filled pores in the soil. This technology is best applied to compounds with high-vapor phase mobility potential and low-water phase partition potential. Soil vapor pore volume reduction works well for most volatile organic (benzene, gasoline, phenol) and inorganic (hydrogen sulfide, ammonia, radium, methyl mercury) compounds. Effectiveness depends upon the nature of the compound (USEPA 1984).

324. Laboratory evaluations made by Farmer et al. (1980), as cited in USEPA (1984), on hexachlorobenzene (HCB) from simulated landfill areas indicated that increases of soil moisture content logarithmically decreased HCB vaporization. The HCB volatilization flux through a water layer was reduced by a factor of 870 as compared to uncovered samples. Bulk density has also been demonstrated to have a large effect upon HCB vapor movement. An increase in bulk density from 0.96 to 1.15 g/cm^3 resulted in a 65-percent reduction of HCB flux (USEPA 1984).

325. This technology is at the laboratory stage of development and has limited application to contaminated sediment. Retreatment is required for continued reduction of volatilization (Cullinane et al. 1986).

Sorption

326. Sorption processes typically involve adding a solid material to soak the free liquid in a soil or waste to produce a product that is easier to handle (USEPA 1987). The process applies to organics and inorganics. Sorbents include natural materials such as fly ash, kiln dust, vermiculite, and bentonite, as well as synthetic materials such as activated carbon, resins, Hazsorb (Dow Chemical), and Locksorb (Radecca Corp.) (Cullinane, Jones, and Malone 1986). In addition to eliminating free liquids, sorption processes may also modify the environment, provide adsorption sites for contaminants, or maintain pH and redox potential to limit waste solubility. Sorbents are inexpensive and plentiful, but are often required in large amounts, producing a problem for disposal (USEPA 1987). The quantity of sorbent for removal of liquid varies according to the nature of the liquid, solids content of the waste, and chemical reactions that may take place (USEPA 1985). Synthetic materials, which are more expensive, have found use where binding of a specific contaminant in the waste is critical (Cullinane, Jones, and Malone

1986). Sorption processes can be applied to contaminated sediment in a manner similar to S/S processes.

Thermoplastic microencapsulation

327. Thermoplastic encapsulation 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 (USEPA 1985). 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 (USEPA 1987). Also, solvents such as xylene and toluene, grease, and chelating and complexing agents such as cyanides and ammonium are not applicable to treatment by this process (USEPA 1985). The normally high water content of dredged material limits application of this process to contaminated sediments without extensive dewatering or drying.

328. Thermoplastic encapsulation requires special equipment as well as highly trained operators to heat and mix the wastes and solidifying agents. The temperature of operation ranges from 130° to 230° C generally, and waste must be thoroughly dried before solidification (USEPA 1985). Water and volatile organics are evaporated, and after the waste/asphalt mixture is cooled, the mass becomes rigid but deformable and resistant to weathering (USAE District, Chicago (in preparation)). Advantages of this process include waste volume reduction, low permeability, free liquid elimination, improved handling, and good strength (USEPA 1987). A possible commercial use for the product (an asphalt-contaminated soil mass) is in the paving or patching of roads (USEPA 1989c). Limitations of thermoplastic microencapsulation are high equipment and energy costs; also, the plasticity of the treated matrix generally requires the matrix be containerized for transportation and disposal, increasing the cost (USEPA 1985). No studies have been conducted on dredged material (USAE District, Chicago (in preparation)). The high energy costs associated with drying dredged material limit the application of this process.

Radiant Energy Technologies

329. Radiant energy technologies utilize either artificial or natural radiant energy (ultraviolet light) in the photodegradation of organic contaminants in sediment and groundwater. Technologies included in the following

discussions include the light activated reduction of chemicals (LARC) process, photolysis, and Ozonics.

LARC process

330. The LARC process is a proprietary physicochemical technology that utilizes isopropanol as a solvent. Isopropanol, which is relatively inexpensive, readily dissolves PCBs. An isopropanol-sediment mix containing 25 percent water is decanted, mixed thoroughly, and decanted again. Sodium hydroxide is injected into the PCB extract to form a 2 percent solution that is placed in a photolytic reactor where hydrogen gas is injected and UV light is used to oxidize the PCBs. Retention time for this process is between 1.5 and 2 hr. Lab results indicate effective PCB extraction from wet or dry soils. Estimated efficiency of this technology on PCBs is greater than 90 percent with an estimated residual of 38 to 50 ppb. To reduce PCBs to background levels, a five-stage extraction unit would be necessary. Tests on the LARC process have been conducted on a small basis, using a single lamp. The cost of the LARC process is estimated to be approximately \$205/yd^3 (Carpenter 1986). This process was dropped from consideration for the Hudson River cleanup by its proprietor (Wilson 1987). Cost will likely eliminate its consideration for remediating contaminated sediment.

Photolysis

331. Photolysis is a physicochemical technology that uses radiant energy from sunlight or UV lamps to photodegrade soil surface contaminants such as complex and toxic organic compounds. Ultraviolet photolysis results in the elevation of a molecule's energy state, increasing the ease with which bond cleavage and oxidation of the molecule can be accomplished (USEPA 1987). Photolysis reactions may aid in microbial degradation due to the oxidation of resistant complex structures. The rate of photolysis is a function of the nature of light used, absorption spectrum of the reaction sensitizer species, reacting species concentration, energy from light absorption, type of reaction media, and contaminant/environment interactions. Photolysis can be enhanced by the addition of proton donors and/or volatilization enhancement.

332. Soil characteristics that affect photolysis are water solubility, K_D values and K_W values, all of which should be low for photolysis treatment. Cupit (1980), as cited in USEPA (1984), indicated that photochemical reactors are more effective pertaining to hazardous compounds than are physical or chemical reactors with respect to their atmospheric removal mechanisms. Limitations of this technology include the inability to penetrate into soil or

opaque solutions for the destruction of pollutants. Therefore the contaminant must first be extracted or stripped from the soil into a liquid or vapor phase. The technology can be improved with the addition of ozone or hydrogen peroxide. This technology is conceptual, with no information in literature on the efficiency of volatilization enhancement. Photolysis with proton donor addition has been demonstrated in the laboratory and observed at several hazardous waste sites. Nitrated waste has been successfully photolyzed in a pilot-scale demonstration (USEPA 1987). The complexity and cost of a process that extracts contaminants from the sediment and then applies photolysis limit the application of this process for contaminated sediment.

Ultrasonics/hydrogen-ozone/UV technology

333. Ozonics Recycling Corporation technology has developed an ultrasonics/hydrogen-ozone/UV technology based upon simultaneous extraction and treatment of a sediment slurry with ultrasound added to increase rates of dissolution of the PCB contaminants and to reduce coalescence of bubbles of gas reactants. This process, the Excalibur/Ozonics process, is designed to treat soils, solids, sludges, leachates, and groundwater contaminated with organic and inorganic substances including PCBs, pentachlorophenols (PCPs), pesticides, herbicides, dioxins, and cyanides. For this technology to be effective, total contaminant concentrations should range from 1 to 20,000 ppm, and soils and solids greater than 1 in. in diameter should be crushed before treatment. This technology uses extraction with ultrapure water and ultrasound to extract contaminants from the soil. This extract is then treated with ozone, UV light, and ultrasound to produce an oxidizing environment where contaminants are oxidized. This process produces an end product consisting of decontaminated soil and inert salts (USEPA 1989d).

334. In this system, contaminated soil is excavated and screened to less than 1 in. in diameter. Any solids not passing through the screen are sent to a hammermill to be crushed and returned for screening. The screened soil is then slurried with ultrapure water in an extractor vessel at a 10-volume water to 1-volume soil ratio. Ultrasound is used as a catalyst to enhance the soil washing process. The soil slurry is then conveyed to a centrifuge or cyclone to separate the decontaminated soil from the contaminated water. After separation, oil is recovered from the contaminated water with an oil/water separator using ozone to aid in oil recovery. The water then flows through a filter to remove fine particles. After filtration, the water flows through an activated carbon filter and a deionizer to reduce the contaminant

load. The water is then pumped into a multichambered reactor where ozone, along with UV light and ultrasound, is applied. The treated water flows out of the reactor into a storage tank and is reused to wash another batch of soil. Off-gases from the reactor are treated with activated carbon. Unit capacity ranges from 1 ft^3 of solids/hr to 27 yd^3 of solids/hr (USEPA 1989d). Estimated cost of treatment is \$128 to \$157/yd^3 (Wilson 1987). Implementation of such a system for contaminated sediment would be difficult because of the complexity of the process and the large amounts of additional water that are required.

Thermal Technologies

335. This section discusses the various thermal technologies that may be considered in treating contaminated sediment. Technologies discussed in the following paragraphs include the processes of pyrolysis, incineration and vitrification; blast furnaces; industrial kilns; low-temperature thermal stripping; radio frequency heating; supercritical oxidation; and wet air oxidation.

Advanced electric reactor pyrolytic process

336. The advanced electric reactor pyrolytic process is a patented thermal treatment technology also known as high-temperature fluid wall incineration (Camp, Dresser, and McKee, Inc. 1986). This pilot-scale batch process (USEPA 1987) is used primarily to treat soils contaminated with PCBs and dioxins but is also used to treat solids, liquids, and gases containing heavily halogenated organics, and nerve gas (Camp, Dresser, and McKee, Inc. 1986). This high-cost technology is limited to treating solids <35 US mesh and liquids atomized to <1,500 μ droplets (USEPA 1987).

337. The unit consists of a vessel with a porous carbon core surrounded by carbon electrodes. A radiation heat shield constructed of multilayered graphite paper backed with carbon felt surrounds the core and electrodes. The heat shield is enclosed by more conventional insulation and a double-walled cooling jacket. Nitrogen acts as a gaseous blanket that isolates the reactants from the core and also acts as a heat transfer medium between the carbon electrodes and porous carbon core. Two postreactor treatment zones are present in the unit. The first vessel provides additional heating (1,095° C) and additional residence time. The second vessel is water cooled and adds more residence time (Camp, Dresser, and McKee, Inc. 1986).

338. Feed materials with masses ranging from 1,580 to 1,927 kg are introduced into the top of the reactor. Nitrogen is introduced at the reactor annulus formed by the external vessel and the porous graphite core to create an inert fluid wall. Smaller nitrogen streams are used in nonprocess applications such as sight glass sweeping and prevention of oxygen leakage at the electrode ports.

339. The waste material flows through the core where thermolysis occurs at a temperature of approximately 4,000° F (2,204° C). After being processed in the reactor, the gas product and waste solids flow through two postreactor treatment zones that ensure complete destruction. Solid residue is collected in a bin while the gas is cooled to less than 538° C in the second postreaction treatment zone prior to downstream particulate cleanup. Fine particles are removed from the product gas in a baghouse, and the gas is subject to a wet caustic scrubber for chlorine removal (Camp, Dresser, and McKee, Inc. 1986). The product gas then passes through activated carbon filters arranged into two parallel banks with a series of five filters each. The product gas, which by now is composed primarily of nitrogen, is then emitted into the atmosphere through the process stack (Carpenter 1986).

340. The principal products of destruction are carbon, carbon monoxide, hydrogen, and inert soils (Camp, Dresser, and McKee, Inc. 1986). The destruction of PCBs in contaminated soils yielded hydrogen gas, carbon dioxide, elemental carbon, and a granular, free-flowing waste (Carpenter 1986). The estimated efficiency of this process on PCBs exceeds 99.9999 percent with an estimated residual of <1 ppb (Carusone and Hickman 1988).

341. The advanced electric reactor is distinguished from other thermal processes by its ability to transfer energy to the waste through radiation instead of combustion, convection, or conduction (Camp, Dresser, and McKee, Inc. 1986). It has a high destruction efficiency and eliminates the production of intermediate pyrolysis products (USEPA 1985).

342. The advanced electric reactor was tested on soils containing an initial Aroclor 1260 concentration of 3,000 ppm. The DREs were 99.9999 percent in all but one of the tests. No HCl, Cl_2, dioxins, or furans were observed at the stack. Chlorine removal efficiencies in the scrubber and activated carbon treatment beds were above 99.9999 percent (USEPA 1989e).

343. The patents to this unit are owned by the J. M. Huber Corporation. This unit has been fully permitted under the Toxic Substances Control Act (TSCA) for the destruction of PCBs (Carpenter 1986). Projected treatment

costs using this process is approximately \$998/yd^3 (Carusone and Hickman 1988). J. M. Huber estimates that treatment cost for a large site would range from \$365 to \$565/ton of waste. Westinghouse also markets an electric pyrolyzer.

Blast furnaces

344. A blast furnace is a unit designed to make iron that could utilize hazardous wastes with high heat content to supplement fuel requirements. With temperatures generally above 3,000° F and reaching 3,400° F, the blast furnace produces molten iron from iron ore and other iron-containing materials. Iron ore, carbon (coke), and limestone are fed into the top of the furnace while iron and slag are removed from the bottom in different layers. Hazardous wastes can be injected above the slag layer for use as fuel. To avoid product quality problems, the composition of the fuel waste should be controlled. Most sediments will have a low fuel value, limiting applicability of this option.

345. Hazardous waste is not known to be used as a fuel for any of the blast furnaces (approximately 80) operating in the United States (USEPA 1987). Waste oils were used in a Hazardous Waste Engineering Research Laboratory test program, which caused concern that the DREs would be reduced as a result of the reduced atmosphere of the blast furnace (USEPA 1987).

Circulating bed combustor

346. A variation of the fluidized bed incinerator is the circulating bed combustor developed by Ogden Environmental Services, Inc. The circulating bed combustor uses high air velocity to circulate solids and create a larger and more agitated combustion zone for the efficient destruction of hydrocarbons (USEPA 1989d). Dry limestone is added to the feed material to react with the acid gas so that a wet scrubber is not necessary (USEPA 1988d). The treated ash is transported out of the incinerator by an ash conveyor for disposal. Hot gases produced during incineration flow through a convective gas cooler and baghouse before being released to the atmosphere (USEPA 1989d). Complete destruction is reported at relatively low temperatures (approximately 1,600° F) due to the high degree of turbulence; thus, a secondary combustion chamber is not required (Camp, Dresser, and McKee, Inc. 1986). The circulating bed combustor can be used in the treatment of soils, slurries, and sludges contaminated with halogenated and nonhalogenated hydrocarbons.

347. Tests conducted on the circulating bed combustor at the GA Technologies, Inc., pilot plant in 1983 showed the following destruction and removal efficiencies: oily water sludge, >99.99 percent; chemical plant

wastes, >99.9 percent; Chlorinated organic sludge, >99.999 percent; aluminum pot linings, >99.999 percent; and PCB soil, >99.9999 percent (Vrable and Engler 1985).

348. Ogden Environmental Services, Inc., of California has modified the circulating bed combustor to include a cyclone that separates hot gases from the solids. The solids from the cyclone reenter the combustion chamber for further treatment. Ogden has received a USEPA permit for a 2-million BTU/hr capacity plant in San Diego, CA, for the incineration of PCB-contaminated soil. The DREs for the Ogden circulating bed combustor are PCBs, 99.9999 percent (below detection limits) with 99.1 percent HCl capture; PCPs, 99.92 percent with >99 percent HCl capture; fuel oil, 99.998 percent; and chlorinated organics in liquids, 99.999 percent with >99.9 percent HCl capture. System throughput for this unit is 9,000 lb/hr for PCB-contaminated soil with 10 percent water content (Dobos 1989).

349. The circulating bed combustor is one of seven incinerators nationwide permitted to burn PCBs (USEPA 1989d). Advantages of this technology are its simple design, minimum nitrogen oxide formation, long life of the incinerator, high efficiency, simplicity of the operation, and relatively low capital and maintenance costs. The circulating bed promotes even temperature distribution, thus eliminating hot spots present in other types of incinerators. The lower combustion temperatures used in the circulating bed combustor prevent the formation of chlorinated dioxins. Heat is retained very well by the sand bed; thus, the system can be shut down and returned to operation quickly (Dobos 1989). Disadvantages include difficulty in residue removal, low throughput capacity, difficulty in handling the ash from the bed, and relatively high operating costs (State of California 1981 and Monsanto Research Corporation 1981, as cited in USEPA 1985).

350. Superburn Systems, Ltd., of Canada has developed a demonstration unit with a capacity of 8 million BTUs/hr near Vancouver, British Columbia. Four test runs were performed resulting in DREs of 99.99 to 99.9999 percent on contaminated wastes (Dobos 1989). The circulating bed combustor will be demonstrated at the McColl Superfund site in early 1990 (USEPA 1989d). The Superburn Systems unit is currently being applied to the decontamination of harbor sediment and has been selected by Environment Canada and the Nova Scotia Department of the Environment for the Sydney Tar Ponds cleanup project (Dobos 1989). Costs of the circulating bed combustor are dependent on fuel

requirements, scale, and site conditions. Cost estimates range from $27/ton to $150/ton (USEPA 1989e).

Eco Logic hazardous waste destruction process

351. Eco Logic is a patented (US Patent 4,819,571) thermochemical destruction process that relies on the ability of hydrogen to dechlorinate organic compounds at high temperatures. This continuous process may be utilized in the treatment of chlorinated wastes, such as contaminated solvents and oils, certain chemical warfare agents and certain wastes produced in the production of explosives, and contaminated sediments. Also treated are organic wastes containing PCBs, halogenated benzene, phenols, cycloalkane, alkanes, dioxin, and dibenzofuran. The Eco Logic process can handle waste concentrations of 100 percent strength.*

352. The Eco Logic unit scheduled for construction is mobile (requires only two standard tractor trailers) and is less costly to operate than a combustion unit (one third to one fifth the cost of incinerators of comparable capacities with capital costs ranging from a factor of one fifth to one tenth lower than incineration processes). Another advantage of this process is that water enhances the reduction reaction. Thus, aqueous wastes may be treated. A third advantage of this process is that the products of the reaction can be recycled or utilized for energy production in the pretreatment stages of the process. For example, the products of the reduction of PCB-contaminated harbor sediment are excess hydrogen, benzene, methane, toluene, ethylene, hydrogen chloride (HCl), and water. The HCl can be scrubbed out, the benzene and toluene can be recovered for recycling, and the methane, ethylene, and excess hydrogen can be used as energy in pretreatment stages. A fourth advantage of this process is the lack of combustion of chlorinated products and the subsequent formation of dioxin or furan by-products. The unit's throughput capacity can be increased by ganging reactor units on a single ancillary support and control system.*

353. Nitrogen is used to initially flush any oxygen out of the reducing vessel to preclude the likelihood of an explosion. A mixture of waste and a gaseous reducing agent (such as hydrogen, gaseous ammonia, natural gas, methane, propane, or water vapor), that has been preheated is injected by nozzles mounted tangentially near the top of the reducing vessel, creating a

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* Personal Communication, 17 Aug 1989, Kelvin Campbell, General Manager, ELI Eco Technologies, Inc.

vortex. The reaction that follows may be performed with or without a metal catalyst such as iron filings or powdered zinc, tin, or nickel. The mixture flows around a central ceramic tube and passes by glo-bar heaters that heat the mixture to approximately 800° to 900° C before it flows out ports in the bottom of the ceramic tube. The reduction reaction is completed in a residence time from approximately 5 to 40 sec. After exiting the reducing vessel, the gases produced flow into a combustion vessel where high-temperature oxidation occurs. Excess air or oxygen can be introduced in this vessel to create a turbulent flow of hot gases from the reducing vessel with oxygen, promoting the complete combustion of the gases at a temperature ranging from approximately 1,200° to 1,400° C with a residence time of 2 sec or more.*

354. After the reaction is completed, the gases are cooled by a direct injection of a water spray. The gases are then controlled at 85° C to reduce approximately half of the amount of water in the gases by condensation, and all of the HCl by condensation and scrubbing with a lime slurry spray. A heat exchanger reduces the gas temperature to approximately 5° C to condense and remove the rest of the water and the recoverable solvents. The heat exchanger also provides heat (150° C) for the preheating of the waste to be processed in the reduction vessel. A cyclone and mist eliminator are also used in this step for the collection of aerosols and particulates. The remaining gases, consisting only of excess hydrogen, hydrogenation products such as methane and ethylene, and some minor amounts of solvent fumes that were not condensed, can then be used as a secondary fuel to the primary fuel source (propane or natural gas) in the boiler after they flow through the fan and flame arrestor. The boiler, which requires a small stack for emissions control, produces steam for the heat exchanger mentioned above. Effluent from the unit consists of grits from the reactor, calcium chloride and particulate sludge from the HCl scrubber, and particulates from the secondary cooling and solvent recovery stage. The cold water spray from this stage may be contaminated but will be recycled through the process. The destruction and recovery process is a semi-closed loop, with no combustion of chlorinated species occurring.*

355. Consistent results of over 40 bench-scale tests have demonstrated that a combination of hydrogen and chlorinated organic waste subjected to temperatures equal to or greater than 800° C for a period of 3 sec results in 99.9999 percent or greater destruction efficiency. The products formed were

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* Personal Communication, Kelvin Campbell.

HCl and dechlorinated organics that could be recovered and recycled. Molar equivalent of Aroclor 1248 was reacted with 22 molar equivalents in the reducing chamber at 875° C and 1 atm during a reaction period of approximately 30 sec. The DRE for Aroclor 1248 was 99.9 percent, and the gaseous reaction product contained HCl, benzene, biphenyl, and chlorobenzene. This mixture was passed into the oxidation/combustion chamber where a 5-percent excess of preheated air was injected. Temperatures ranged from 1,000° to 1,200° C with a residence time of 2 sec. This was effective in the completion of the oxidation of the remaining reactants in the mixture. A full-scale project for this destruction process has been funded by the Department of National Defense of Canada for an estimated cost of $1,270,200. Eco Logic is currently preparing to run bench-scale tests on harbor sediments and is planning to test aqueous sediment waste as part of a pilot-scale demonstration.*

Flame reactor process

356. The flame reactor process is a patented thermal technology developed by Horsehead Resource Development Company, Inc. The process treats solids including soils, flue dusts, slags, and sludges containing heavy metals. Waste flows into feed bins and is gravity fed into the flame reactor where the waste reacts with a reducing gas at temperatures above 2,000° C. The reducing gas that reacts with the waste is produced from the combustion of solid or gaseous hydrocarbon fuels in oxygen-enriched air. Volatile metals are captured in a vapor and dust collection system while the nonvolatile metals are encapsulated in the slag. The waste is reduced to nonleachable slag and a recyclable heavy metal-enriched oxide. Organic compounds should be destroyed by the high temperatures of this process. This process requires a feed material with a moisture content of 15 percent or less and smaller than 200 mesh. Larger particles (up to 20 mesh) can be processed, but the efficiency of metals recovery is usually reduced (USEPA 1989d).

357. The flame reactor is currently set up as a demonstration plant at Monaca, PA, with a throughput capacity of 1.5 to 3 tons/hr. A SITE demonstration will probably be conducted under a pending RCRA Research Development and Demonstration permit that will allow treatment of Superfund wastes containing high concentrations of metals but only negligible amounts of organics (USEPA 1939d).

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* Personal Communication, Kelvin Campbell.

Fluidized bed incineration

358. Fluidized bed incineration is a nonproprietary thermal destruction technology used widely in the United States paper industry and on European waste (USEPA 1988d). A demonstration-scale unit for hazardous waste is available (USEPA 1987). A full-scale unit has successfully completed its Part B Permit trial burn on RCRA and other toxic waste, and one commercial mobile unit has been built by Ogden Environmental Systems (USEPA 1988d).

359. This technology is used to treat solids, liquids, gases, slurries, sludges (USEPA 1985), contaminated soils containing halogenated and nonhalogenated organics, pharmaceutical wastes, phenols (Camp, Dresser, and McKee, Inc. 1986), and methyl methacrylate in addition to municipal wastewater treatment plant sludges, oil refinery wastes, and pulp and paper mill waste (USEPA 1985). The unit consists of a cylindrical, vertical, refractory-lined vessel that contains an inert granular material, usually sand, on a perforated metal plate (USEPA 1985). If contaminated soil is being treated, the soil mass acts as the bedding material.

360. In this process, combustion air is introduced at the bottom of the incinerator and bubbles through the inert bedding material, causing the bedding material to become fluidized and agitated. The waste is pumped into the vessel and is combusted within the bubbling inert material. The temperature within the inert bed ranges from 1,400° to 1,600° F, and residence times range from a few seconds for gases to a few minutes for liquids (State of California 1981, as cited in USEPA 1985). The solid material is either removed from the bottom of the vessel as decontaminated ash or becomes small enough to become particulates in the exhaust gas. Exhaust gases and volatile compounds pass into a secondary combustion chamber where they are combusted for a retention time of approximately 2 sec. Exhaust gases, after passing through air pollution control equipment (such as a cyclone, wet scrubber, baghouse, or electrostatic precipitator), are released into the atmosphere. If the wet scrubber is used for air pollution control, there will be an effluent of wet scrubber water that will need to be treated and disposed.

High-temperature slagging incineration

361. High-temperature slagging incineration is a Belgian thermal destruction technology that transforms waste including low-level radioactive wastes and most stable chlorinated aromatics into a mechanically strong and chemically stable basalt-like material in granular or bulk form. The first phase of the process is a pretreatment stage in which wastes are sorted,

shredded to 7 cm, and mixed in bins to create a homogeneous waste stream that is fed into the combustion chamber by screw feeders. A fuel- and oxygen-powered burner then heats the top of the waste into a layer of molten slag at approximately 1,400° C. The waste layer that separates the molten slag, and the refractory lining serves as a thermal barrier. The lower layer of waste pyrolyzes, generating dust particles that are absorbed by the oxidizing upper layer of molten slag. The slag droplets flow from the refractory bell to a granulator where they are quenched, causing them to burst into granules. The off-gas simultaneously flows into a postcombustion chamber fueled by oil or combustible liquid wastes where they are oxidized completely and cooled to 900° C. A stage of cleaning units consisting of Teflon bag filters, followed by a scrubber unit and a series of high efficiency particulate air filters, purify the off-gas, resulting in a very low flue-gas organic and particulate content (USEPA 1988b).

362. Due to its low capacity, this technology has not been able to process regular quantities of hazardous waste. Test runs on PCB-laden material indicate PCBs were combusted to an efficiency of 99.99977 percent at 957° C, and the off-gas concentrations for pentachlorodibenzodioxin and pentachlorodibenzofuran were below detection. Because the decontamination factor for the complete off-gas system is between 10^4 and 10^6, the DRE for PCBs is expected to be >99.9999 percent. The cost of this full-scale process with a capacity of 60 kg/hr is $3.50/kg (USEPA 1988b). Modifications to the high-temperature slagging incineration process include the SCK/CEN and HAWAI (USEPA 1988b).

363. Another modification of high-temperature slagging incineration is the cyclone combustor developed by Babcock and Wilcox Company. This emerging technology is designed to decontaminate soils or solids contaminated with organics and metals. Combustion air entering the combustor is induced to undergo a swirling pattern that increases the heat release rate and efficiently mixes the air and fuel to increase combustion temperature and residence time. As the combustion air swirls through the unit, fly ash and other waste particulates are retained along the walls of the combustor. Organic contaminants are vaporized and incinerated by the increased temperatures within the combustor. This technology was accepted into the SITE Emerging Program in October 1989 (USEPA 1989d).

Industrial kilns (cement, lime, aggregate, clay)

364. Industrial kilns are a conventional, well-demonstrated technology used to treat liquid organic wastes, while recovering heat. At least 15 cement and 6 aggregate kilns are now using hazardous wastes as a supplemental fuel in the United States. The unit consists of steel, refractory brick-lined rotary kilns that are longer than the conventional rotary kiln incinerator (USEPA 1987).

365. Kilns are generally limited to liquid wastes containing organics. The heavy metal, ash, chlorine, and sulfur content of the waste must be controlled to prevent problems in kiln operations and product quality. This technology is not applicable to contaminated sediments (USEPA 1987).

Infrared incineration

366. Infrared incineration is a thermal destruction technology used to destroy halogenated and nonhalogenated organics including PCBs in CERCLA wastes (USEPA 1988d). Other waste types treated by this process include dioxins; spent activated carbon; contaminated soils, sludges, and solids that are smaller than a specified size; and sediment.

367. A mobile unit, developed by Shirco Infrared Systems, Inc., consists of a waste preparation system and weigh hopper, an infrared primary combustion chamber, a propane-fired secondary combustion chamber, an emission control system, and a process management and monitoring control center. Solid waste is processed by waste preparation equipment that prepares the waste to the consistency and particle size treated by the unit. The waste feed is then weighed and conveyed to a hopper mounted over the conveyor belt leading to the furnace. This wire mesh conveyor belt feeds waste into the infrared primary chamber where temperatures produced by infrared radiators (silicon carbide elements) and fuel oil combustion reach 1,850° C. The material is stirred gently by rotary rakes or cakes breakers to ensure proper mixing and to complete combustion. A blower providing air at selected locations along the conveyor belt is used to control the burning rate of the waste. The waste remains in the primary combustion chamber for a residence time ranging from 10 to 180 min. Fine-grained material sifting through the wire mesh and settling on the floor of the chamber is removed intermittently. The ash is quenched with scrubber water effluent, removed to an ash hopper, and then transported to a holding area. The scrubber effluent flows into a clarifier where sludge settles and is then removed for disposal. The effluent may receive further treatment by carbon while gaseous volaties exit the primary

chamber into the secondary chamber where temperatures reaching 2,200° to 2,400° F destroy any residual organics present. These gases are then vented through an emission control system where the particulates are removed and the acid vapor is neutralized in a venturi/scrubber section, while the clean gases are drawn form the scrubber into a free-standing stack. The primary process variables include temperature, residence time, waste layer thickness, and combustion air flow rate (USEPA 1988d). Residuals produced are ash, scrubber water, and off-gas.

368. At Peak Oil in Brandon, FL, the following efficiencies were obtained using a full-scale unit developed by Shirco Infrared Systems, Inc.: DRE values for PCBs in excess of 99.99 percent were achieved; residual PCBs in the ash were less than the 1-ppm operating standard (ranging from 7 to 900 ppb); a destruction efficiency ranging from 83.15 to 99.88 percent for PCBs based on the PCB content of furnace ash was achieved; and SO_2 in the off-gas was removed by more than 99.9 weight percent (Rosenthal 1988). Another Shirco unit was tested at the Times Beach Dioxin Research Facility. The waste treated was silty soil containing 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) at a concentration ranging from 156 to 306 ppb. Two tests were performed, with residence times of 15 and 30 min. In both tests, levels of TCDD were reduced to below 38 parts per trillion and particulate emissions were well below the standard of 0.08 grains/standard cubic foot at 7 percent oxygen (USEPA 1989e).

369. A number of fixed infrared units are available, but operating experience as a mobile technology is limited. These fixed units have been used primarily for industrial wastes. However, the only mobile unit is being applied to hazardous waste on a pilot-scale basis. Several full-scale commercial units for hazardous waste treatment will be available in the near future (Camp, Dresser, and McKee, Inc. 1986). The estimated O&M cost of the mobile skid-mounted unit is approximately $416/ton of soil (Rosenthal 1988).

In situ vitrification

370. In situ vitrification is a patented thermal destruction technology developed for the US Department of Energy by the Pacific Northwest Laboratory, a division of Battelle Memorial Institute and is applied commercially by Geosafe (Reimus 1988). This batch process converts contaminated soils containing hazardous waste and radionucleides (including organics, inorganics, heavy metals, and PCBs) into a chemically inert and stable glass and crystalline

product (Reimus 1988) more resistant to leaching and more durable than granite or marble (USEPA 1988d).

371. Four large electrodes are vertically inserted in a square arrangement in the contaminated soil, and graphite is placed on the surface to complete the circuit between electrodes. Sand, glass frit, or soda ash can be added to the soil to improve the process. Electrical currents pass through the graphite, oxidizing the graphite and creating a melt that gradually encompasses the entire hazardous waste/soil matrix. The electric current creates temperatures between 1,600° and 2,000° C (USEPA 1989d), causing encapsulation of the nonvolatiles, such as heavy metals, in the molten mass. Nitrates and organics are destroyed by pyrolysis and gases, and other pyrolytic by-products migrate to the surface and combust in the presence of oxygen. The electric current is turned off, and the molten mass cools and solidifies. The combustion gases generated are drafted into a hood arranged over the processing area and drawn into an off-gas treatment system (Reimus 1988) consisting of a quench tower, pH-controlled venturi scrubber, mist eliminator, temperature controller, HEPA filters, and carbon adsorbers (USEPA 1988c). This technology allows soil or sludge vitrification over an area of approximately 540 yd^3 (27 ft/side and a depth of 20 ft) in 7 to 10 days. A period of several months to a year or more is required for the soil to cool.

372. Advantages of in situ vitrification are that (a) the majority of gas evolved by the process is pyrolyzed into low molecular weight molecules or diatomic gases that pose no significant danger to the environment or onsite workers (USEPA 1988c); (b) saturated soils can be treated, but the initial energy will be used for water evaporation in the soil or sludge around the graphite and glass frit starter path (Reimus 1988, USEPA 1988c); (c) cement inclusions are completely dissolved within the vitrified mass, (d) various soil types throughout the United States can be treated by this technology, (e) the remaining vitrified mass has a very low susceptibility to leaching (Reimus 1988), and (f) volume reduction occurs since void volumes are removed and organic materials are combusted (USEPA 1989d).

373. Disadvantages are that (a) soils with permeabilities greater than 10^{-4} cm/sec are difficult to treat if ground flowing water is present, thus requiring groundwater diversion; (b) if buried metals occupy over 90 percent of the distance between electrodes, electrical shorting may occur (USEPA 1988b, 1988c), (c) a negative pressure must be maintained in the off-gas treatment hood by the off-gas treatment system, (d) the process is limited by

the amount and concentration of combustible organics in the waste (USEPA 1988c), and (e) operating cost will be increased by a high water content (USEPA 1985).

374. In situ vitrification has been tested successfully in 59 bench-, engineering-, pilot-, and large-scale tests, proving the widespread feasibility and application of the technology. The process has been patented in the United States, Canada, Japan, Great Britain, and France, and a partially exclusive license on these patents has been transferred to Geosafe Corporation for non-Federal US government nonradioactive waste (Reimus 1988).

375. A feasibility study completed on PCB-contaminated sediment from New Bedford Harbor provided the following results: PCBs found in the off-gas were below analytical detection limits, TCLP tests showed metal leaching concentrations below regulatory limits, very small amounts of volatilized cadmium and lead were produced (<2 percent), the low chlorine release levels posed no concern for off-gas system corrosion, and the soil-to-off-gas DRE for PCBs is >99.9985 percent (this represents PCBs not released to the off-gas system and is based on analytical detection limits). The soil-to-stack DRE is estimated to be >99.99999 percent, assuming the use of a single-stage activated carbon filter having a 99.9-percent organic removal efficiency. The overall PCB mass balance indicated a destruction of the total PCBs to be >99.94 percent. Estimated cost ranged from $290 to $330/ton of sediment (Reimus 1988).

Liquid injection incineration

376. Liquid injection incineration is a well demonstrated conventional technology (USEPA 1987) used in the destruction of almost any pumpable organic waste or gas that contains PCBs, pesticides, halogenated and nonhalogenated organics, dioxins, pumpable acid and phenolic sludges, polymer wastes, and still and reactor bottoms. Wastes that are not amenable to the process include heavy metal wastes and wastes high in inorganics. A pollution control device is necessary to control air emissions (Monsanto Research Corporation 1981, as cited in USEPA 1985). Since this process will not handle solids, it will not be further discussed.

Low-temperature thermal stripping

377. Low-temperature thermal stripping is a demonstrated technology used in the removal of volatile organics and PCBs from soils. The rationale for low-temperature thermal stripping is that only enough heat to volatilize the organic contaminants is needed, and any more heat addition is costly and inefficient. Volatilized contaminants are treated in a follow-on treatment

unit. Low-temperature thermal stripping processes and variations thereof are offered by American Toxic Disposal, Inc., Canonie, Chemical Waste Management, and Roy F. Weston.

378. American Toxic Disposal vapor extraction system. The vapor extraction system developed by American Toxic Disposal, Inc., is a low temperature thermal stripping technology designed to treat soils, sludges, or sediments containing less than 5 percent total organic contaminants and 30 to 90 percent solids. The vapor extraction unit uses a low-temperature fluidized bed to remove contaminants such as volatile and semivolatile organics including PCBs, PAHs, and PCPs, volatile inorganics, and some pesticides. Nonvolatile inorganic contaminants such as metals do not impede the process, but are not treated (USEPA 1989d).

379. Contaminated materials are fed into a fluidized bed where they are mixed with gases at approximately 320° F flowing from a gas-fired heater. The hot gas forces volatile contaminants and water out of the solid waste and into the gas stream, which flows to a gas treatment system. A cyclone and a baghouse remove most of the particulates from the gas stream. Vapors from the cyclone are cooled in a venturi scrubber, countercurrent washer, and chiller section before they are sent to a carbon adsorption system for treatment. The liquid effluent is clarified and passed through a series of activated carbon treatment beds. Sludge is centrifuged, and the liquid after centrifugation is passed through the activated carbon treatment beds (USEPA 1989d).

380. By-products of this system include the following: (a) 96 to 98 percent of solid waste feed as clean, dry dust; (b) a small quantity of pasty sludge containing organics; (c) a small quantity of spent adsorbent carbon; (d) wastewater that may need further treatment; and (e) small quantities of dust from the cyclone and baghouse (USEPA 1989d). This process has been selected as a candidate process for the Hudson River cleanup (Sanders 1989).

381. Canonie low-temperature thermal aeration. The low-temperature thermal aeration system developed by Canonie is an onsite process that processes 15 to 20 yd^3 of contaminated material/hour and removes all chlorinated solvent constituents and aromatic hydrocarbons detected in the USEPA method 601/602 to below detection limits (0.02 ppm). The PAHs can be removed to levels less than 1 ppm, while extractable hydrocarbons can be removed from oily soils to a level less than 100 ppm.

382. In this process, a stream of heated air is injected countercurrent to the flow of soils in a rotary drum. Soils are heated to 300° F, VOCs are

removed from the treated soil, soil is discharged from the drum and quenched with water, and the soil is replaced onsite. The airstream containing dust, VOCs, and acid vapor flows through cyclones and into a baghouse to remove the dust, to a wet scrubber to remove acid vapors, and through granular activated carbon to remove the VOCs. The clean air is vented into the atmosphere, and the carbon is transported offsite for regeneration.

383. This process has been successfully demonstrated at the McKin Superfund site in Maine and will be demonstrated at the Ottati and Goss Superfund sites in New Hampshire (Canonie 1989). The average cost of treating the soil at the McKin Superfund site was \$252/yd^3 (USEPA 1989e).

384. Chemical Waste Management X*TRAX system. A mobile system developed by Chemical Waste Management called X*TRAX employs a process in which organic-contaminated soils are heated in the presence of water. This causes evaporation of water and vaporization of the organic contaminants, leaving a dry material containing traces of residual organics. The X*TRAX unit consists of a rotary kiln indirectly fired with propane and an off-gas treatment system. Contaminated solids or sludges are augered or pumped into the kiln and heated to temperatures ranging from 500° to 800° F. The volatilized water and organics are transported by nitrogen gas to an off-gas treatment system consisting of a three-stage cooling and condensing unit that treats low-, intermediate-, and high-volatility organic compounds in a stepwise fashion, while the nitrogen is heated and recirculated throughout the kiln. Small amounts of the nitrogen are treated with a filter and a carbon adsorption drum and released to the atmosphere. Undesirable oxidation reactions are prevented by the presence of nitrogen in the relatively low-temperature heating process. This system is applicable to the treatment of solids or sludges containing organics with boiling points less than 800° F, less than 10 percent total organics, and less than 60 percent moisture. The system is set at a temperature between 50° and 150° C and can handle up to 22,000 ppm VOCs with 99-percent removal efficiency (Camp, Dresser, and McKee, Inc. 1986). Solid feeds must be <1.25 in. in diameter and, for pumpable waste, solids <0.4 in. in diameter must be removed.

385. This technology has been used on soils at a CERCLA site and was proposed for testing on mixed hazardous and radioactive waste and PCB contaminated soils in late 1988-1989 (USEPA 1988d). Both laboratory- and pilot-scale systems have been tested. The laboratory-scale unit is capable of reducing PCB concentrations from approximately 6,000 ppm to less than 2 ppm in soils.

The pilot-scale system was tested on two wastewater sludges in October 1988, and phenol concentrations were reduced 99 percent. The USEPA plans to conduct a SITE demonstration at the Kettleman Hills facility in 1990 on three soil types. Two of the soils will be contaminated with PCBs while one will be contaminated with other organics (USEPA 1989d).

386. Weston low-temperature thermal stripping (Holo-Flite Screw). The Weston unit (US Patent 4,738,206) is a full-scale system that uses a heated helical auger to heat and mix contaminated soils. Hot oil, provided as a heat transfer fluid, flows through the hollow auger and heats the soil to approximately 350° C. Some of the combustion gas from the oil heater is passed through the thermal processor at approximately 375° C in order to maintain a temperature high enough to avoid condensation of the contaminants on the walls of the exhaust system. Volatile and semivolatile contaminants are volatilized and processed in an afterburner. The vapor from the thermal processor contains contaminants, steam from the soil, and exhaust gases from the oil heater. These vapors exit at a temperature of approximately 150° C and flow through a fabric filter to reduce the particulate load in the vapor. An air-cooled condenser then reduces the temperature to approximately 52° C, condensing steam and organics to reduce the load on the afterburner. The afterburner is operated at 982° C with a minimum of 3 percent excess oxygen to incinerate fumes generated in the process. The exhaust is quenched to approximately 82° C and then flows through a caustic scrubber system to neutralize acid gases formed in the afterburner. The aqueous stream produced by the condenser flows through an oil/water separator to separate any hydrocarbons present from the water. The water then flows through fabric filters and granular activated carbon and is used as make-up water for the scrubber and dust control for the treated soil. The organic phase is either disposed off-site or injected into the afterburner. Discharges from the system are scrubber stack exhaust, processed soil, spent granular activated carbon, filter cake, and the organic phase from the oil/water separator, if it is not injected into the afterburner.

387. The Weston low-temperature thermal stripping unit has been demonstrated on a full-scale for the removal of JP4 and trichloroethylene from an abandoned sludge dump at Tinker AFB, Oklahoma. The DRE values for TCE were 99.9855 and 99.9955 percent for two runs completed at 315° C and 204° C, respectively. Other contaminants that were removed to below detection were 1,2-dichlorobenzene (initial concentrations 35,000 and 15,000 ppb),

1,3-dichlorobenzene (initial concentrations 3,500 ppb and below detection), 1,4-dichlorobenzene (initial concentrations 8,700 ppb and below detection), toluene (initial concentrations 8,700 and 8,300 ppb), naphthalene (initial concentrations 4,300 and 5,000 ppb), and total xylene (initial concentrations 5,900 and 11,400 ppb). A sustained throughput rate of 9,091 kg/hr was established. Costs of remediation with this process were between $90 and $100/metric ton of soil (Nielson and Myler 1989).

Lurgi pelletizing process

388. Lurgi Canada, Ltd., a company based in Germany, has developed a process in which contaminated harbor sediments are allowed to dewater in open-air beds. This dewatered material is formed into small pellets that are incinerated to destroy the organic contaminants. The residual solids are recovered and used commercially as a viable construction material. Unfortunately, no further information on the process is available (Dobos 1989).

Molten glass vitrification

389. Molten glass vitrification is a thermal destruction technology based on existing glass-making technology that destroys solid or liquid organics including plastics, asphalts, PCBs, or pesticides by using a pool of molten glass as a heat-transfer mechanism. Acid gas and any particulates produced during the destruction process are released as emissions requiring off-gas treatment, while all residuals remain in the molten glass matrix.

390. This process significantly reduces the volume of the waste and produces a stabilized nonbreaking glass. The process is inappropriate for waste with high ash content, and problems may arise if the final glass product contains more than 1 percent sodium sulfate. This unit is commercially available for uses other than hazardous waste treatment (USEPA 1987).

Molten salt incineration

391. Molten salt incineration is a thermal destruction technology that is in the developmental stage. A pilot-scale unit is available (USEPA 1987) for the destruction of hazardous liquids and low-ash solids containing chlorinated hydrocarbons, PCBs, chlorinated solvents, and malathion, all of which have been effectively destroyed (Kiang and Metry 1982).

392. In this process, wastes undergo catalytic oxidation via their contact with molten salt (90 percent sodium and 10 percent sodium sulfate) (Kiang and Metry 1982) maintained at temperatures ranging from 1,400° to 2,000° F, causing the hydrocarbons to form carbon dioxide and water vapor. Other salts used in this process include potassium carbonate, which allows for

lower incineration temperatures; sodium carbonate, which removes acid gases including hydrogen chloride and sulfur dioxide; and sodium sulfate, which serves as the catalyst for carbon combustion (Kiang and Metry 1982). Phosphorus, sulfur, arsenic, and halogens react with the molten salt bed to form inorganic salts (USEPA 1985, 1987). These salts build up in the molten mass and must eventually be removed to maintain the fluidity of the molten bed and retain the ability to absorb the acid gases from an effluent gas stream (USEPA 1987). The hot gases bubble through the molten salt, pass through a secondary reaction zone, and flow through an off-gas cleanup system before being released into the atmosphere (Kiang and Metry 1982).

393. Typical destruction efficiencies for this process are as follows: PCBs, 99.94 percent at temperatures ranging from 1,381° to 1,650° F; chloroform, 99.999 percent at 1,500° F; trichloroethane, 99.999 percent at 1,540° F; para-arsenilic acid, 99.999 percent at 1,695° F; and malathion, 99.9998 percent at 1,650° F (Kiang and Metry 1982).

394. A distinct disadvantage for application of molten salt incineration is that low water content is required for the unit to operate efficiently. The acid gases, which must be neutralized, cause problems ranging from corrosion to reduction of the molten salts' fluidity, requiring replacement of the spent material and placement of this material in a landfill (USEPA 1987). The process is also sensitive to high-ash solids that must be removed in the purge system (USEPA 1985). The formation of nitrogen oxide is low due to the low temperatures required by the process (Kiang and Metry 1982).

Multiple hearth incineration

395. Multiple hearth incineration is a process used in the destruction of all combustible industrial waste materials such as sludges, tars, solids, liquids, and gases. This unit, which is best suited for the destruction of hazardous sludges, consists of a refractory steel-lined shell, a rotating central shaft, a series of solid flat hearths, a series of rabble arms with teeth for each hearth, an air blower, waste-feeding and ash-removal systems, and fuel burners mounted on the walls (Monsanto Research Corporation 1981, as for tar injection can also be installed on the multiple hearth incinerator. The temperature in the incinerator ranges from 1,400° to 1,800° F with possible lengthy residence times. Provided that solids are pretreated by shredding and sorting, the multiple hearth incinerator can treat the same wastes as rotary kiln incineration. The primary advantages of multiple hearth incineration are the following: high residence time for sludge and low-volatile

compounds, the ability to treat a variety of sludges, the ability to evaporate large quantities of water, high fuel efficiency, and the utilization of a variety of fuels. The process is vulnerable to thermal shock and is unable to treat ash-containing waste, which fuses into large rocklike structures, or waste requiring very high temperatures for degradation. The firing of supplemental fuels is also difficult to control. The operating and maintenance costs are high (Monsanto Research Corporation 1981 and State of California 1981, as cited in USEPA 1985), but can be reduced by using the liquid or gaseous combustible waste as fuel (Monsanto Research Corporation 1981, as cited in USEPA 1985).

Plasma arc incineration

396. The plasma arc incinerator is a pilot-scale technology used to destroy liquid organic wastes and finely divided, fluidized sludges containing PCBs, chlorinated organics, and other complex organics such as pesticides and dioxins. Although there is limited information on the treatment of soils contaminated with metals, the plasma arc incinerator has been used to recover metals from low-grade ores. When applied to metal-contaminated soils, this process will probably result in the formation of a liquid melt, rather than oxidative destruction that occurs with PCB-contaminated soils (Kesari et al. 1987). The unit includes a plasma generator, reactor vessel consisting of atomization and equilibrium zones, and air pollution control equipment. The atomization zone reaches temperatures greater than 10,000° F with a residence time of 500 microseconds, while the equilibrium zone only obtains a temperature of 1,700° to 2,700° F for 1 to 2 sec. The principle of plasma arc incineration is the breaking of bonds between organic constituents accomplished in an atomization zone where a plasma or electric arc is generated by a colinear electrode and is stabilized by field coil magnets (Camp, Dresser, and McKee, Inc. 1986). A gas that has been energized into its plasma state by the electrical discharge is mixed with the waste material. The plasma torch and the hearth at the bottom of the reactor act as opposite electrodes to produce an electrical discharge causing plasma temperatures to reach approximately 9,000° F. A small amount of gas introduced to the center region is ionized and transfers energy to the waste causing pyrolysis to occur. Since the scale of the equipment is small with a high throughput, it is potentially attractive as a mobile unit. Another advantage of this method is the possible use of the exit gas as a fuel after the contaminants have been removed by a scrubber. Also, no hazardous interim combustion products are formed, and the process has

a high efficiency (USEPA 1985). No costs are presently available (State of California 1981, as cited in USEPA 1985).

397. Hazardous waste treatment by plasma arc incineration is hindered by the lack of operating experience and the possibility of generating contaminated gases and dusts, the latter possibly requiring disposal in a landfill. Westinghouse has developed a unit capable of treating 1 gpm of sludge (USEPA 1987; Camp, Dresser, and McKee, Inc. 1986). Although no full-scale performance data exist for contaminated wastes, metallurgical studies indicate that scale-up should be achievable (Kesari et al. 1987). A modification of the plasma arc incinerator is the centrifugal reactor that utilizes a rotating reactor well to create turbulence that disperses heat and electric energy evenly throughout the molten mass.

Pyretron incinerator

398. The Pyretron incinerator is a thermal destruction technology developed by American Combustion Technologies, Inc., that is used to treat solids and solid sludge mixes containing hazardous organics. The Pyretron oxygen fuel burner utilizes oxygen and natural gas to incinerate hazardous wastes at a higher temperature (up to 4,500° F) than a conventional burner (up to 2,400° F) without addition of extra air. Faster ignition and higher burn efficiency of wastes are accomplished by an advanced fuel injection system and mixing concepts. The oxygen added to the system is adjusted by a computer sensitive to sudden changes in the heating value of the waste. The Pyretron incinerator can be fitted onto any conventional combustion unit used for incinerating liquids, solids, and sludges (USEPA 1988c).

399. Advantages of the Pyretron incinerator include (a) the use of less air than conventional burners since nitrogen in the air reduces the heat, stresses the air pollution control devices, and requires a longer retention time for incineration; (b) reduction of costs due to the increased feed rate, and (c) more complete combustion of hazardous wastes due to higher temperatures, thus reducing emissions and increasing DREs. Pyretron offers no advantages over incineration with regard to processing aqueous waste, RCRA metal wastes, or nonorganic waste (USEPA 1988c).

400. The Pyretron incinerator has been demonstrated on contaminated soil from Stringfellow Acid Pit Superfund site in California and decanter tank tar sludge in November 1987. The demonstration was conducted at EPA's combustion Research Facility in Jefferson, AR. The Pyretron incinerator achieved DREs >99.99 percent for the following PAHs: naphthalene, acenaphthalene,

fluorine, phenanthrene, anthracene, and fluoranthene. Solid residues were contaminant free, while particulate emission levels in the scrubber system discharge were significantly below the hazardous waste incineration performance standard of 180 milligrams/dry standard cubic meter at 7 percent oxygen. The Pyretron unit with oxygen enhancement achieved a waste throughput double that possible with conventional incinerators. This technology can be an economical addition to an incinerator when operating and fuel costs are high and oxygen costs are relatively low (USEPA 1989d).

Pyrolysis

401. Pyrolysis is a commercially available destruction technology that thermally ruptures the chemical bonds of molecules (Carpenter 1986) in the absence of oxygen and at high temperatures to reduce toxic organics to elemental gas and water (USEPA 1988d). Wastes processed by this technology include viscous liquids, sludges, solids, high-ash waste, salts, metals (USEPA 1987), and organics (USEPA 1988d). Also treated are halogenated waste nonconducive to conventional incineration, containerized waste, and waste containing volatile metals or recoverable residuals. Pyrolysis can operate as a continuous operation if the waste is a flowable solid or liquid or as a batch operation if the waste is containerized (USEPA 1987).

402. The pyrolysis system consists of a primary combustion chamber, a secondary combustion chamber, and pollution control devices. In the primary combustion chamber, wastes are heated to temperatures ranging from 1,000° to 1,400° F to separate volatile compounds, such as water vapor and combustible gases, from the char and ash that contain metals and salts. The volatile organic gases, combustibles, and water vapor are heated to 2,200° F and hazardous components are destroyed in the secondary combustion chamber. The decontaminated gases are vented to an energy recovery system and then subjected to air pollution devices to remove particulates before being released to the atmosphere.

403. This process requires an auxiliary fuel, currently has a low waste feed capacity, and requires residual disposal as a hazardous waste since the metals and salts in the char and ash may be leachable. The feed material must be free of waste containing sulfur, nitrogen, or sodium and must be predried for correct process operation.

404. Pilot-scale tests with soils indicate a destruction efficiency of 99.9995 percent or better for PCBs. The soils in these tests were dried to a moisture content of 3 percent or less and sized to a particle size of 35 mesh.

Since the particle size and moisture content of the soils are significant operational limits, pyrolysis of dredged material will probably not be practical (USAE District, Chicago 1989). The Wright Malta process is a variation of pyrolysis that uses an alkaline catalyst. Wright Malta is being considered for the Hudson River cleanup (Sanders 1989).

Pyrometallurgy

405. Pyrometallurgy, or smelting/calcination, is a well developed, widely available commercial technology that is applicable to the treatment of most metal-bearing wastes. High levels of metals or metal oxides can be recovered from waste materials containing high levels of metals since effectiveness is directly proportional to the metal content of the waste. However, the potential for formation of toxic sludges and high process costs exists (Palmer et al. 1988).

Pyroplasma pyrolysis process

406. The Pyroplasma pyrolysis process uses a thermal plasma field to pyrolyze liquids or pumpable wastes contaminated with chlorinated organics, such as pesticides, wood preservatives including PCP and creosote compounds, and petroleum compounds. The Pyroplasma unit can be transported to waste sites to perform cleanup treatment or used in emergency response for hazardous waste cleanup (USEPA 1988c).

407. The pyroplasma unit consists of a plasma torch contained in a 48-ft trailer that requires only 4,160-volt, three-phase power; water; and sanitary sewer discharge lines. Electric power is used to produce an electric arc across a colinear electrode assembly inducing the formation of a thermal plasma ranging from 5,000° to 15,000° C due to the ionization of a low-pressure airstream injected into the unit (USEPA 1988c).

408. Waste feed enters the unit and is completely dissociated into atomic components by the thermal plasma field. These atomic components form nontoxic gases, such as nitrogen, hydrogen, methane, and ethane. There is some production of carbon monoxide. Acid gases and particulate carbon formed during chlorinated waste destruction are neutralized and cooled in a wet scrubber containing caustic soda and removed. The off-gas is then drawn off by an induction fan and directly flared or routed to a combustor to recover heat. Disadvantages include the possible degradation of arc and refractory material due to high temperatures, sensitivity to voltage drops and energy/mass balance, and possible durability problems. The process also requires highly trained operators. A 750-kw unit operating at a feed rate of 1 ton/hr

is currently available for the Site Demonstration Program. Costs for this technology are not available, but estimates indicate the costs would be comparable to conventional thermal technologies (USEPA 1988c).

409. Retech, Inc., has developed a centrifugal reactor that uses a plasma torch to create a molten bath that is used to detoxify soils or sludges contaminated with metals and hard to destroy organic compounds. In this process, contaminated soils are fed into the rotating reactor. Centrifugal force created by the rotation of the reactor prevents an outflow of molten material and waste through the bottom of the reactor vessel. This rotation also aids in transferring heat and electrical energy evenly. Molten solids are emptied into a collection chamber where they solidify, and gas flows through a secondary combustion chamber where any organics remaining in the gas phase will be removed. The gases then pass through air pollution control devices to remove particulates and acid vapors. The centrifugal reactor was scheduled for demonstration in early 1990 at a Department of Energy research facility in Butte, MT (USEPA 1989d).

Radio frequency heating

410. Radio frequency heating is a thermal technology developed for the decontamination of landfills containing organics. This technology involves excitation of rows of horizontal conductors placed on a landfill with electromagnetic energy in the radio frequency band. The steam-assisted decontamination occurs at a temperature between 300° to 400° C with a residence time of approximately 2 weeks. Off-gases generated by the volatile organics are collected by a gas or vapor recovery system on the landfill surface. Field tests indicate that levels of radiation leakage did not exceed the recommended ANSI Standard C-95. Preliminary design and cost estimates for a mobile onsite unit indicate a 2 to 4 times cost reduction in comparison to excavation and incineration cost. This technology shows potential for certain situations concerning the in-site destruction of organic contaminants, but more research is necessary for verification of its effectiveness (USEPA 1985).

411. A successful field test for radio frequency heating has been conducted in which 500 ft^3 of sandy soil containing jet fuel and chlorinated solvents was decontaminated. Aroclor 1242 removal efficiencies of 72 to 99 percent were obtained, depending on the treatment conditions. Removal efficiencies for fuels and solvents ranged from 90 to 99 percent. The cost of radio frequency heating was developed for an area covering 74,000 ft^3. The capital cost of the radio frequency heating unit is estimated to be

$1.6 million, with operation and maintenance costs ranging from $1.60 to $2.90/ft^3 depending on the moisture content of the soil (5 to 20 percent) and treatment temperature (100° to 250° C). Advantages of radio frequency heating include the feasibility of true in situ processing of contaminated soil and the cost effectiveness of the process; in addition, heat-transfer fluids and fuel combustion products do not dilute the gases and vapors, and heating is not dependent on the relatively slow processes of convection or conduction (Dev et al. 1989).

Roasting

412. Roasting is a technology that has been used primarily in Japan for the remediation of dust or wastes contaminated with metals but can also be applied to the remediation of organic-laden wastes. The roasting process has successfully treated metal hydroxide sludges. Although roasting has not been applied to contaminated soils, the naturally occurring silicates present may offer some benefit in the vitrification of the soils. There are four operating stages to which the waste is subjected. The water in the waste is evaporated, hydroxides and salts are decomposed to form the corresponding oxides, sintering (the fusing together of solids without obtaining the liquid state) occurs at approximately two-thirds of the melting temperatures, and heavy metal oxides are melted at temperatures of approximately 2,000° C. To aid in prevention of the volatilization of metals, kaolinite, sodium hydroxide, and ferric oxide may be injected to the melt to increase viscosity and the boiling point of metal compounds present in the melt. The furnace used in this process is either the rotary kiln or Flammenkammer oven. Residuals from the roasting process include a glasslike, vitrified monolith containing heavy metals and baghouse dust that may be contaminated with metals such as mercury or arsenic that volatilize at lower temperatures. The monolith that contains the immobilized heavy metals may be backfilled onsite or disposed in a non-secure landfill if the metal leachability results are below the EP toxicity levels. If the baghouse dust is contaminated with heavy metals, the dust will require further treatment or disposal in a secured landfill. Off-gas from the roasting process should flow through emission control devices before being released into the surrounding environment. There is no information on full-scale soil applications, but experimental data available for simulated metal hydroxide sludge seem to indicate that the metals are immobilized in the vitrified monolith that has a very low leachability. Disadvantages of this

process include high energy costs and excavation costs associated with backfilling and disposal (Kesari et al. 1987).

Rotary kiln incineration

413. Rotary kiln incineration is a nonproprietary thermal destruction technology that is widely available commercially as a mobile or fixed unit. This technology is used primarily on organic solids and sludges, including CERCLA, RCRA, and other contaminated wastes (USEPA 1988d). The unit can be used to treat any form of waste (liquid, solid, gaseous, or a mixture) containing any of the following substances: PCBs, dioxins, halogenated organics, nonhalogenated organics, pesticides, tars, obsolete munitions, PVC, or bottoms from solvent reclamation operations. High inorganic salt wastes and high toxic metal wastes are not recommended because of slagging of ash and potential refractor degradation and elevated emissions of toxic air pollutants difficult to collect with conventional air pollution control equipment (USEPA 1988d; Camp, Dresser, and McKee, Inc. 1986). Ashes produced may require solidification before disposal in a landfill (USEPA 1987; Camp, Dresser, and McKee, Inc. 1986) and high particulate emissions may be created, requiring postcombustion control (USEPA 1987). A brine solution of scrubber water effluent is also produced from the ash quench and the wet scrubber (USEPA 1988d).

414. The rotary kiln incinerator consists of a solid feed system, a primary combustion chamber, an inclined, rotating refractory-lined cylinder, a secondary combustion chamber or afterburner, an air pollution control unit, and a process stack. Natural gas, oil, or pulverized coal are used as fuel for the unit. In this process, waste is fed into the primary combustion chamber at the elevated end and passes through the combustion zone where temperatures range from 1,200° to 1,800° F. As the primary combustion chamber rotates, the waste is agitated, increasing combustion efficiency. The residence time for solids ranges from 15 to 45 min up to several hours and is controlled by rate of rotation, inclination, feed rate, and internal structure of the kiln (e.g., dams, chains, "bellies") (Camp, Dresser, and McKee, Inc. 1986). The ash residue is discharged at the lower end of the primary combustion chamber. The exhaust gases pass into the secondary combustion chamber or afterburner where the temperature is increased to approximately 2,400° F for approximately 2 sec. The gases then pass into a gas scrubber where particulates and acid gas are removed. The remaining gases are then released out a process stack.

415. This technology has been used at various sites, two of which are El Dorado, AR (operated by ENSCO), and Deer Park, TX (operated by Rollins Environment Systems), both in 1980. Wastes treated included empty shredded capacitors, chlorinated hydrocarbon wastes, PCBs, and diesel fuel. Conclusions from the assessment at these sites show that incineration of PCBs is a viable destruction procedure under proper conditions (Exner 1982).

416. Because of the ability to treat any physical form and their high destruction efficiency, rotary kilns are the preferred method for treating mixed solid residues (Lee, Keitz, and Vogel 1982). Rotary kilns are limited in regard to their susceptibility to thermal shock, need for careful maintenance, high particulate loadings, relatively low thermal efficiency, poor reputation with the public, and a high capital cost for installation.

Supercritical water oxidation

417. Supercritical water oxidation is a thermal wet oxidation technology that utilizes supercritical water temperatures (above 374° C) and pressures (above 22.09 MPa) to oxidize sediments containing hazardous organics such as PCBs, dioxins, solvents, and pesticides into carbon dioxide, water, and other less harmful molecules (USAE District, Chicago (in preparation)).

418. Laboratory-scale tests conducted on soils contaminated with PCBs indicate PCB reduction to background levels. An advantage of treatment with supercritical water oxidation is the use of a closed system with minimal air emissions. Mobility of metals in sediments after supercritical water oxidation is unknown and could present a problem for solids disposal. For full-scale treatment of sediments, the processing rate would need to be increased above that presently available. The high processing rate required and the high operating temperatures necessary for this operation require thick reaction vessel walls, special metals for construction, and complex reactor interiors to provide for proper mass transfer and reaction kinetics (USAE District, Chicago (in preparation)). Handling large volumes of sediment would be difficult for this type of equipment.

419. This process operates on a continuous basis and has been developed by Modar, Inc., and Vertox Corporation, with the major difference being the placement of the reaction vessel. Modar uses a pressurized aboveground reaction vessel while Vertox utilizes a well that is between 8,000 and 10,000 ft deep.

420. This process is a relatively new thermal technology having limited operating experience restricted to bench- and pilot-scale systems that are

potentially mobile (Camp, Dresser, and McKee, Inc. 1986). The bench-scale results demonstrate essentially complete destruction of PCBs (>99.999 percent) and other chemically stable compounds at projected costs within those for other hazardous waste operations (\$184 to \$554/m^3) (Carusone and Hickman 1988).

Taciuk process

421. The Taciuk process is a thermal technology that extracts oils from bituminous sands and potentially recovers liquid hydrocarbons from oil shale and other waste material containing hydrocarbons. The processor consists of a rotating vessel that has been operated on a pilot scale to treat waste materials containing hydrocarbons, water, and soils. The processor's capacity ranges from 3 to 25 tons/hr and consists of four compartments designed to recover and separate various product streams. Waste enters the first compartment, the preheat zone, where it is indirectly heated by hot, spent sand, and combustion flue gases producing steam from water present in the waste. This steam is released and condensed externally. In the next compartment, the reaction zone, the preheated oil sands/waste is mixed with hot recycled sand from the third compartment, the combustion zone. The bitumen is thermally cracked, yielding a hydrocarbon vapor that is condensed outside the processing unit and a liquid oil. Coke-coated sand particles are also produced. In the combustion zone, air and supplemental fuel (if necessary) are introduced, increasing the temperature and burning the coke off the sand. A portion of the heated sand from the combustion zone is recycled and injected into the reaction zone, while the remaining sand and combustion flue gases flow into the cooling zone. The temperature of the hot sand and flue gases is reduced by indirect thermal transfer to the incoming sand in the preheat zone. Tailings sand free of hydrocarbons is discharged, quenched, and transported to a Pit while flue gases are discharged to a treatment plant for the removal of particulates and sulfides. Solids discharged from the processor do not have to be treated to pass USEPA leach tests (AOSTRA, undated; Canonie 1989).

422. The Taciuk process has been demonstrated on a pilot scale for PCB-contaminated sediments at the Waukegan Superfund site. Full-scale remediation using this process is planned at the Waukegan Superfund site (AOSTRA, undated; Canonie 1989).

Vitrification

423. Vitrification is an emerging thermal destruction technology that utilizes pyrolysis to solidify and combust soils, sediments, and sludges that

are contaminated with toxic organics, inorganics, metals, and low-level radioactive material. The vitrification unit consists of a reaction chamber divided into two sections that are lined with refractory material and have separate electric (480-volt, 3-phase) heating sources. The upper section is the site of feed material introduction and contains gases and other pyrolysis products, while the lower section contains a two-layer molten zone for the metal and siliceous components of the waste (USEPA 1988d).

424. Wastes are introduced to the reactor on a conveyor belt. Large electrodes are inserted into the waste (mixed with silicates) that is covered with graphite to connect the electrodes to the soil. Heat generated by the high currents of electricity passing through the electrodes and graphite causes a melt that volatilizes semivolatile and volatile organics, while nonvolatile organics and inorganics are solidified within the cooling mass of vitrified material. Temperatures in the reactor reach approximately 1,650° C to accomplish the melting of the waste. Off-gas produced is drawn from the reactor by an induction fan and is treated in a cyclone, baghouse, and an acid gas scrubber to remove particulates and acid gas. The particulate and gas streams can then be recycled to the reactor. Residuals produced include molten glass, molten metals, scrubber water, and off-gas (USEPA 1988d).

425. Vitrification has been demonstrated on a field scale (USEPA 1987), and large-scale tests solidifying 300,000 kg/melt have been demonstrated (Timmerman 1985, as cited in Carpenter 1986). Vitrification has been demonstrated on a pilot scale for some applications (Ikalainen 1987). Vitrifix is developing a full-scale unit for asbestos waste, while Retech has developed a prototype unit yet to be used on CERCLA or RCRA waste. Westinghouse has a commercial prototype unit that was used in 1986 to treat Superfund waste that is expected to be available commercially in 1989 (USEPA 1988d). Geotech Developmental Corporation and Penberthy Electromelt also offer vitrification systems.

426. Advantages of this technology over other thermal technologies include the lack of oxidation products and large air emissions and the reduced leachability of inorganic materials, such as heavy metals (USEPA 1988d). With regard to solidification processes, vitrification processes offer a greater degree of immobilization. Disadvantages include high energy requirements, specialized equipment, and specially trained personnel (USEPA 1985). A plant configuration for the vitrification of dredged material placed in a batch or

continuous-flow reactor may be feasible, but is only conceptual (USAE District, Chicago (in preparation)).

Wet air oxidation

427. Wet air oxidation is a commercially proven (Congress of the United States 1983) thermal oxidation technology in which aqueous waste streams contaminated with pesticides, phenolics, organic sulfur, cyanide, or organics (<5 percent) (USEPA 1987) are oxidized in a high-temperature, high-pressure aqueous environment (Camp, Dresser, and McKee, Inc. 1986). The high pressure, which can range up to 3,000 psig, prevents this aqueous waste stream from boiling and also increases the solubility of oxygen (Ammon 1983). This process has been utilized commercially as a pretreatment process for biological wastewater treatment plants (Congress of the United States 1983).

428. In wet air oxidation, a waste and compressed air mixture flows through a heat exchanger where this mixture is heated indirectly by heat exchange with the hot oxidized effluent to obtain the proper exothermic reaction conditions that will increase the temperature to 250° to 325° C. The heated influent then enters an oxidation reactor where oxidizable waste reacts with oxygen in the air. If the heat obtained in the reaction is insufficient to maintain the operating temperature, either steam is injected or a heat exchanger is placed before and after the feed heat exchanger. The hot reactor effluent flows through the heat exchanger, heating the incoming aqueous stream. The resultant gas stream and oxidized liquid stream flow through a separator that diverts the gas stream, containing low molecular weight compounds such as acetaldehyde, acetone, acetic acid, and methanol, to an off-gas treatment device such as a scrubber, fume incinerator, or carbon adsorption filter. The liquid effluent containing primarily carboxylic acids and other carbonyls is treated either by biological technologies or by a combination of a biological technology and activated carbon. After treatment, the effluent usually will contain suspended solids consisting of metal oxides and insoluble salts that should be dewatered and disposed of properly. Typically, 80 percent of the organic substances will be completely oxidized to carbon dioxide and water (USEPA 1987, Congress of the United States 1983). This technology is not recommended for aromatic halogenated organics, inorganics, or large volumes of waste and is not appropriate for solids or viscous liquids (USEPA 1987).

429. Modifications to the wet air oxidation technology are aimed at the oxidation of more stable highly chlorinated organics utilizing catalysts to

enhance oxygen transfer at lower temperatures (150° to 200° C), thus lowering fuel and capital costs. Bench-scale tests conducted by IT Enviroscience demonstrated a bromide-nitrate catalyst promoting complete oxidation (Congress of the United States 1983). The destruction and removal efficiencies for PCBs are approximately 60 percent. This process has not been demonstrated full-scale on soils or dredged material, which is important since dredged material contaminants have to be desorbed before they can be oxidized (USAE District, Chicago (in preparation)).

430. Bench-scale tests performed by Zimpro/Passavant, Inc., on Indiana Harbor sediments during August and September 1988 revealed a destruction efficiency of 52 percent of the original PCB concentration (from 619 μg/day to 297 μg/ℓ). The treated solids were then tested according to EP toxicity and TCLP methods that demonstrated that the solids would not be classified as a hazardous waste under RCRA. The cost for wet air oxidation is approximately \$25/yd^3 (USAE District, Chicago (in preparation)).

PART V: DISPOSAL TECHNOLOGIES

Beneficial Use Technologies

431. Beneficial use technologies are generally encouraged for non-contaminated or moderately contaminated sediments dredged for navigation. These technologies should also be considered for the residuals from treatment processes, but physical and chemical changes or residual extraction fluids may impair potential uses such as agriculture or aquaculture.

Agriculture, horticulture, and forestry

432. Dredged material has been used as pasture for livestock, for incorporation into marginal soils, and for amendment of marginal soils for agriculture, forestry, and horticulture purposes. For waterways containing polluted or contaminated sediment, care must be taken in how the dredged material will be used (USACE 1987).

433. Agricultural use of dredged material/treated residual soil can occur if the material is free of nuisance weeds and high levels of contaminants and has the proper balance of nutrients beneficial for crop production. The application of dredged material might alter the physical and chemical characteristics of a marginal soil to the extent that water and nutrients become more available for crop production and growth. Also, the addition of a cover of dredged material may improve surface drainage and reduce flooding, thus lengthening the growing season (USACE 1987).

434. Horticultural use of dredged material can be applied to vegetable production, orchards, ornamental plant nurseries, sod farms, and Christmas tree farms. The best types of dredged material for vegetable production would be sandy silts or silty dredged material that can be incorporated into an existing silt or clay site. The dredged material should also be low in contaminants or pollutants. Although no dredged material disposal sites have been used for orchard growth, such application is probably feasible (USACE 1987).

435. The use of dredged material for the timber industry is a feasible option. The dredged material can be trucked to a site with poor soil to enhance nutrients in the soil, or trees could be planted at abandoned dredged material disposal sites. Tolerance levels of the timber crops for heavy metals and other contaminants as well as the physical characteristics of the dredged material would be limiting factors (USACE 1987).

Aquaculture

436. Aquaculture is a desirable beneficial use option due to the increasing difficulty and expense of obtaining dredged material containment acreage. Aquaculture is desirable because of its potential for (a) producing nutritious low-cost protein; (b) partially satisfying increased demand for seafood in the United States; (c) increasing employment in fish farms, feed mills, processing plants, and other supporting industries; and (d) providing larval stock for commercially and recreationally important natural populations currently stressed due to pollution and habitat loss (USACE 1987).

437. Dredged sediment or residual materials to be placed into containment sites may be contaminated to some degree with heavy metals, pesticides, petroleum hydrocarbons, and PCBs. Because of the way contaminants are retained within the sediment, they may be unavailable to aquatic animals. Site-specific testing is required to assess the potential for contaminant uptake in the harvested species (USACE 1987).

438. Aquaculture has been applied in the Pacific Northwest, California, New England, Chesapeake Bay, the Carolinas, Florida, and in the Gulf Coast states. Aquaculture appears to be a feasible, cost-effective, and compatible multiple use of containment sites (USACE 1987).

Beaches and beach nourishment

439. The development of beaches as well as beach nourishment is one of the most desirable cost-effective uses of clean dredged material for shore protection. However, the use of contaminated dredged sediment for beach construction or nourishment is not recommended. The material used should match the natural beach sediment and have low concentrations of fine-grained sediment, organic material, and pollutants. Minimum damage to beach animals will occur when clean sand is placed on a sandy substrate, whereas damage to the benthic organisms would increase if fine-grained sediments high in organic material and pollutants are used. Areas where beach nourishment has been accomplished include Mayport, Florida (USACE 1987); Ogden Dunes beach, Indiana; Perkins Beach, Ohio; Grand Haven, Michigan; and Ludington, Michigan.

Habitat development

440. Habitats may be developed to establish a relatively permanent and biologically productive animal and plant environment. Clean or decontaminated dredged material can be used for habitat development as an attractive and feasible alternative to more conventional disposal options. Four general habitats suitable for establishment on dredged material are wetlands, upland,

aquatic, and island. Wetlands are described as periodically inundated communities that are covered with water-tolerant vegetation. Upland habitats are characterized as a broad category of terrestrial communities with vegetation that is not normally inundated with water. Aquatic habitats are submerged habitats that extend a few feet below the sea, river, or lake level. Island habitats are wetland habitats that are upland or high zone and are distinguished by their isolation, particular uses, and the fact that they are surrounded by wetlands or water (USACE 1987). Island habitats are used primarily for recreational sites (see parks and recreation, paragraph 462) and for wildlife habitats. The islands are used primarily by nesting sea and wading birds, but this is dependent upon the vegetation present, size and configuration of the island, and level of disturbance the island receives. Wading birds will use dredged material sites for nesting because they will nest in areas containing woody vegetation supported by the dredged material deposits. They will also fly long distances from their natural habitat to feed in the protected shallow water present at these dredged material sites (Landin 1988). Several sites outside the Great Lakes that have utilized the concept of habitat development are the Buttermilk Sound salt marsh in the Altamaha River, Georgia; the Gaillard Island confined disposal facility in lower Mobile Bay, Alabama; and the Bolivar Peninsula upland and marsh site located on Goat Island in eastern Galveston Bay, Texas (USACE 1987). In 1987, there were 11 CDFs throughout the Great Lakes with nesting colonies. The CDFs that incorporate bodies of water inside or behind their dikes have become prime fish habitats as well. Several sites within the Great Lakes that have been used for habitat development include the Saginaw CDF, Mud Island, Point Mouilee CDF, and St. Mary's River (specifically for the endangered piping plover) in Michigan and the Times Beach and Irondequoit Bay wetland in New York (Landin 1988).

Harbor and port facility development

441. Numerous examples can be cited of dredged material sites used in harbor and port development. These sites provide additional acreage above the floodplain for port and related industrial or commercial facilities. Examples include the Presidents Island-Memphis Harbor Project 5 miles southwest of Memphis, TN; the harbor at Vicksburg, MS; the port and shipping facilities at Texas City, Galveston, and Houston, TX; port facilities on the Duwamish River in Seattle, WA; facilities at the Blakely and Brookley Island complexes in

upper Mobile Bay, Alabama (USACE 1987); port facilities near Buffalo, NY; and a small boat harbor at Mannitowoc, WI.

Parks and recreation

442. Of all the types of beneficial uses of dredged material on land, recreational or park construction on containment sites is one of the most common. Recreational uses of dredged material disposal are practically unlimited, ranging from the simple fill for a recreation access road to the complex Mission Bay development in San Diego, CA, that encompasses 4,500 acres. The nature of recreational sites with requirements of a lot of open space and lightweight structures is especially suited to the weak foundation conditions associated with fine-grained dredged material. The recreational use of dredged material containment sites is one of the more promising beneficial uses of dredged material, but is heavily dependent on financial support at the local level. Parks and recreational sites have been built on dredged material containment areas at several sites, including East Potomac Park in Washington, DC, Patriots Point 1 mile east of Charleston, SC; Kalawa recreational area in Kalawa, WA; Belle Island Park, Michigan; Windmill Island, Michigan; and Gull Island on St. Clair River, Michigan. At sites where incremental dredging is still occurring and where recreational use is not desired, barriers such as fences, ditches, and berms should be constructed. Serious consideration must also be given to liability from accidental or purposeful human intrusion onto the active disposal portion of the site (USACE 1987).

Residential and urban use

443. Dredged material containment sites have become sites of multiple-building high- and low-rise residential and business complexes in spite of poor foundation qualities of some types of dredged material. Examples of residential and business complexes built on dredged material include almost the entire city of Galveston, TX, residential areas in the burrough of Bronx in New York City; businesses at Jackson, MS, where borrow material was dredged from inside the Pearl River levee and pumped into place outside the levee for foundation material; and a huge industrial/residential/commercial complex, including a marine park, built on sandy dredged material at San Diego, CA (USACE 1987).

Solid waste management

444. Dredged material can be used as a suitable cover material for a sanitary solid waste landfill at sites previously considered unsuitable due to lack of native cover soil. The use of dewatered dredged material as cover is

operationally feasible since this material can be easily hauled, spread, and compacted by conventional earth-moving equipment. Clean dredged material has been used by both the St. Paul and Mobile Districts as caps for urban landfills (USACE 1987).

Strip mine reclamation

445. Strip mine and solid waste landfill reclamation are two fairly new concepts that have proven feasible in laboratory, field, and Corps District tests. Both uses require large quantities of dewatered dredged material that could be moderately contaminated and would ultimately provide nonconsumptive vegetative cover to unsightly areas. These areas could be further reclaimed for minimal-use recreation sites and/or wildlife habitat (USACE 1987).

446. Dewatered dredged material can be used for surface mine reclamation in much the same way as topsoil or agricultural soil to provide a surface with desirable physical and engineering properties. An alternate concept of strip mine reclamation that has not been field tested, but appears promising, is the use of slurried dredged material. Vegetation cover must be established quickly in strip mine reclamation due to the possibility of soil erosion (USACE 1987).

Other construction and commercial uses

447. Airports have been built with dredged material in areas where insufficient land was available. Examples include New York City, St. Paul, Burke Island lakefront, New Orleans, Brookley Air Force Base, and San Francisco. The Corps of Engineers uses dredged material in the construction of dikes, levees, and containment facilities. By using dredged materials for these uses, overall project costs can be reduced. Dredged material has also been used as fill material and as foundation for road construction. As an example, in the St. Paul District, dewatered sandy dredged material was used as fill in an abandoned gravel quarry. Dredged material use for island and historic preservation occurred in Mississippi after Hurricane Camille almost totally demolished the beachfront, with its historic colonial and antebellum landmarks, and Ship Island, where historic Fort Massachusetts is located. These beneficial uses, coupled with their minimal handling requirements, make these disposal options inexpensive and attractive (USACE 1987).

Open-Water Disposal

448. Open-water disposal is generally prohibited for contaminated sediment in the Great Lakes. However, it remains an option for mildly contaminated material or treated residuals and separated clean material following pretreatment or treatment processes. Where concern for contamination remains, several control measures are available to reduce the potential for impacts.

Capping

449. Capping offers a means for effectively isolating and containing contaminants associated with dredged sediment (Marine Board 1989). Capping has been selected as a remedy for several locations since it creates few adverse impacts and provides environmental benefits that are greater than other remedial action alternatives (Ficklin, Weitkamp, and Weiner 1989).

450. Contained aquatic disposal (CAD). The CAD design involves the excavation of a pit within the bottom of a waterway (15 to 50 ft) where dredging has not occurred. The design is similar to shallow-water confinements, but it does not contain an underwater dike. Escape pathways are the same as for shallow-water confinements, but the losses are reduced to levels similar to those of deep-water design (Cullinane et al. 1986).

451. Deep-water confinements. Deep-water confined disposal requires placement of the material into a natural or man-made depression in the water body floor and use of a vertical pipe for construction of underwater diking and further encirclement of the site. The only means for escape of contaminants are soluble diffusion and convection. The design for deep-water confined disposal is more expensive than deep-water mounding due to site preparation (Cullinane et al. 1986).

452. Deep-water mounding. Deep-water mounding is the placement and capping of contaminated dredged material at a chosen ocean depth (60 to 500 ft). The dredged material is placed on the bottom of the body of water by bottom dump or vertical pipeline diffuser. The bottom is not lined; therefore, the contaminated sediment must be concentrated in one location as much as possible. The cap should be no more than 3 ft thick due to the low energy environment, but the cap should sufficiently cover the mound at the chosen depth. The only concerns for contaminant loss are soluble diffusion and convection over time. Groundwater movement is nonexistent, causing the reduction of contaminant movement through the ground (Cullinane et al. 1986).

453. Shallow-water mounding and confinement. Shallow-water mounds and confines are constructed similarly to deep-water mounds, but are easier to construct between a natural border and underground dike because of shallower depths involved. The mounds may be used in open water, aquatic shelves, or pristine environments (affected by tides, currents, and storms). Mounds and confines require thick caps (*6 ft) or armoring within an elevation of -10 ft mllw to -60 ft mllw. The only difference between the two is that the confine is bordered on one side by upland and not the existing bottom. Shallow-water mounds and confines use a buffering layer of clean sediment to protect the integrity of the cap from erosion and bioturbation. Pathways for escape are by tidal- or current-induced convection and leaching. Groundwater infiltration may also be a concern (Cullinane et al. 1986).

Site selection

454. Site selection can reduce the potential impacts of open-water disposal. Sites can be selected where sediment transport by currents is unlikely and where reduced impacts on aquatic organisms can be achieved. A contaminated site might also be chosen to allow capping of the contaminated material with cleaner sediment.

Submerged discharge

455. The techniques of submerged discharge and use of a closed conduit (channel) are used to ensure accurate placement of material and to reduce the exit velocity during a surge phase. A conduit extends to the bottom of the site and isolates material from the water column during descent. The conduit also reduces entrainment and cancels current or stratification effects. A conduit should be used only for placement problems or for material with a high moisture content that flows rather than mounds on impact (Cullinane et al. 1986).

456. Pumpdown of materials from scows, barges, or hopper dredges causes less resuspension (turbidity) of contaminated sediment. Conventional pumpdown barges pump capping material from a scow or land-based storage area through a discharge pipe set close to the bottom of calm, deep water (7 to 20 ft). Use of a hopper dredge pumpdown system is more applicable than a pumpdown barge in unprotected waters. The hopper dredge pumpdown system requires modifications in equipment to change the original pump to a downward direction through a drag arm. The maximum effective depth for this modification is 36 to 60 ft depending on the length of the drag arm. The drag head is 10 ft wide, making navigation difficult for a full cover. Availability, speed of operation, and

draft hinder use of hopper dredge pumpdown. The modified hopper dredge has been used in conjunction with a diffuser head for capping in the Port of Rotterdam (d'Angremond de Jong, and de Waard 1984). Another submerged diffuser design has been demonstrated at Calumet Harbor, Illinois (Hayes, McLellan, and Truitt 1988).

457. The gravity fed downpipe is site specific in operation and consists of a large-diameter conduit extending from the surface through the water column to some point near or above the bottom of the column. Dredged material is either slurried or mechanically removed from a scow for placement into the column of water. Placement accuracy is improved by isolation of the water column. Little reduction in momentum or impact energy takes place (Cullinane et al. 1986).

458. A submerged diffuser is a device used in the controlled placement of materials in a confined disposal facility or a contained aquatic disposal site to reduce turbulence and resuspension (Palermo and Pankow 1988), reduce scouring of the bottom area, and control sediment spreading to reduce bottom impacts (Cullinane et al. 1986). Slurry can be routed through a combined turning and radically divergent diffuser section. Discharge is released parallel to the bottom of the system at a lower velocity because of an operating diffuser head. The diffuser head causes radical divergence of flow by varying the height of discharge above the bottom. As a result, impact velocity and thickness of cover can be controlled. The design of the entire system can be manipulated to suit project criteria. A typical diffuser system can be modified to reduce exit velocity by a factor of 8 to 16 without affecting discharge flow rate. The diffuser can work with a hydraulic barge/pipeline system to lower the diffuser as close as 3 ft from the bottom. The diffuser discharge can be raised or lowered up to 100 ft by a derrick on the barge. The pipe connecting the barge to the diffuser can be small in diameter and semirigid. or can be flexible if the diffuser head is independently controlled by cable (Cullinane et al. 1986).

459. The submerged diffuser was originally designed as part of the Corps of Engineers' Dredged Material Research Program, and has now been utilized successfully in the placement of contaminated material in a Rotterdam Harbor contained aquatic disposal site (d'Angremond, deJong, and deWaard 1984). This equipment demonstration was part of the Calumet Harbor, Illinois, study. At Calumet Harbor, disposal using the diffuser took place in a CDF (25 to 35 ft) to ensure a controlled environment. The diffuser was supported 3 ft

off the bottom by a support barge cable. Flexible plastic dredge pipe connected the diffuser to the pipeline. First, clean water was flushed through the pipe to establish background suspended solids. Velocity meters were connected at the diffuser and 25 ft above the diffuser. The diffuser performed as expected, with velocities of 25 to 40 percent of the pipeline velocity. Exit material remained confined to 3 to 4 ft from the bottom. Water samples taken at the diffuser and in the middle to upper portion of the water column measured no turbidity (Hayes, McLellan, and Truitt 1988).

Confined Disposal

General

460. Prior to 1967, sediments dredged from Great Lakes harbors and waterways for navigation were disposed in the least costly manner. In most cases, this meant open-water disposal. Disposal to diked areas had occurred before this time, but was generally limited to new work dredging or maintenance dredging of navigation projects far removed from the open lake. Diked disposal areas were used in the early 1960's for the Rouge River at Detroit and the Maumee River in Toledo.

461. Environmental concerns about the impacts of open-water disposal of dredged materials from industrialized harbors on the water quality of the Great Lakes caused this practice to be reconsidered. In 1969, a 2-year study was completed by the Corps of Engineers in cooperation with the Federal Water Pollution Control Administration (USAED, Buffalo 1969). This study evaluated alternate disposal methods for dredged materials. Disposal alternatives considered included incineration, composting, discharge to wastewater treatment facilities, and a few of the treatment technologies identified in this report. Diked (or confined) disposal facilities were also considered as part of this evaluation.

462. This study could not document substantial impacts on water quality or benthic communities resulting from open-water disposal of dredged materials. Impacts were of a transient nature. The report concluded, though, that open-water disposal of polluted dredged material is "presumptively" undesirable. Recommendations of this report included additional research on the environmental effects of dredging and disposal and the development of a program for the confinement of polluted dredged material around the Great Lakes.

463. Section 123 of the River and Harbors Act of 1970 (PL 91-611) had two provisions of special importance to dredged material management. The Act directed the Corps of Engineers to conduct a 5-year research program on dredged material disposal. The Dredged Material Research Program (DMRP) was subsequently conducted between 1973 and 1978, and produced over 270 technical reports on the environmental impacts of dredging and disposal and ways to minimize these impacts.

464. Section 123 of PL 91-611 also gave the Corps of Engineers authority to construct, operate, and maintain confined disposal facilities for maintenance dredgings from Great Lakes navigation projects. These CDFs were for dredged materials determined unsuitable for open-lake disposal. This law had specific requirements for local sponsorship. CDFs constructed under this authority were to accommodate 10 years of dredging.

465. Since 1970, a total 27 CDFs have been constructed under this authority to serve Great Lakes navigation projects. Some 16 other CDFs have been constructed around the Great Lakes by the Corps under the authorizing legislation of individual navigation projects. The Canadian government has constructed five CDFs to serve navigation projects.

466. Confined disposal, as the name implies, involves the placement of dredged materials into a site or facility prepared to contain the dredged materials and associated pollutants. A confined disposal facility is an upland or in-water structure constructed solely for the disposal of contaminated dredged materials. Commercial landfills licensed to receive sanitary, RCRA, or TCSA materials might also be used for the disposal of dredged materials. The components of a disposal facility (i.e. barriers, leachate collection systems, caps, and covers) will be discussed. Then, the application of these components and operational considerations at CDFs and commercial land-fills will be described.

Barrier systems

467. Barriers are layers of low-permeability materials designed to prevent vertical or lateral migration of water and minimize groundwater contamination. Barrier systems might utilize soils, synthetic membranes, grout mattresses, and slurry walls. Barrier systems can employ a single layer or multiple layers. Complex barrier systems may sandwich layers for lateral drainage, leachate collection or detection between low-permeability layers. Landfills licensed for hazardous and toxic wastes have strict requirements on the type, number, thickness, and permeability of barriers.

468. Soil barriers can use natural geologic formations of low-permeability material if available at a site or constructed layers. Soil liners can be used on the sides and bottom of a containment area. Adequate compaction is accomplished by spreading the soil in loose 6-in. (or less) deep lifts, wetting and drying to 2 percent or more above the optimum moisture content, and rolling to the specified relative compaction with a sheeps-foot-type roller (Cullinane et al. 1986). Fine-grained sediments may have permeabilities comparable to clay barriers following compaction.

469. A synthetic membrane liner is generally constructed of polymers of rubber, plastics (PVC), polyolefins, and thermoplastic elastomers that range in thickness from 20 to 140 mil. Effectiveness of these materials depends on quality control during installation. Installation may be difficult in areas of tidal fluctuation and high groundwater table. The membranes are susceptible to leakage due to improper seaming and punctures during installation. Chemical compatibility is a concern with concentrated wastes, but is generally not a problem for dredged material. Installation of the primary liner must include protective soil layers above and below the liner. During placement of the primary liner, random samples of seams should be extracted and laboratory tested (Cullinane et al. 1986).

470. Grout mattresses are geotextile "bags" that are filled with a slurry of cement and sand. They are commonly used for streambank or shoreline erosion protection, but have also been used as a lateral barrier on the dikes of a CDF at Monroe, MI. The empty geotextile mattresses were placed against the dike face, then filled with the cement/sand slurry. The product was a layer of hardened concrete, several inches in thickness.

471. A slurry wall is a low-permeability subsurface cutoff wall constructed for the purpose of redirecting groundwater away from a contaminated area to prevent formation of leachates and/or controlling horizontal leachate movement away from the area (Yang et al. 1987). Slurry walls are the most common subsurface barriers because they are a relatively inexpensive option for the reduction of groundwater flow in unconsolidated earth materials (Cullinane et al. 1986). The slurry wall is constructed by filling a vertical trench under excavation with a bentonite or bentonite-soil-cement slurry.

472. Slurry walls can be placed circumferential, upgradient, or downgradient. Circumferential placement is most common and offers the following advantages: (a) uncontaminated groundwater entering the contaminated area is reduced, thus reducing the leachate volume generated, (b) the amount of

leachate leaving the area on the downgradient side will be reduced, and (c) if used in conjunction with an infiltration barrier and leachate-collecting system, the hydraulic gradient can be maintained in an inward direction, thus preventing leachate escape. Upgradient placement refers to the placement of a slurry wall on the side of the contaminated area that is the groundwater source side. This method could be used for the diversion of clean groundwater around a site. This will not stop leachate generation, but could reduce it (USEPA 1985).

Leachate collection/detection

473. Leachate is water that has had contact with a fill or waste material and may transport contaminants to groundwater. Leachate collection and detection systems are components of landfill designs required for some regulated wastes. Leachate collection/detection systems are essentially the same as the subsurface drainage systems discussed with dewatering technologies. They provide lateral drainage through a network of perforated pipes within a layer of sand or other media. These systems may be positioned above, below, or between barrier layers. The low permeability of fine-grained sediments following consolidation may limit the need for and effectiveness of leachate collection/detection systems.

Groundwater pumping

474. Groundwater pumping is an effective, widely used technology that removes, contains, or prevents development of a plume through groundwater management. For disposal facilities, these same techniques can be used to collect leachate or seepage from contaminated dredged material. Plume containment and removal is accomplished primarily with extraction wells that are placed in or around the disposal facility. Selection of a well depends on depth of contamination and hydraulic or geologic characteristics of the media (USEPA 1985). The process directs flow of groundwater toward a well or wells by pumping. Migration of contaminants away from the well field or out of the disposal facility is prevented. Therefore, the contaminated leachate can be recovered and treated. Groundwater pumping applies to granular soils that transmit water. Low-permeability soils, including clay and shale, can adversely affect the process.

475. Well points are effective in many hydraulic situations and are most suitable for disposal facilities where extraction is not generally necessary below 22 ft. Well point systems are driven, not drilled, into the ground just below the leachate plume. Groundwater is piped to a suction header and

is then drawn by centrifugal pump to a treatment system (Yang et al. 1987). Contour grading, revegetation, surface sealing, cutoff walls, and leachate treatment may be used to assist the system (Rishel, Boston, and Schmidt 1984). Costs for well point systems range from $803 to $8,284 per well (Yang et al. 1987).

Confined disposal facilities

476. Of the existing CDFs on the Great Lakes, about two-thirds are in-water and one-third upland. Upland confined disposal facilities may be formed by the construction of earthen dikes or use existing pits or depressions. In-water CDFs are generally formed by stone-filled dikes similar in appearance to a breakwater. The size and shape of a CDF are determined by the required storage capacity and local site conditions. Sizes range from a few acres to several hundred.

477. There is no single, best CDF design. The structural and environmental design is very site specific. The principal design criterion for CDFs has been to retain as high a percentage of the sediment particles as practical. This criterion stems from a basic conclusion of the Dredged Material Research Program. Most sediment contaminants are tightly bound to the sediment particles, and a disposal method that contains the sediment particles will effectively contain these contaminants.

478. Key important considerations of a CDF design are related to the anticipated methods of dredging and transport. A CDF designed to receive hydraulically dredged/disposed sediments must provide adequate detention times for settling and be able to drain and treat large volumes of water. This may require larger facilities, sometimes divided into two or more compartments to allow for secondary settling basins. A CDF designed for mechanically dredged materials has virtually no settling requirements and will drain less than one-fifth the volume of water.

479. The necessity for barrier systems, caps/covers, effluent/leachate treatment, and other controls should be determined by the application of laboratory testing procedures developed specifically for dredged materials (Francingues et al. 1986). These procedures are used to determine the mobility of sediment contaminants through a number of pathways. These testing results are combined with information about potential CDF sites and the resources to be protected to develop designs for controls. This dredged material management strategy was applied in a study of disposal alternatives for

highly contaminated sediments from Indiana Harbor (Environmental Laboratory 1987).

Covers and capping

480. A cap is a barrier layer placed on top of a filled CDF or landfill to minimize the infiltration of precipitation and limit direct contact between humans and other terrestrial organisms and the fill material. Covers are generally soil layers placed on top of the cap to protect the cap from erosion and sustain certain types of vegetation. The vegetative layer on top should be 2 ft or more in thickness, depending upon frost depths, root penetration, and the rate of soil loss. Lateral drainage layers may be incorporated into a cap/cover design.

481. Caps may utilize soil or synthetic membrane liners. Landfills for some regulated wastes have specific requirements for the thickness and permeability of caps. The effectiveness of a cap is highly dependent on the grading and compaction of the fill. Dredged materials may require one or more years to be dewatered/consolidated adequately for cap installation. Uneven settling and consolidation of fill materials can cause localized ponding or cap failure, and requires periodic maintenance.

Operational techniques

482. Confined disposal facilities can be managed to control surface water, to maintain or eliminate ponded water, or to control effluent flow rate. Ponded water affects the oxidation state of the dredged material, thereby influencing contaminant mobility and biodegradation rates. Fugitive dust and volatilization are minimized by ponding water over the dredged material. On the other hand, additional water depth increases the head or driving forces for movement of leachate from the site. Trade-offs must be made to manage the site for minimization of losses to critical pathways. Water management must also consider the type of material and the water content acceptable to the treatment process.

Sanitary landfills

483. Sanitary landfills should be considered for disposal of dewatered dredged material and for treatment residuals. Sanitary landfills are facilities designed for the disposal of solid wastes on the land. Wastes are usually emptied into cells, spread, compacted, and covered daily with a 6-in. layer of soil or other suitable material. Most solid wastes placed in sanitary landfills originate from residential and commercial sources. Wastes that may pose a substantial present or future hazard to human health or other

living organisms are excluded from a conventionally designed sanitary landfill. State regulations of sanitary landfills vary, and contaminated sediments may not be disposed in some locations. Some states have "special" landfill categories more restrictive than sanitary fills but less restrictive than hazardous (RCRA) or toxic (TSCA) landfills which may allow dredged materials. The beneficial use section of this report describes the potential for using uncontaminated dredged material for landfill cover material, which has been practiced in a number of locations.

484. Disposal of dredged material in a landfill would likely require elimination of free-draining water either by dewatering and drying or by solidification. Implementation and cost are affected by the distance and cost for transport to a landfill that will accept the material. Landfill fees are also significant. Because landfills are commonly used for municipal waste disposal, there may a local landfill relatively close to the project area. However, the demand for landfill capacity has resulted in restrictions on what many landfills will accept, particularly for large volumes of material.

485. Sanitary landfills are regulated under the Solid Waste Disposal Act of 1965 as amended by the Resource Act of 1970 and the Resource Conservation and Recovery Act. Federal regulations providing guidelines for land disposal of solid wastes are presented in 40 CFR Part 241. These guidelines state that landfills should avoid effects on groundwater and surface water, but design requirements are much less stringent than those presented in more recent regulations for RCRA hazardous waste facilities. Increased awareness of the potential hazards of landfills is being reflected in more stringent interpretation of design requirements for these facilities that will protect the environment.

RCRA landfills

486. The RCRA landfills are permitted for the disposal of certain hazardous wastes as defined under RCRA and the Hazardous and Solid Waste Amendments of 1984. RCRA landfills must meet requirements specified in 40 CFR Part 264. These requirements include lining the bottom and sides of the site with two or more liners, a leachate collection system above the top liner, and a leachate detection system between the two liners. The top liner is a geosynthetic material referred to as a flexible membrane liner (FML), and the bottom liner is an FML or a 3-ft-thick, compacted clay liner. The USEPA currently favors a bottom liner that is a composite of an FML underlain by a clay liner. Closure of an RCRA landfill requires (at a minimum) a three-layer

cover consisting of a vegetative top cover, a drainage layer, and a composite (FML over compacted clay) liner. In addition to monitoring the leachate collection and removal system, a groundwater monitoring program is also required for a RCRA landfill.

487. Permitted RCRA facilities are few in number, their availability for contaminated dredged material is limited, and the cost for transportation and disposal will be great. USEPA regulations prohibit placement of liquids in RCRA landfills. Therefore, dredged material will have to be dried or solidified before the landfill will accept it. The E. C. Jordan Company (1989) estimated that landfill disposal of solidified New Bedford sediment would cost $350/yd^3 (based on in situ sediment volume removed) tipping fee at the landfill. Cases of RCRA disposal of highly contaminated dredged material are not known. However, one site near Lorraine, OH, has constructed a facility to RCRA standards for containment of highly contaminated sediment.*

TSCA landfills

488. The TSCA landfills are defined here as chemical waste landfills designed and constructed to comply with the provision of the TSCA as defined in 40 CFR Part 761. This regulation establishes prohibitions of, and requirements for, the manufacture, processing, distribution in commerce, use, disposal, storage, and marking of PCBs and PCB items. In contrast to RCRA regulations for hazardous waste, which do not mention dredged material specifically, the TSCA regulation states that all dredged materials containing PCBs at concentrations greater than 50 ppm shall be disposed of in an incinerator (required if the concentration is greater than 500 ppm), in a TSCA landfill, or other method subject to the approval of the USEPA Regional Administrator.

489. Requirements for TSCA landfills include a requirement to locate in thick, relatively impermeable formations or to provide a 3-ft-thick compacted clay liner with permeability less than 1×10^{-7} cm/sec. An FML with a minimum thickness of 30 mils and that has proven chemical compatibility with the waste may be substituted for the clay liner. The bottom of the site must be at least 50 ft above the historical high water table. Groundwater monitoring and leachate collection systems are also required. As with RCRA landfills, materials containing free-draining liquids cannot be placed in the landfill for final disposal.

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* Personal Communication, April 1990, Howard Zar, USEPA Region V, Chicago, IL.

490. The availability of landfills designed specifically to meet TSCA requirements is limited. Disposal alternatives considered for dredged material contaminated with PCBs at concentrations greater than 50 ppm have included confined disposal facilities designed to TSCA standards. These standards are in some ways less stringent than RCRA. However, the requirement to locate 50 ft above the water table would prohibit implementation in many areas. Cost of this option is expected to be in the same range as for RCRA landfills.

PART VI: EFFLUENT/LEACHATE TREATMENT TECHNOLOGIES

Suspended Solids Removal

General

491. Water that has been collected during dewatering of sediments for treatment or disposal may require varying levels of subsequent treatment prior to discharge. Discharge options for this water include release to waterways or discharge to a sanitary sewer. Discharges to a sanitary sewer may be limited by the flows and must meet pretreatment requirements of the local sanitary treatment facilities. In most cases, treated effluent/leachate will be returned to the waterway nearest to the dewatering or disposal facility.

492. The treatment requirements for effluent/leachate are determined by the applicable state water quality standards for the receiving waters. Even when the dredged materials are not placed into waters of the United States, the discharge of return water from an upland disposal/dewatering facility is regulated under Section 404 of the Clean Water Act. Section 401 of the Clean Water Act requires a certification from the appropriate state regulatory agency that this discharge will not violate applicable state water quality standards.

493. A number of laboratory testing procedures have been developed to predict the quality of water drained from dredged material disposal facilities (Francingues et al. 1986). These include settling tests, modified elutriate tests, and tests for specific treatment technologies. The vast majority of contaminants in water drained from contaminated sediments will be associated with suspended matter. Consequently, most effluent/leachate treatment requirements will be directed to controlling suspended solids. Certain contaminants may have dissolved levels of metals or organics requiring additional treatment.

494. Most of the effluent/leachate treatment technologies for suspended solids removal are commonly used in municipal and industrial wastewater treatment. Many of these technologies have been applied at confined disposal facilities.

Settling

495. Settling has already been discussed as a dewatering technology, but is also an important technology for removal of suspended solids. Primary settling occurs within a confined disposal facility used to retain dredged

material solids while releasing the supernatant from the disposal area after a retention time of up to several days. The actual release of the supernatant is controlled by the hydraulic characteristics of the area and the discharge weir. Weir overflow is controlled by static head and the effective weir length provided. The depth of the pond water is controlled by the weir crest elevation. The ponded surface area of the site is less than the total surface area enclosed by the dikes because of the mounding of the coarse-grained solids and the minimum freeboard requirements. Internal dikes can be built to improve the settling efficiency by altering flow patterns, modifying currents, and allowing longer periods for settling (Cullinane et al. 1986).

496. A properly designed and operated confined disposal area can be extremely efficient in the removal of suspended solids and contaminants associated with these solids from water, especially saltwater. Palermo (1984) observed retention efficiencies for suspended solids in three saltwater disposal areas that were above 99.9 percent (inflow solids concentrations on the order of 100 g/ℓ and effluent suspended solids concentrations on the order of tens of milligrams per liter). Similar retention efficiencies for the total concentration of metals were observed, ranging from 84.5 to 99.9 percent. Hoeppel, Myers, and Engler (1978) described similar efficiencies for the retention of organics, such as PCBs and DDT, that remain closely associated with particles.

Granular media filtration

497. Granular media filtration is a process that uses a bed of granular material to treat water or wastewater. Filtration is the most commonly used technology for treatment of drinking water. Granular media for filtration include fine gravel, sand, anthracite, and coal. Systems may function using gravity drainage through filter media, with pumps, or under pressure.

498. In many wastewater treatment applications, filtration is the final step of a treatment system (sometimes called polishing). All filters eventually clog, and in most cases water should be pretreated by settling, chemical clarification, or other methods to reduce suspended solids before filtration. Granular media filtration may be applied to water drained from contaminated sediments in a number of ways. These include permeable filter dikes or weirs, filter cells, and "package" filter systems.

499. Most of the in-water and some of the upland CDFs around the Great Lakes have been constructed with permeable dikes. Many in-water CDFs have a core of granular material (gravel, sand, or combinations). Upland CDFs have

been constructed with a section of the dike formed of granular material. As water moves horizontally through the dikes, suspended solids are removed by the filter media. The effluent suspended solids content is dependent on the particle size and thickness of the filter media and the suspended solids levels of influent.

500. Permeable treatment beds have been tested at bench and pilot scales to provide the preliminary quantification of permeable treatment bed effectiveness. Laboratory tests indicate that permeable treatment beds may be practical for removing suspended solids from effluent when solids concentrations are as high as 1 g/ℓ for periods of approximately 1 year before clogging (Krizek, Fitzpatrick, and Atmatzidis 1976). Filter dikes will become clogged as sediment particles are trapped by the filter media. Proper management of a disposal facility is required to ensure that the filter dikes are not overloaded, and clog prematurely.

501. Filter cells, or sand-filled weirs, provide filtration in a vertical gravity flow mode and may be more flexible than permeable filter dikes/beds, allowing easier replacement and maintenance. They consist of several cylindrical or rectangular cells containing the filter medium. The filter medium depth is obtained at the deepest level possible to provide for better solids retention. The filter medium used is typically sand with a particle size of approximately 1 mm. Excessive maintenance is required if the influent contains more than 1 g/ℓ suspended solids (Krizek, Fitzpatrick, and Atmatzidis 1976). Sand-filled weirs can remove 60 to 98 percent of the suspended solids and sediment-bound contaminants from wastewater. Typically, the effluent suspended solids concentration is reduced to 5 to 10 mg/ℓ (Cullinane et al. 1986).

502. Filter cells constructed with steel-sheet piles, using sand filter media, have been used at a number of in-water CDFs on the Great Lakes. Concrete filter cells with sand and carbon filter media have been used at CDFs in Chicago with suspended solids removal efficiencies of up to 90 percent. Depending on the design of the filter, the nature of the dredged material, and the loading rate, a filter cell can effectively remove most of the suspended solids from the effluent from several dredging operations before it becomes clogged (Barnard and Hand 1978).

503. Portable wastewater treatment systems are commercially available, including granular media filtration. These "package" systems may be mounted on a trailer bed or installed onsite. Most of these package treatment systems

are intended for small flow rates, but can be run in parallel or series if necessary To prevent clogging of the filter media, water is backflushed through the filter at high velocity to remove solids that have become lodged within the filter media pores. This backwash water requires further treatment since it contains high concentrations of solids (De Renzo 1978, as cited in USEPA 1985).

Chemical clarification

504. Chemical clarification is defined as the use of coagulants or flocculants to promote settling of the smaller colloidal-size particles in dredged material. These particles settle very slowly and often have high contaminant concentrations compared to the bulk sediment. Coagulation causes these particles to agglomerate into larger particles with sufficient size and density to settle more rapidly (Jones, Williams, and Moore 1978). Coagulants include inorganic chemicals, such as the salts of iron and aluminum widely used in the water treatment industry, and organic polyelectrolytes. Wang and Chen (1977) evaluated inorganic and organic coagulants for application to dredged material and recommended organic polyelectrolytes for dredging operations because they are less dependent on pH and require lower dosages compared to inorganic coagulants. Chemical clarification is efficient for treating effluent from a settling process. Treatment of dredged material slurry was demonstrated in pilot studies by Jones, Williams, and Moore (1978) and by Schroeder (1983). Simple processes of mixing concentrated polyelectrolyte and water and a pump to meter the solution into a port in the pipeline are readily available. Turbulence in the pipeline provides energy and mixing for the polyelectrolyte and solids. A settling process must follow to complete the chemical clarification process. Large polymer loadings can achieve near 100-percent reduction in turbidity and suspended solids in the slurry based on small column tests of treated pipeline slurry. Chemical clarification can be highly efficient, but full-scale field conditions would likely result in a lower efficiency because of inefficiencies of the settling process.

Clarifiers

505. The conventional clarifier consists of either rectangular or circular settling basins that typically contain a mechanism for solids collection and removal. In the rectangular clarifier, wastewater sludge containing a high concentration of suspended solids is pumped into one end, solids settle along the length of the clarifier, and an effluent with relatively low suspended solids exits the clarifier through trough-type overflow weirs. Most

rectangular clarifiers move the settled solids toward the inlet end of the tank, but some move the solids to the effluent end of the tank, corresponding to the density current flow direction. There are two general types of circular clarifiers. Center feed circular clarifiers have the waste pumped into the center well, and effluent overflowing weirs along the outside. Peripheral feed clarifiers have waste pumped from outside, and the effluent overflowing in the center of the vessel. Clarifiers can remove particles down to 10 to 20 μ with the aid of flocculants (Mallory and Nawrocki 1974). A sludge with a solids concentration ranging from approximately 10 to 15 percent is produced (Metcalf and Eddy 1979, as cited in USEPA 1985), and solids are separated according to grain size by attaching clarifiers in series and allowing sufficient retention times for removal of materials of a specific grain size. Most clarifiers are capable of removing 90 to 99 percent of suspended solids.

506. Clarifiers are best suited for small- to medium-scale operations or large-scale operations where impoundment basins cannot be used. Clarifiers can also be barge mounted for solids separation during dredging operations. Circular clarifiers are usually more efficient than rectangular clarifiers in solids removal, but rectangular clarifiers are more suitable for barge-mounting and sites requiring limited construction area.

507. Another clarifier, the high-rate clarifier, uses stacked multiple plates, tubes, or trays to increase the effective settling surface area of the clarifier and decrease the surface area necessary for effective settling. High-rate clarifiers allow higher loading rates than conventional clarifiers. The plates, tubes, or trays guide the flow of the influent, reducing short circuiting and promoting better influent velocity distribution. Therefore, optimum hydraulic characteristics for sedimentation are obtained. High-rate clarifiers can handle 2 to 10 times the loading rate of conventional clarifiers, therefore limiting the area used (Jones, Williams, and Moore 1978). High-rate clarifiers are suitable wherever conventional clarifiers can be applied, and are particularly applicable on sites with limited area or where barge mounting is required. They are not applicable for removal of particles larger than 0.1 in. or less than 10 μ. If the sediments or soils that are fed into the systems are cohesive, the trays, tubes, or plates may become clogged (Jones, Williams, and Moore 1978).

Membrane microfiltration

508. E. I. Dupont De Nemours and Company Oberlin Filter Company have developed a membrane microfiltration process that uses a low-cost, submicron

filter media and a fairly high operating pressure (up to 60 psig) for the microfiltration of liquid hazardous wastes in a sealed chamber. Wastes amenable to treatment are heavy metal effluents, groundwater leachates, stilling basin leachate and runoff, oily wastes, radioactive waste, etc., with solids concertrations ranging from 10 to 300,000 ppm. This unit is best suited for wastewater with low solids content (less than 5,000 ppm solids) containing contaminants such as inorganics, organics, or oily waste with a wide variety of grain sizes. Volatile wastes may be processed as well as wastewaters with viscosities as high as 16 cp. This unit produces a dry solids cake that is 40 to 60 percent solids content and ready for further treatment (landfilling, incineration, etc.). A limitation of this unit is that if solids in the wastewater increase to a level above 5,000 ppm, cake capacity and handling become the limiting factors. This technology is proposed for demonstration at the Palmerton Zinc Superfund site in Palmerton, PA. The shallow aquifer at the site, contaminated with dissolved heavy metals, has been selected as the waste feed. Pilot studies on the groundwater have shown that this system can produce a 35- to 40-percent solids filter cake and a filtrate with levels of heavy metals below detection (USEPA 1989d).

Ultrafiltration

509. Ultrafiltration is also discussed in the section on Metals Removal Technologies (see paragraphs 543-546). However, the discussion that follows pertains to treatment of suspended solids. Lightsey and Espinoza (1980) define ultrafiltration as a process of separation in which a solute is separated from a solvent by use of pressure and a semipermeable membrane. The solute must be molecularly larger than the solvent. The solute size must be greater than the membrane pore size to be retained and concentrated. Smaller molecular weight impurities filter through the membrane. A combination of a chemical-ultrafiltration treatment can be used for the remediation of groundwater colloidal solids and heavy metals such as arsenic, cadmium, lead, selenium, and silver.

510. The collection of the larger solute material on the surface of an ultrafiltration membrane can lead to fouling (concentration polarization) of the membrane and a drop in the rate of the flux through the entire filter. This problem can be avoided by keeping a rapid flow of liquid across the membrane surface. Gel polarization is a caking on the membrane when the solute precipitates or forms a thixotropic gel (Lightsey and Espinoza 1980).

Wetlands construction

511. Wetlands construction is also discussed in the sections on Metals Removal Technologies and Organic Treatment Technologies (see paragraphs 547-553 and 611-617).

512. Wetlands are areas, constructed or natural, that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to maintain saturated conditions. Natural wetlands consist of marshes, swamps, bogs, and cypress domes and stands. Constructed wetlands involve the creation of a marsh where one did not previously exist using intensive construction involving earth moving, grading, impermeable barriers, or erection of containers such as tanks or trenches. Wetlands are typically less than 0.6 m deep with slow-moving water in which dense stands of water-tolerant plants (i.e., cattails, bulrushes, or reeds) are grown (USEPA 1988f).

513. Three basic functions of wetlands make them potentially attractive for wastewater or effluent treatment (USEPA 1988f):

a. Physical entrapment of pollutants through sorption in the surface soils and organic litter.

b. Utilization and transformation of elements by microorganisms.

c. Low energy and low maintenance requirements to attain consistent treatment levels.

514. Natural wetlands are effective as wastewater treatment processes since the quiescent water conditions of a wetland are conductive to the sedimentation of wastewater solids. Other aspects of wetlands that facilitate wastewater treatment are the adsorption/filtration potential of the aquatic plants' roots and stems, the ion exchange/adsorption capacity of wetlands' natural sediments, and the mitigating effect that the plants have on climatic forces such as wind, sunlight, and temperature (USEPA 1988f).

515. Construction of wetlands is an emerging technology that uses natural geochemical and biological processes such as filtration, ion exchange, adsorption, absorption, and precipitation to remove and accumulate suspended solids from effluent waters.

516. Current experience with wetland systems is generally limited to the further treatment of secondary effluents. Factors to be considered are potential disruption of the existing wildlife habitat and ecosystems in a natural wetland, loss of water via evapotranspiration for all wetlands in arid climates, the potential for increased breeding of insects, and the development of odors caused by volatile components. The major costs and energy

requirements for constructed wetlands are associated with preapplication treatment, pumping and transmission to the site, distribution at the site, minor earth work, and land costs. In addition, a constructed system may require the installation of a barrier layer to limit percolation to groundwater and additional containment structures in case of flooding (USEPA 1988f).

517. Constructed wetlands offer the engineer greater hydraulic control for general use and are not restricted by many of the environmental concerns and user conflicts associated with natural wetlands. Unlike natural wetlands, which are confined by availability and proximity to the wastewater source, constructed wetlands can be built anywhere, including lands with limited alternative uses and in CDFs. They also offer greater flexibility for design and management options and thus may provide superior performance and reliability (USEPA 1988f).

Metals Removal Technologies

518. Most of the technologies that will be discussed for the removal of metals from effluent and leachate are commonly used in industrial wastewater treatment. However, several processes that will be discussed are developmental. These include biological ion exchange, electrocoagulation, and ultrafiltration. A relatively new concept for retention of heavy metals from effluents that will be discussed is the use of natural or manmade wetlands.

Adsorptive filtration

519. The University of Washington has developed an adsorptive filtration process for the removal of metals from liquids. Ferrihydrite is applied to the surface of sand and placed in a vertical column. Liquids contaminated with heavy metals flow through the vertical column, and the metals present in the liquid are adsorbed onto the ferrihydrite-coated sand. Once the ferrihydrite-coated sand has adsorbed its sorptive capacity of metals, the metals are stripped with very strong acids. Treatment efficiencies have been shown to remain constant even after several regeneration cycles. Advantages of this technology over conventional metals removal technologies are that it removes metals present as complexes (including organic complexes), removes anions, and removes suspended matter from liquids. This process has been tested extensively at the bench-scale level and was accepted into the SITE Emerging Program in October 1989 (USEPA 1989d).

Biological ion exchange process

520. Biological ion exchange processes involve preparation of a resin that binds both metallic cations and oxoanions excluding chlorides or sulfates. This technology, which removes heavy metal ions from aqueous solutions, is based on the strong, natural affinity of algal cell walls for heavy metal ions. One technology developed by Bio-Recovery Systems, Inc., AlgaSORB, consists of two columns containing approximately 0.25 ft^3 each of algal cells immobilized in a silica gel polymer. Groundwater or leachates containing metal ions and a high level of dissolved solids pass through the columns, removing aluminum, cadmium, copper, chromium, cobalt, iron, lead, silver, gold, platinum, uranium, vanadium, and zinc. The immobilization of the algal cells in the silica gel kills the algae, protects the dead algal cells from other microbes, and produces a hard material that can be packed in columns, which when pressurized, exhibits good flow characteristics. Once the algal cells are saturated with metal ions, reagents such as acids or bases are used to release the metals from the algal cells, producing a concentrated metal solution that must be detoxified by further treatment (USEPA 1988c).

521. An advantage of this technology over conventional ion exchange is that the components of hard water (calcium or magnesium, or monovalent cations such as sodium and potassium, do not interfere significantly with toxic, heavy metals binding to AlgaSORB). This technology is scheduled for field testing on mercury-contaminated groundwater in the fall of 1988, after which experiments determining the optimum flow rates, binding capacities, and stripping agents will occur (USEPA 1988c).

522. The AlgaSORB biological ion exchange process was demonstrated in fall 1989 at a mercury-contaminated groundwater site in Oakland, CA. The process is being commercialized for groundwater treatment and for industrial point source treatment (USEPA 1989d).

Electrocoagulation

523. The CURE electrocoagulation process is a continuous wastewater treatment process that electrolytically treats wastewater to cause the precipitation of suspended solids and certain metals and organics, allowing for collection and reuse or disposal of the water. The present systems use 10 lengths of standard pipe attached to a direct power source. The outer tubes are 1-1/2 in. in diameter and generally have a flow rate of 5 to 50 gpm with a 10-gpm average. The unit has a voltage requirement that varies from 5 to 100 volts with an average of 25 volts. The electrocoagulation unit also

draws between 5 and 100 amps/tube with an average of 15 amps/tube. Bench- and pilot-scale tests have been performed (Renk 1989).

524. General areas of application include the reduction of hardness and the breaking of oil emulsions in oil field wastewaters; the removal of heavy metals, selected organics and salts, oil and grease, and detergents from industrial wastewaters; the reduction of organics, algae, and bacteria; the removal of fats, oil, grease, metals, selected salts, phosphates, and nitrates; the improved settling of sludges; and the thickening of sludges in municipal wastewaters. The CURE electrocoagulation process has achieved the following percent removals on various contaminants in wastewater: arsenic, >37 percent; cadmium, 98 to >99.8 percent; chromium (total), >98 to >99.9 percent; copper, 97 to 99.8 percent; lead, >76 to >98 percent; biochemical oxygen demand, 32 to 89 percent; oil and grease, 93 to >99 percent; total organic carbon, 96 to 98.6 percent; and total suspended solids, 94 to 99.8 percent (Renk 1989).

525. Costs for the CURE electrocoagulation process range from $0.01 to $10/1,000 gal for power and the tubes, and are a function of power required and energy costs. The buying of a license to use the unit may be less costly depending on the size of the operation. In general, capital costs and operating costs have the same range ($0.25 to $0.50/1,000 gal) (Renk 1989).

526. An electrocoagulation process developed by Electro-Pure Systems, Inc., utilizes an alternating current to separate stable aqueous suspensions containing <5 percent oil. An advantage of this process over conventional coagulation/flocculation processes is that expensive polyelectrolytes are not necessary. Generally, the rate of separation is faster than that occurring with chemical flocculation, and the solids are often more dense. By-products produced in this process are a water phase that could be discharged to a wastewater treatment plant for further treatment, a solid phase that would be disposed off-site, and a dewatering filtrate that would be recycled. Any floatable material is reclaimed, refined, recycled, or disposed (USEPA 1989d).

527. The Electro-Pure electrocoagulation process has been used in the removal of fines from coal washwaters and colloidal clays from mine ponds in capacities up to 750 gpm. This process has also been used to remove suspended solids and heavy metals from pond water and creosote-based contaminants from groundwater. This technology was accepted into the SITE Emerging Program in October 1989 (USEPA 1989d).

Flocculation/coagulation

528. One method for reducing the levels of fine-grained suspended solids in the effluent involves treatment of the CDF effluent or the dredged material slurry with chemical flocculants. Flocculation is the conglomeration of suspended colloidal and finely divided suspended material by adding chemical compounds and by physically mixing the solution. First, the flocculating agents are gently mixed into the effluent to allow for formation of larger particles (Camp, Dresser, and McKee, Inc. 1986). These larger colloidal particles are composed of fine-grained particles that contain PCBs and toxic metals. These particles become too heavy to stay suspended and fall out of solution. The PCBs and metals are separated later from the waste stream by sedimentation (provided there are sufficient density differences), direct filtration, or some other similar process (Dragun 1988).

529. Two basic types of flocculants are used to treat dredged material slurries: inorganic compounds (such as aluminum sulfate, hydrated lime, ferric chloride, or ferric sulfate) and synthetic organic polymers or polyelectrolytes. Inorganic flocculants are used primarily on municipal and industrial wastewater and drinking water, but are not generally recommended for dredged material slurries due to the large doses of flocculant that would be required. The pH of the slurry must be controlled to obtain optimal flocculation.

530. Organic polyelectrolytes are classified as cationic, anionic, or nonionic, depending on the net charge of the chemical groups arranged along the polymer chain. Cationic polyelectrolytes appear to possess the most potential in the flocculation of freshwater dredged material slurries. All three polyelectrolyte types are potentially effective in the flocculation of dredged material slurries from saltwater sites. Polyelectrolytes cost more than inorganic flocculants, but a lower dose is required for optimum treatment (Barnard and Hand 1978).

531. Schroeder (1983) tested flocculating agents for CDF effluents and reported that flocculation can remove up to 95 percent suspended solids and achieve an effluent quality of 25 mg/ℓ suspended solids. Field results for effects on heavy metal contaminants in CDF effluents are not available. Final selection of a flocculant should be based on its cost, chemical composition, handling properties, mode of application, and its potential effectiveness for the specific site.

Freeze separation

532. A freeze crystallization technology, developed by Freeze Technologies Corporation, is designed to remove both inorganic and organic contaminants from wastewater. The process is designed based on the principle that the crystal structure formed by freezing water contains only water, excluding any contaminants. In this process, refrigerant is injected into the wastewater, forming ice crystals that are recovered and washed with pure water to remove adhering contaminants. Stripping units are used to remove the refrigerant from the pure water (after the ice has melted). The stripper units operate under vacuum and contain heaters that generate low-pressure steam that aids in refrigerant removal. This system was accepted into the Site Demonstration Program in July 1988, and a demonstration of this process was scheduled for late November or early December 1989 at the Stringfellow Superfund site in Glen Avon, CA (USEPA 1989d).

Ion exchange

533. General. Ion exchange is a reversible reaction in which anions and cations electrostatically attached to a solid resin material exchange with dissolved metal ions of similar charge in an aqueous solution or waste stream. The process is normally used to recover metal ions from wastewater and domestic water. The negatively charged site at which positive ions are taken up is called a cation exchanger, and an anion exchanger is a positively charged site that takes up negative ions (USEPA 1985). Ion exchange is applicable to metallic ions ($Cr_2O_7^{-2}$, SeO_4^{-2}, AsO_4^{-2}) and cations (Ni^{+2}, Cd^{+2}, Hg^{+2}), halides, sulfates, cyanides, carboxylics, sulfonics, some phenols, and organic bases such as amines (Camp, Dresser, and McKee, Inc. 1986). The resins that contain the exchange ions are originally coated with weakly held nonvalent anions and cations such as chloride, hydroxyl, sodium, or hydrogen ions (Ikalainen 1987). These resins are usually regenerable synthetic organic materials that hold up under a wide range of temperatures and pHs, and exhibit selectivity toward specific ions. Other materials that serve as ion exchange sources include clay and zeolite (natural exchange material). Residuals of the process include spent resins, acid, caustic, or brine (USEPA 1987). Ion exchange is a widely used, proven technology.

534. DeVoe-Holbein process. The DeVoe-Holbein process is a newly developed process similar to ion exchange used in metal finishing industries, ore benefication, precious metals recovery, and chloralkali plants. The DeVoe-Holbein process is effective for the treatment of both dilute and

concentrated waste streams containing metals. This process requires a regenerant but has good metal recycling potential. The DeVoe-Holbein process shows high specificity, but more data are necessary to assess this technology (Palmer et al. 1988).

Permeable treatment beds/dikes

535. Permeable treatment beds use walls or beds filled with limestone, crushed shell, activated carbon, glauconitic green sands, or synthetic ion exchange resins and constructed perpendicular to leachate or groundwater flow to treat the plume as it flows through the treatment bed. Permeable treatment beds can potentially reduce the contaminants present in leachate plumes moving through CDF dikes. Permeable treatment beds can neutralize acidic waters through the use of calcium carbonate. Organics can be removed from the water through the use of limestone, activated carbon, or crushed shell. Zeolites and synthetic ion exchange resins effectively remove heavy metals.

536. Permeable treatment beds have been tested at bench- and pilot-scales to provide the preliminary quantification of permeable treatment bed effectiveness. Laboratory tests indicate that permeable treatment beds may be practical for removing suspended solids from effluent when solids concentrations are as high as 1 g/ℓ for periods of approximately 1 year before clogging (Krizek, Fitzpatrick, and Atmatzidis 1976). Fuller and other researchers (USEPA 1978, as cited in USEPA 1985) have discussed the use of crushed limestone as an effective, low-cost liner for landfills in order to aid in facilitating the migration of certain heavy metals from solid waste leachates (USEPA 1985). Costs for the permeable treatment bed range from \$14/ft^2 for limestone bedding to \$267/ft^2 for activated carbon bedding (Yang et al. 1987).

Precipitation

537. Precipitation is a physical/chemical process often used in conjunction with flocculation in which dissolved chemical species, such as toxic metals, are transformed into a solid phase for removal. Precipitation is based on the alteration of the chemical equilibrium of inorganic species in order to alter solubility. Metals may be precipitated from solution as hydroxides with the addition of lime, and as sulfides with the addition of sodium sulfide. Metals can also be precipitated as carbonates or other salts. To achieve precipitation, an acid or base is added to adjust pH such that metals are least soluble, in order to facilitate precipitation for selective metal ions. An oxidizing agent may also be added to aid in the precipitation process. Once the metal ions are converted to solid form, coagulation,

flocculation, and sedimentation techniques can be used for final removal. Precipitation equipment includes a reaction tank with a rapid mixer, chemical storage tanks, chemical feed pumps, and pH controls (Camp, Dresser, and McKee, Inc. 1986). This system is operated at ambient conditions. Water flows into the reaction tank, mixes with the agent, forms agglomerated solids that settle, and separates by sedimentation or filtration. Later, dewatering may be required. Most organics are not removed except for in adsorptive carryover (USEPA 1987).

538. Heavy metals amenable to treatment include cadmium, zinc, lead, iron, some forms of arsenic, chromium, mercury, copper, manganese, and nickel (Camp, Dresser, and McKee, Inc. 1986). All divalent metal cations at a pH between 9 and 12 can be precipitated using sulfide, phosphate, hydroxide, or carbonate agents (in their order of effectiveness, respectively). Sodium sulfate with sodium hydroxide can also precipitate heavy metals. Precipitation agents that may be mixed into the soil include lime for hydroxide precipitation, limestones for carbonate precipitation, trebel superphosphate for phosphates (not for use on arsenic), and calcium sulfide or sodium sulfide for sulfide precipitation (USEPA 1984).

539. Lime (hydroxide precipitation) is the most common and proven agent. The lime removes hardness and alkalinity in a narrow pH range to cause the dissolved metals to precipitate as their corresponding hydroxide. Usually the amount of lime added is three times the stoichiometric amount that would be added to reduce solubility due to common ion effect. However, if too much is added and the metal is amphoteric, the waste metal becomes soluble again. The pH must be lowered before discharging the water. As much as 99.9 percent or as little as 10 percent metal can be removed by lime precipitation (USEPA 1985).

540. Sulfides are ideal agents due to their broad pH range and low solubilization stability. Chelating agents and anion competition is negligible. The extent of sulfide precipitation is reliant upon pH, type of metal, sulfide content, and interfering ions. Solubility of metal sulfides decreases with increasing pH (except with arsenic). Sodium sulfide addition may have adverse effects on soil physical properties. Calcium sulfide must be prepared as a slurry due to its low solubility. Sulfides may oxidize to form soluble metal sulfates in anaerobic conditions. If pH increases, hydrogen sulfide gas may be produced. Sulfides have been used to treat river water and wastewater in the field. Laboratory studies have been conducted as well (USEPA 1984).

541. Possible limitations associated with precipitation are that (a) not all metals have a common pH level at which they precipitate (USEPA 1987), (b) organic compounds may form organometallic complexes to inhibit precipitation, (c) cyanide and other ions may mix and complex as well, (d) soil pore space may become clogged, and (e) the agent being used may become a groundwater pollutant (USEPA 1985).

Reduction of metals

542. Chemical reduction of metals is the lowering of the oxidation state of a metal by the addition of electrons to the atom. Reducing conditions can depend on pH adjustment. Chemical reduction can be selective, depending on how well the pH is controlled, and will reduce all other constituents capable of being reduced along with that particular waste. Reducing agents include alkali metals, sulfur dioxide, sulfite salts, and ferrous sulfate (USEPA 1988d). All of these reagents have been shown to degrade certain toxic organic constituents by electron donation. Metal reduction is more commonly applied than organic. It is used primarily for reduction of hexavalent chromium, mercury, hexavalent selenium, and lead (USEPA 1984). Equipment required for reduction includes mixers with agitators, meters, and storage tanks.

Ultrafiltration

543. Lightsey and Espinoza (1980) define ultrafiltration as a process of separation in which a solute is separated from a solvent by use of pressure and a semipermeable membrane. The solute must be molecularly larger than the solvent. The solute size must be greater than the membrane pore size to be retained and concentrated. Smaller molecular weight impurities filter through the membrane. A combination of a chemical-ultrafiltration treatment can be used for groundwater colloidal solids and toxic metals such as arsenic, cadmium, lead, selenium, and silver.

544. Atomic Energy of Canada, Ltd., has developed a method for chemical ultrafiltration designed to treat groundwater contaminated with heavy metals. A chelating agent is added to the aqueous waste, and complexes form from the contact of the agent and the heavy metal. The solution is subjected to the membrane where the complexed ions remain, and the uncomplexed ions (sodium, potassium, calcium, chloride, sulfate, nitrate, etc.), water, nontoxics, and simple ions go through. The complexed ions are collected for solidification, discharged for further treatment, or recycled to reduce volume. Removal efficiencies are as high as 100 percent (USEPA 1988c),

545. The collection of the larger solute material on the surface of an ultrafiltration membrane can lead to fouling (concentration polarization) of the membrane and a decrease in the rate of the flux through the entire filter. This problem can be avoided by keeping a rapid flow of liquid across the membrane surface. Gel polarization is a caking on the membrane when the solute precipitates or forms a thixotropic gel (Lightsey and Espinoza 1980).

546. Ultrafiltration has been tested by laboratory methods, and a pilot-scale mobile unit has been proposed. Bench-scale experiments were designed to identify dominant variables that affect fouling of the membrane and to determine the DREs of this unit on heavy metals. The DREs were as follows: cadmium and mercury, up to 99 percent; lead, 90 percent; and arsenic, between 10 and 35 percent. Tests indicate that arsenic is not removed as effectively as other metals since arsenic is an anionic species. These bench-scale studies also indicated that this process does not require the production of large particles like conventional precipitation technologies. Therefore, ultrafiltration may be more applicable to waste with a high variability in metals concentrations (USEPA 1989d).

Wetlands construction

547. Wetlands are areas, constructed or natural, that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to maintain saturated conditions. Natural wetlands consist of marshes, swamps, bogs, and cypress domes and stands. Constructed wetlands involve the creation of a marsh where one did not previously exist using intensive construction involving earth moving, grading, impermeable barriers, or erection of containers such as tanks or trenches. Wetlands are typically less than 0.6 m deep with slow-moving water in which dense stands of water-tolerant plants (i.e., cattails, bulrushes, or reeds) are grown (USEPA 1988f) (see paragraph 513).

548. Three of the basic functions of wetlands make them potentially attractive for wastewater or effluent treatment (USEPA 1988f) (see paragraph 513).

549. Natural wetlands are effective as wastewater treatment processes since they support a large and diverse bacterial population important in the removal and degradation of organic contaminants in wastewater. In addition, the quiescent water conditions of a wetland are conductive to the sedimentation of wastewater solids. Other aspects of wetlands that facilitate wastewater treatment are the adsorption/filtration potential of the aquatic plants' roots and stems, the ion exchange/adsorption capacity of wetlands' natural

sediments, and the mitigating effect that the plants have on climatic forces such as wind, sunlight, and temperature (USEPA 1988f).

550. Construction of wetlands is an emerging technology that uses natural geochemical processes such as ion exchange, adsorption, absorption, accumulation by plants, and precipitation to remove and accumulate metals from effluent waters. Metals that are removed include lead, copper, nickel, molybdenum, zinc, manganese, iron, aluminum, and cyanide. Hydroxides and sulfides will likely be removed by oxidation in the aerobic zone and reduction in the anaerobic zone (USEPA 1988c).

551. Current experience with wetland systems is generally limited to the further treatment of secondary effluents. Factors to be considered are potential disruption of the existing wildlife habitat and ecosystems in a natural wetland, loss of water via evapotranspiration for all wetlands in arid climates, the potential for increased breeding of insects, and the development of odors caused by volatile components. The major costs and energy requirements for constructed wetlands are associated with preapplication treatment, pumping and transmission to the site, distribution at the site, minor earth work, and land costs. In addition, a constructed system may require the installation of a barrier layer to limit percolation to groundwater and additional containment structures in case of flooding (USEPA 1988f).

552. Constructed wetlands offer greater hydraulic control for general use and are not restricted by many of the environmental concerns and user conflicts associated with natural wetlands. Unlike natural wetlands, which are confined by availability and proximity to the wastewater source, constructed wetlands can be built anywhere, including lands with limited alternative uses and in CDFs. They also offer greater flexibility for design and management options and thus may provide superior performance and reliability (USEPA 1988f).

553. A pilot-scale wetland-based treatment process developed by the Colorado School of Mines has been constructed to assess the effectiveness of wetlands in treating effluent from the Big Five Tunnel near Idaho Springs, CO. Optimum results of the first year of this pilot-scale operation are as follows: (a) increase in pH from 2.9 to 6.5; (b) reduction in copper concentrations to below detection; (c) 97-percent reduction in zinc concentrations; (d) 80-percent reduction in iron concentrations; (e) 90- to 100-percent reduction in aluminum, cadmium, and lead concentrations; and (f) 50-percent reduction in cobalt and nickel concentrations.

Organic Treatment Technologies

554. Numerous technologies are available for the removal of organics from effluent or leachate. These processes are biological, chemical, and physical in nature and have varying degrees of effectiveness, greatly dependent upon concentration and flow rate of the effluent.

Aerobic biodegradation

555. Aerobic biodegradation is a highly developed and widely used treatment technology in which aerobic microorganisms metabolize biodegradable organic, toxic, and hazardous contaminants in wastewater (USEPA 1987). Equipment utilized for activated sludge processes includes aeration tanks and basins, clarifiers, compressors, aerators, and recycle pumps. The wastewaters are pumped into aeration tanks where the contaminants are degraded by the microorganisms. Aeration is accomplished by supplying a gas stream of breathing air or oxygen to the reactor. During degradation, the bacteria produce carbon dioxide, water, and metabolic by-products as well as more bacterial cells. Following degradation, the wastewater/microorganism mix is discharged from the aeration tanks into a clarifier where the liquid effluent is separated from the microorganisms. A portion of the microorganisms is returned to the aeration tanks to maintain the essential microorganism balance, while the remainder is removed as waste sludge.

556. A sufficient supply of nutrients for the growth of aerobic microorganisms must be available. Nitrogen and phosphate are the most common nutrient sources of microbes involved in biodegradation while oxygen is provided to the water by the use of air, pure oxygen, hydrogen peroxide, or ozone. Other potential nutrients include iron, trace metals, magnesium, potassium, calcium, sodium, sulfur, and manganese. An organic carbon source such as citrate or glucose may be added if the compound to be treated is only degraded by cometabolism and a primary carbon source is required (USEPA 1985). Dredged material effluent or leachate normally has an insufficient concentration of organic carbon and other nutrients to maintain biomass for an efficient suspended growth system. Therefore, these processes have limited application to effluent or leachate treatment.

Air stripping

557. Cullinane et al. (1986) define air stripping as a mass transfer process in which low-level volatile contaminants in groundwater, wastewater, and, sometimes, soil come in contact with and evaporate into the air.

Organics such as 1,1,1-trichloroethane, trichloroethylene, chlorobenzene, vinyl chloride, toluene, and dichloroethylene are amenable to treatment. The traditional function of air stripping is ammonia removal as well as the removal of phenol and hydrogen sulfide. The feed stream must be low in suspended solids, and the pH may need adjustment to >9.0 to reduce solubility and improve evaporation of these organic acids and bases. The types of air stripping units include the diffused aeration water cascade and the countercurrent packed tower (Camp, Dresser, and McKee, Inc. 1986).

558. The equipment for air stripping is extremely simple. However, the design of the packed tower is most suited for hazardous waste site application (Yang et al. 1987). Other types of air stripping systems exist for certain chemical/physical characteristics of a waste stream and for specified removal efficiency. Each of these systems has a removal efficiency of 50 to 90 percent (Camp, Dresser, and McKee, Inc. 1986).

559. Some restrictions apply to air stripping. Smooth operation of a system depends upon pressure, air-to-water ratio, surface area, and especially temperature. Stripping efficiencies can vary with ambient temperatures, and suspended solids may reduce efficiency. Volatile organic compound concentrations must not be over 100 ppm. The most important factor to observe after completion of air stripping is the collection of volatile contaminants for further treatment (USEPA 1987).

Anaerobic biodegradation

560. Anaerobic biodegradation or digestion is an available, low-cost treatment technology that uses the following microbes to achieve the degradation of low to moderate levels of organic contaminants in wastewater: hydrolytic bacteria that catabolize saccharides, proteins, and lipids; acetogenic bacteria that catabolize the products of hydrolytic bacteria such as fatty acids and neutral end products; homolactic bacteria that catabolize multicarbon compounds to acetic acid; and methanogenic bacteria that metabolize acetic and higher fatty acids to methane and carbon dioxide. These strictly anaerobic bacteria are commonly referred to as methanogenic consortia and are found in anaerobic sediments or sewer sludge digesters. This process can be used to treat aqueous waste streams with high concentrations of organic contaminants such as halogenated organics, nitrosamines epoxides (reduced to olefins), and aromatic structures (USEPA 1987). Nutrient requirements and maintenance of an anaerobic environment limit the application of anaerobic biodegradation processes to process or CDF effluent or leachate.

Biotrol aqueous treatment system

561. Biotrol, Inc., has developed an aerobic biodegradation system that is effective in the treatment of groundwater contaminated with organic compounds such as pentachlorophenol and creosote and certain inorganic compounds such as nitrates, but this treatment was not developed to treat heavy metals. In 1986, a successful pilot-scale field test was performed on groundwater at a wood-preserving plant. This process has also been tested at the Gibbs Superfund site in New Brighton, MN (USEPA 1989d).

Carbon adsorption

562. Carbon adsorption is an operation in which certain molecules sorb onto the large internal surface area of carbon substrate. Carbon with a high surface-to-weight ratio (500 to 1,400 m^2/g), which is characteristic of a good absorbent, is termed as "activated." Activated carbon adsorption applies to trace, low-soluble organics that are resistant to biochemical treatment and a few inorganic materials within the waste stream. Organic compounds include volatiles, organic nitrogen compounds, organic liquids with metals and halogens (Camp, Dresser, and McKee, Inc. 1986), chlorinated hydrocarbons, aromatics (phenol), and PCBs (USEPA 1987). Carbon adsorption appears to be very effective in the removal of PCBs. Test results indicate a reduction in PCB levels to less than 1 ppb (Carpenter 1986). Inorganics treated include antimony, arsenic, bismuth, chromium, tin, silver, mercury, cobalt, zirconium, chlorine, bromine, iodine, and other heavy metals. Highly polar contaminants, oil, and grease are not amenable to treatment due to activated carbon's electrically interactive properties (USEPA 1985).

563. Carbon adsorption systems are either pressure or gravity controlled and are composed of filter bed vessels in which carbon is placed, carbon storage vessels, and provisions for thermal regeneration. These filter bed vessels are usually circular for pressure systems and rectangular for gravity flow systems. All units have field loading rates from 2 to 10 gpm/ft^2 of bed cross section and bed depths of 4 to 20 ft (Cullinane et al. 1986). Vessels are oversized because of possibility of change in influent conditions. Multiple carbon columns in series, parallel, and series grouped in parallel are used for continuous operation (Ammon 1983). Series connections increase service life between regeneration of the carbon bed, and parallel connections provide maximum hydraulic capacity.

564. Activated carbon is well suited for mobile treatment systems and onsite construction. Calgon Corporation markets mobile units with single or

multiple prepiped adsorber vessels handling flows up to 200 gpm (Cullinane et al. 1986). Activated carbon has been used to treat effluents from CDFs for the Duwamish PCB spill (Hand et al. 1978). USEPA's Mobile Physical-Chemical Treatment System has demonstrated 99-percent removal of dissolved organics from impounded water (Carpenter 1986).

565. Carbon adsorption has high capital and operating costs. These prices range from $0.10/gal to $0.40/gal (Yang et al. 1987). The lower cost does not include disposal or regeneration costs. Construction requirements include housing, concrete foundation, and equipment (Cullinane et al. 1986). Primary operation and maintenance costs include electricity and carbon replacement (Yang et al. 1987).

Catalytic dehydrochlorination

566. USEPA (1987) describes catalytic dehydrochlorination as the reaction of polychlorinated hydrocarbons with high-pressure hydrogen gas in the presence of a catalyst. The operating temperature should range from 350° to 375° C with 30 to 50 atm pressure. Feed must be in organic liquid or gaseous form. The quantity of catalyst is usually less than 1 percent of pollutant weight and is deactivated by impurities such as tar or sulfur compounds. The process is expensive, and the catalyst may be a toxic chemical.

Chemical hydrolysis

567. Chemical hydrolysis was discussed in Part IV, Chemical Technologies section (see paragraphs 210-212).

568. Hydrolysis is the reaction of any substance with water that changes or alters that substance. Hydrolysis occurs when a compound undergoes bond breakage and dissolves into a water-ionic solution mixture. Hydrolysis can be carried out as a batch process in open tanks or by continuous flow in large towers. Hydrolysis can treat liquids contaminated with aliphatics and aromatics, such as esters, phosphates, and nitriles (Metry 1980), but is not applicable for the treatment of inorganic contaminants. Temperature, solvent composition, catalysis, and pH are environmental factors affecting the rate of hydrolysis. An acid, alkali, or enzyme can be used as a catalyst to aid in the process (Metry 1980).

569. Some toxic by-products may form according to the materials being used in the reaction (Metry 1980). Chemical hydrolysis is a common industrial method that must be carefully implemented to avoid mobilizing heavy metals (USEPA 1987).

Electrolytic reduction

570. Electrolytic reduction requires passing a dilute organohalogen wastewater between a platinized titanium anode and a woven carbon fiber cathode (diameter 10 μ). The applied voltage causes displacement of chlorine atoms and replacement with hydrogen atoms. These treated organics are either ionic or polar aqueous solutions. Contaminants must be miscible in the solution and are currently limited to 1 g/ℓ in solution. Because of their immiscibility, PCBs have not been treated using this process. A suitable solvent must be developed before this process can be economically applied to PCB-contaminated waste (USEPA 1988b).

571. The TNO Division of Technology for Society has successfully implemented electrolytic reduction in bench-scale treatment for pentachlorophenol (PCP), P-chloronitrobenzene (CNB), and dichlorovos (DDVP). Tests indicate that addition of surface active agents in small amounts improves efficiency and decreases energy consumption by 45 percent (USEPA 1988b). Costs are approximately $0.02/gal for electrolytic reduction with a division of expenditures of 40 percent energy, 40 percent capital, and 20 percent operation and maintenance (USEPA 1988c).

Laser-simulated photochemical oxidation photolysis

572. Laser-simulated photochemical oxidation is a physicochemical technology developed by Energy and Environmental Engineering, Inc., which simulates radiant energy by the use of an argon-fluorine laser. Organic groundwater contaminants and organic industrial wastewaters are photochemically oxidized into nontoxic compounds. The system consists of a filtration unit and the photolysis reactor. The exact system configuration depends upon contaminants in the groundwater. As a pretreatment to this system, chemical precipition or carbon adsorption may be required if heavy metals or high concentrations of organics are present. Contaminated groundwater is collected in a feed well and then pumped at a rate of 10 gpm through a filter unit for particulate removal. The resultant filtrate is then irradiated by the ultraviolet radiation supplied by the argon-fluorine laser. Air is then bubbled through the solution to maintain the dissolved oxygen. The absorbed energy fragments the aromatic ring of organic compounds, promoting oxidation. The radiation is not significantly absorbed by the water molecules in the solution (USEPA 1988c).

573. The detoxified solution, containing carbon dioxide, hydrochloric acid, and some volatile organics, flows into a degassing unit where volatiles

are released to the atmosphere. Some of the detoxified groundwater is injected into the surrounding soil while the remainder is used as a particulate wash at the filtration unit, causing desorption of organics from the particulates that were separated by the filters in the initial step. The particulate wash is then returned to the photolysis reactor for destruction of toxic material while the cleaned particles are disposed. This technology effectively oxidized single- and multiple-chlorinated benzenes, phenol, and benzenes in laboratory demonstrations (USEPA 1988c).

Neutralization

574. Neutralization requires the addition of an acid or base to a waste to produce a pH level of approximately 7. The most commonly used acids are sulfuric and hydrochloric. The most commonly used bases include lime, caustic soda, and soda ash (Ammon 1983). Reaction products are water, salts, and precipitated solids. Neutralization is applicable to any liquid waste and to some sludges, slurries, and gases (Camp, Dresser, and McKee, Inc. 1986).

575. Neutralization is not used as a primary treatment process. It provides a pretreatment step for carbon adsorption, ion exchange, air stripping, and in situ biodegradation. Oxidation, reduction, and precipitation occasionally require neutralization to aid in prevention of evolving toxic gases such as hydrogen sulfide and hydrogen cyanide (USEPA 1985).

Oil separation

576. Oil separation units used batch or continuous processes employing various equipment configurations that provide surface contact for de-emulsifying oil particles from the waste (Camp, Dresser, and McKee, Inc. 1986). Flow rates in continuous processes must be maintained at a minimal rate to avoid any mixing since separation occurs when the oil is allowed to settle or float out of the liquids (USEPA 1987). These systems may be used along with other treatment technologies as a polishing step for residual low-level contaminant removal (Yang et al. 1987).

577. The two general types of separators are the floating skimmer and the coalescing plate separator, which employs a tank. In the floating skimmer unit, the liquid waste is allowed to settle in a quiescent chamber, or a CDF. An oil skimmer is used to skim the oil off the top, while the water or effluent flows out the bottom portion of the chamber (USEPA 1987). The coalescing plate separator uses a series of horizontal and vertical hydrophilic and hydrophobic plates for oil flotation enhancement.

578. Acids may be used for de-emulsifying an oil/water mixture to provide greater efficiency. Effectiveness of the oil/water separator process is influenced by flow rate, temperature, and pH. Costs for a coalescing plate separator are estimated to be $289,200 for capital and $50,000/year ($2.70 to $4.16/gal at 1,000 to 1,500 gal/month) for operation and maintenance. These costs were derived using the assumption that the oil separator is used as an auxiliary to a larger treatment system. Accessory and control costs are not included, causing an underestimate of the capital costs (Yang et al. 1987).

Oxidation of organics

579. The oxidation of organics was discussed in Part IV, Chemical Technologies section (see paragraphs 224-228). Additional information pertaining to treatment of cyanide compounds in effluent/leachate is discussed in the following paragraphs.

580. Calgon, Oxymetal Industries, Exxon Chemicals, Inc. (in conjunction with Rio Linda Chemical Company), and DuPont have commercial units for removal of cyanides in industrial effluents. Calgon uses cupric ions to catalyze cyanide oxidation. DuPont uses Rastone, or 41-percent hydrogen peroxide and formaldehyde, to convert cyanide to cyanate. Oxymetal Industries utilizes a package unit that oxidizes 5 lb sodium cyanate/hour (Kiang and Metry 1982). The Exxon Chemicals process is applicable to groundwater or industrial wastewater contaminated with organics, pesticides, and cyanide (USEPA 1989d).

Ozonation

581. Ozonation is a chemical oxidation reaction in which ozone (a good oxidizing agent) breaks down many organic and a few inorganic compounds that are not amenable to biological treatment techniques. Ozonation can be applied to aqueous streams containing less than 1 percent oxidized compounds but not to sludges and solids. Ozonation is also limited by its nonselective nature (USEPA 1987), which causes natural organics to be oxidized as well as the contaminants of interest. Toxic by-products may also be formed (Cullinane et al. 1986).

582. Ozone is produced by high-voltage ionization of oxygen (USEPA 1987) in a separate generator. The ozone is injected into a contactor where it is mixed with the waste. The ozone reacts with oxidizable species such as chlorinated hydrocarbons, alcohols, chlorinated aromatics, pesticides, and cyanides. The rate of reaction can be controlled by pH adjustment. The contactor must be large due to mass transfer-limited reaction rates (Cullinane et al. 1986).

583. Ozone is acutely toxic and corrosive, so safety and use of special materials is advised. Stainless steel, aluminum, and Teflon are suitable construction materials (Culliname et al. 1986). Ozone has effectively reduced the concentrations of dissolved organic carbons in groundwater containing oil products. One gram of ozone per gram dissolved organic carbon resulted in water ozone concentrations of 0.1 to 0.2 ppm. Dissolved oxygen increases may also result in improved microbial degradation of organic contaminants (USEPA 1984).

584. A number of pilot- and full-scale studies have been conducted. Liquid cyanide effluents have been treated at the Michelin tire factory in Clermont, France, by adding 3.5 lb ozone per pound cyanide into a unit with a capacity of 90 gpm. Cyanide levels were reduced from 25 mg/ℓ to below detection. Phenols can also be removed from biologically treated effluents. Ozone at 20 to 40 ppm reduced phenol concentrations from 380 to 12 ppb at the City Service Refinery in Bronte, Ontario (Kiang and Metry 1982).

PACT process

585. The powdered activated carbon treatment (PACT) process developed by Zimpro/Passavant, Inc., is primarily a biological treatment technology that uses powdered activated carbon to treat industrial and municipal wastewaters containing organic pollutants, as well as chemical plant wastes, coke oven flushing liquors, contaminated groundwater, dye production waste, pharmaceutical wastes, and synthetic fuel wastes. Carbon is added to an active biomass in an aeration basin to enhance adsorptive removal of the contaminants. Effectiveness of the process is dependent on the dosage of carbon, the hydraulic detention time of the aeration basin, and the solids residence time for the carbon-biomass mixture in the basin (USEPA 1988c).

586. Many conditions must be satisfied for the PACT process to be effective. Wastes should be aqueous and contain nutrients for growth of microorganisms in the basin. Waste temperature must be maintained between 40° and 100° F. The pH must be maintained between 6 and 8. Hydraulic detention time must be long enough for destruction of biodegradable constituents (2 to 4 hr). Carbon in higher concentrations will enhance settleability of sludges removed from the basin and reduce air stripping of organics (USEPA 1988c).

587. The PACT system is used in conjunction with a wet air oxidation unit to regenerate powdered carbon and destroy organics in the biomass (USEPA 1988c). Mobile or stationary units are available, with the mobile units capable of treating from 2,500 to 10,000 gpd while the larger stationary units

treat up to 53 million gallons/day. The PACT process has been tentatively selected for demonstration at the Syncon Resins Superfund site in Kearny, NJ. The shallow aquifer at this site is contaminated with several organic solvents (USEPA 1989d).

Reduction of organics

588. Chemical organic reduction involves the lowering of oxidation state by addition of electrons to the atom. Reduction reactions can be used to reduce toxicity or solubility, or to transform the organic to an easily handled form. Reduction depends primarily upon pH adjustment (USEPA 1987). It is nonselective and treats all other constituents along with the contaminants of interest unless the pH is properly controlled (Camp, Dresser, and McKee, Inc. 1986). There are currently no practical applications for reduction of organic compounds, but reduction can occur with the use of catalyzed metal powders (aluminum, iron, and zinc) and sodium borohydride as reagents (USEPA 1985). Other reduction agents that may work include alkali metals (sodium and potassium), sulfur dioxide, sulfite salts, and ferrous sulfate (USEPA 1988d). All of these reagents have been shown to degrade toxic organic constituents by electron donation (USEPA 1984). Treatable wastes include chlorinated organics (Camp, Dresser, and McKee, Inc., 1986), unsaturated aromatics, and aliphatics (USEPA 1988c).

589. Use of reducing agents for treatment is unlikely because of their high reactivity (USEPA 1987). However, catalyzed metal treatment of organics has been used in wastewater treatment systems (USEPA 1984) on specific constituents such as PCBs, chlordane, kepone, and atrazene by passing the wastewater through beds of reactant diluted with inert solid. Total consumption of metal in these wastewaters produces 1 to 5 mg/ℓ of metal in solution (low amounts of toxic substances are treated). The powder can also be applied to soil surfaces and mixed with conventional agricultural equipment. Iron powders are best adapted for soil systems. They react best with certain organic constituents by removing the halogen with hydrogen or a hydroxyl ion, or saturating an aromatic structure (USEPA 1984). All of the catalyzed metal is consumed in the reaction (Camp, Dresser, and McKee, Inc. 1986). Use of catalyzed metals affects treatment through mechanisms including hydrogenolysis, hydroxylation, saturation of aromatic compounds, rearrangement of toxic compounds to innocuous form, and ring opening (USEPA 1984).

590. Camp, Dresser, and McKee, Inc. (1986) states the equipment required for reduction is the same as for oxidation (mixers with agitators,

meters, storage tanks). Slurries and soils may require larger reaction vessels and longer detention times than aqueous wastes. Laboratory and pilot-scale tests are required to determine feed rates and reactor retention times (Cullinane et al. 1986).

Resin adsorption

591. Resins can be used in sorption processes as well as ion exchange processes. Laboratory studies have indicated that resin adsorption can affect phthalate esters, ketones, alcohols, aldehydes, esters, chlorinated alkanes, alkenes, pesticides, aromatics, amines, and chlorinated aromatics. Resins can be of nonpolar or intermediate polar polymeric construction. Resins can also be carbonaceous (between a polymeric adsorbent and activated carbon). Resin adsorption applies to removal of color due to organic material and to wastewater with high levels of dissolved organics (Ikalainen 1987).

Reverse osmosis

592. General. Reverse osmosis is a process in which a solvent (i.e., water) is removed from a solution by a pressure-driven semipermeable membrane system. Solvent molecules are forced through membrane pores by hydrostatic pressure (200 to 800 psi) that overcomes the osmotic pressure. Particles or molecules larger than the pores remain as concentrate on the influent side and require further treatment. Reverse osmosis reduces concentrations of dissolved high molecular weight organic and charged inorganic anion and cation solids in brackish water and aqueous metallic wastes. Multivalent ions are treated more effectively than univalent ions (USEPA 1985). Recent advancements have made it possible to treat PCBs, chlorinated organics, water with high BOD levels, insecticides (Camp, Dresser, and McKee, Inc. 1986), and low molecular weight organics such as alcohols, ketones, amines, and aldehydes (USEPA 1985). Maximum concentration levels of organics in the feed is approximately 1 mg/ℓ feed.

593. Reverse osmosis can remove between 90 and 99 percent of solute in a single stage. Inorganic recovery is between 98 and 99 percent, and 80 to 99 percent removal of larger organic molecules has been demonstrated. In some tests, removal of halogenated compounds was impossible, but other tests indicate that up to 99 percent removal is possible. Between 50 and 80 percent removal of phenols and compounds with high vapor pressures, compared to water, has been demonstrated (Ammon 1983).

594. Cross-flow pervaporation system. This variation of reverse osmosis developed by Wastewater Technology Center uses semi-permeable membranes

and application of a vacuum to separate organic contaminants from groundwater, leachate, rinse water, or lagoon water. The membrane is nearly impermeable to water. However, organic contaminants are osmotically drawn through the membrane, creating an organic phase and an aqueous phase. This system is conceptual and was accepted into the SITE Emerging Program in October 1989. Design and construction of a pilot unit was scheduled to begin during spring 1990 (USEPA 1989d).

Rotating biological contactor

595. The rotating biological contactor is a full-scale technology that is a form of fixed-film biotreatment used to treat groundwater contaminated with pesticides and aqueous waste streams containing alcohols, phenols, phthalates, cyanides, and ammonia. Disks made of metal, polyvinyl chloride, or polystyrene that are 6 to 12 ft in diameter are mounted vertically on a horizontally rotating axis in treatment tanks. The process, which usually contains two or more trains of disks consisting of several stages, consists of primary treatment for solids removal in an equalization basin to prevent drastic environmental changes from shocking the microorganisms followed by the rotating biological contactor treatment. The TAUW process (USEPA 1988b) uses an equalization basin, two parallel rotating biological contactors, and a polishing step consisting of two sand filters and three activated carbon filters.

596. The rotating disks are exposed alternately to atmospheric oxygen and to the organic material contaminating the wastewater. Microorganisms attached to the disks degrade the organic contaminants in the wastewater to form carbon dioxide, water, and other metabolic by-products. The rotation, which is variable, mixes and aerates the wastewater and causes sloughing of excess microorganisms as growth continues. The wastewater is eventually routed to a clarifier where these solids are removed.

Steam stripping

597. Steam stripping was discussed in Part IV, Extraction Technologies section (see paragraphs 288-289).

598. According to Camp, Dresser, and McKee, Inc. (1986), steam stripping is the injection of steam into a liquid or slurry to evaporate organic contaminants. Steam stripping can be used to treat volatiles (VOCs), phenols ketones, phthalates (Camp, Dresser, and McKee, Inc. 1986), chlorinated hydrocarbons, xylenes, alcohols, and chlorinated aromatics (USEPA 1987). Water-miscible organics and metals are not amenable to steam stripping.

599. Direct injection of steam and multiple-pass heat exchangers are the most reliable systems for steam stripping. Direct injection is an energy-intensive method used for aqueous and mixed waste with lower level volatile organics that cannot be stripped with air (Camp, Dresser, and McKee, Inc. 1986).

Submerged fixed-film bioreactor

600. The submerged fixed-film bioreactor is a groundwater/wastewater treatment technology that has been used to treat biodegradable organics such as methyl ethyl ketone and benzene, as well as some chemicals that are initially more resistant to biodegradation, such as chlorobenzene. The system can biologically treat liquids containing low concentrations (<20 ppm) of readily biodegradable materials, can discharge the wastewater at a concentration in the low-parts per billion range, and can remain operable at hydraulic retention times as low as 1 hr.

601. This system consists of an aboveground fixed-film reactor, supplemental nutrient storage tank and pump, sump tank and pump, cartridge filter, and a final activated carbon filter. The process, which operates on a one-pass, continuous-flow basis, begins when wastewater is evenly dispersed over the reactor packing through the use of a header-distribution system. Plastic medium with a high surface area packs the reactor and is used as a medium for microbial growth while the water level is set to cover the microbe-covered plastic disks. Organic contaminants are removed by the microbes that are supplied with oxygen by an air distribution system placed underneath the plastic medium.

602. Treated wastewater is collected by an effluent water header system, pumped through a cartridge filter for biological solids removal, and pumped through an activated carbon canister for removal of any remaining organics. The contaminated water being treated should be free of toxic or inhibiting compounds, have a pH within the range of 6.5 to 8.5, and be within the temperature range of 60° to 95° F. Depending on the discharge criteria for the treated water, the cartridge and carbon filters may not be necessary. Efforts are under way to find a suitable site for demonstration of this technology (USEPA 1988c).

Trickling filter

603. The trickling filter, a process consisting of a rotary distributor, an underdrain system, and filter media, uses crushed rock, slag, or stone as a surface for microbial growth and passages for liquid and air (Carpenter

1986). In biological towers, a modification of the trickling filter, the microbial growth medium is PVC, polyethylene, polystyrene, or redwood stacked to form towers approximately 18 ft tall. Contaminated wastewater is sprayed over the microbial surface where the organic contaminants are removed (USEPA 1985). The microbial components of the system may include bacteria, fungi, and protozoa. Nitrogen-fixing bacteria are contained at the bottom of the system. No data have been found relating to the destruction of PCBs by this system (Carpenter 1986).

UV/ozonation

604. Ultraviolet light/ozone oxidation is a combination process in which PCB- or halocarbon-contaminated waste is exposed to ultraviolet radiation and sparged ozone (Carpenter 1986). The process destroys toxic organic compounds (chlorinated hydrocarbons) in diluted wastewater. It is applicable to sources such as groundwater, industrial wastewaters, or leachates containing compounds such as trichloroethylene, methylene chloride, phenol, pesticides, and PCBs (USEPA 1988c).

605. In bench-scale tests, wastewater was carried through a multiple-staged reactor with 30- to 40-watt low-pressure UV lamps. Ozone was distributed into each stage, producing a strong oxidizing environment for the waste. Bench-scale tests demonstrated 91- to 100-percent destruction of PCBs (Carpenter 1986).

606. Ultrox International UV/ozone oxidation process. Ultrox International provides a unique process of UV/ozone oxidation. This technology oxidizes toxic or refractory compounds (ones resistant to biological oxidation) in concentrations of parts per million or parts per billion. Equipment consists of a reactor module, air compressor, ozone generator module, and a hydrogen peroxide feed system (hydrogen peroxide is used with the ozone). Influents flow into the reactor, are exposed to UV radiation, and react with ozone and hydrogen peroxide which are injected through sparging ports in the tank to provide an environment for photochemical oxidation. End products are carbon dioxide, water, and salts. Off-gases go through a catalytic ozone decomposing unit. No residues, sludges, or spent absorbents are formed (USEPA 1988c).

607. The Ultrox module was used for a pilot study by the US Army Construction Engineering Research Laboratory at Fort Dix, New Jersey during 1985. The groundwater wastestream contained volatile halogenated organics (VHOs), purgeable organic halides (POCs), and toxic organic compounds. The DREs for

contaminants using an ozone flow of 0.75 gpm were 89 to 93 percent for POCs, no change in concentrations of TOCs, and between 49 and 70 percent for VHOs (Scholze, Maloney, and Buhts 1986).

608. The Ultrox International UV/oxidation unit was demonstrated in March 1989 at a hazardous waste site in San Jose, CA. The DREs were approximately 99 percent for trichloroethylene and approximately 90 percent for total VOCs. However, removal efficiencies for TOCs were very low, indicating a partial oxidation of organics without a complete reduction to CO2 and H20 (USEPA 1989d).

609. Atlantic Research Corporation and Ozonic Technology, Inc., UV/ozonolysis treatment system. Developers at Atlantic Research Corporation and Ozonic Technology, Inc., have also produced an UV/ozonolysis treatment for pulp and paper plants. This process is effective for PCBs on solid surfaces. The system is based on the simultaneous extraction of PCBs with ultrasound and treatment with UV/ozone or UV/hydrogen. Sediments are added as slurry (20 percent solids by weight) into a mixing tank where detergent and sodium hydroxide are injected. The mix is pumped into a reactor containing an ultraviolet light source and increasing amounts of ozone. Ultrasonics provide turbulence while the slurry is fed into a cyclone where solids are removed and neutralized (Wilson 1987).

UV/hydrogen peroxide

610. Hydrogen peroxide is a dependable oxidizing reagent for in situ treatment, or for surface treatment of groundwaters and sludges (USEPA 1985). It can react directly with the substrate by degradation with UV light to form hydroxyl free radicals and by autodecomposition in the presence of a metal catalyst. Hydrogen peroxide is nonselective and can be used in conjunction with ozone to degrade compounds normally unreactive to either of these processes individually. Effectiveness may be inhibited since hydrogen peroxide simultaneously increases mobility and decreases sorption sites. Hydrogen peroxide is effective for oxidizing cyanides, aldehydes, dialkyl sulfides, dithionate, nitrogen compounds, phenols, and sulfur compounds (USEPA 1984).

Wetlands construction

611. Wetland construction was discussed earlier in Part VI (see paragraphs 547-553, Metals Removal section). Wetlands are areas, constructed or natural, that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to maintain saturated conditions. Natural wetlands consist of marshes, swamps, bogs, and cypress domes and stands.

Constructed wetlands involve the creation of a marsh where one did not previously exist using intensive construction involving earth moving, grading, impermeable barriers, or erection of containers such as tanks or trenches. Wetlands are typically less than 0.6 m deep with slow-moving water in which dense stands of water-tolerant plants (i.e., cattails, bulrushes, or reeds) are grown (USEPA 1988f).

612. Three basic functions of wetlands make them potentially attractive for wastewater or effluent treatment (USEPA 1988f) (see paragraph 513).

613. Natural wetlands are effective as wastewater treatment processes since they support a large and diverse bacterial population important in the removal and degradation of organic contaminants in wastewater (USEPA 1988f).

614. Wetlands construction uses geochemical and biological processes such as adsorption, absorption, and accumulation by plants and microbes to remove and accumulate organics from effluent waters. Hydroxides and sulfides will likely be removed by oxidation in the aerobic zone and reduction in the anaerobic zone (USEPA 1988c).

615. Current experience with wetland systems is generally limited to the further treatment of secondary effluents. Factors to be considered are potential disruption of the existing wildlife habitat and ecosystems in a natural wetland, loss of water via evapotranspiration for all wetlands in arid climates, the potential for increased breeding of insects, and the development of odors caused by volatile components. The major costs and energy requirements for constructed wetlands are associated with preapplication treatment, pumping and transmission to the site, distribution at the site, minor earth work, and land costs. In addition, a constructed system may require the installation of a barrier layer to limit percolation to groundwater and additional containment structures in case of flooding (USEPA 1988f).

616. Constructed wetlands offer greater hydraulic control for general use and are not restricted by many of the environmental concerns and user conflicts associated with natural wetlands. Unlike natural wetlands, which are confined by availability and proximity to the wastewater source, constructed wetlands can be built anywhere, including lands with limited alternative uses and in CDFs. They also offer greater flexibility for design and management options and thus may provide superior performance and reliability (USEPA 1988f).

617. A pilot-scale wetland-based treatment process developed by the Colorado School of Mines has been constructed to assess the effectiveness of

wetlands in treating effluent from the Big Five Tunnel near Idaho Springs, CO. Optimum results of the first year of this pilot-scale operation indicated a reduction of the biotoxicity to fathead minnows and *Ceriodaphnia* by factors of 4 to 20.

PART VII: NONREMOVAL TECHNOLOGIES

Containment Technologies

618. Containment technologies involve isolating the contaminated sediment in situ rather than removing the sediment. Containment options considered for remediation of in situ sediment include Armorform, clean sediment capping, geomembrane capping, and structural isolation.

Armorform

619. Armorform articulating block mats are permeable double-layered, polypropylene or nylon panels that are filled with mortar. These mats are placed on the bottom of a waterway and filled with clean mortar. The permeable panels retain solids and allow excess water to escape as the solids harden into a concrete structure. Armorform has been used in conjunction with filter fabric and clean sediment for treatment of contaminated sediment at the Marathon Battery site. Here, the filter fabric was placed onto the contaminated sediment, and the mats were placed on top of the fabric. Clean sediment covered the entire configuration. The fabric performed poorly because of an undefinable cap life, tearing of filter fabric during placement, cap penetration by aquatic biota, and an installation time of 17 months (Carusone and Hickman 1988).

Clean sediment capping

620. Control of contaminant migration from bottom sediments can be provided by covering the contaminated sediment with a layer of clean sediment of suitable thickness and physical characteristics. The cap hinders diffusion and convection of contaminants to the overlying water column and prevents direct contact between aquatic biota and the contaminants. Suspension and transport of the contaminated sediment are also eliminated once the cap is in place. Sediment with silt and clay is generally more effective in limiting movement of contaminants. Use of plastic clay-sized sediment presents difficulties in placement of the cap within a waterway; therefore, most capping projects have used silt-sand mixtures. A cap thickness of approximately 3 ft has generally been proven in lab and field studies to provide an effective cap. However, scouring of the cap by hydrodynamic forces must be considered. Capping has been used frequently for confining dredged material placed in open-water sites but has not been widely applied as a remedial action for in situ sediments.

Geomembrane capping

621. Geomembranes are synthetic flexible materials that are nearly impermeable. Caps constructed from sheets or rolls of these materials can be joined together and sunk to the bottom of a waterway to cover contaminated sediment. This option has not been demonstrated for large sites. Effectiveness and reliability are expected to be poor because of the ease with which these membranes can be punctured during and after placement. By covering the bottom sediment, years would be required for recovery of suitable substrate for benthic organisms.

Structural isolation

622. Structural isolation involves the construction of a physical barrier around a contaminated area in a waterway. The area is generally backfilled to cover the contaminants and isolate them from the environment. This practice has been performed for port construction activities.

In Situ Treatment Technologies

623. In situ treatment technologies are used to remediate sediment without removing the sediment from its existing environment. In situ treatment options include aerobic and anaerobic biodegradation, grout injection, and in situ stabilization.

Aerobic biodegradation

624. Aerobic biodegradation was discussed in Part IV (see paragraphs 186-188) and also in Part VI (see paragraphs 555-556). Aerobic biodegradation requires that the sediment have a continuous supply of oxygen. This is not feasible for bottom sediments in areas where organic concentrations and oxygen demands are high.

Anaerobic biodegradation

625. Anaerobic biodegradation was also discussed in Part IV (see paragraphs 189-193). In situ anaerobic biodegradation for most organic contaminants proceeds at a very slow rate. Methods to accelerate the process are conceptual, but could include injecting deficient nutrients, seeding with cultivated microorganisms, or other amendments to the sediment. Implementability for this concept is complicated by the necessity to add other potential contaminants to the waterway to make the process work.

Grout injection

626. Sediment grouting is the injection of special liquids that solidify into a rock or soil body to seal, reduce permeability, and increase mechanical strength. Theoretically, in situ solidification by grout injection can be accomplished by the addition of grout into bored holes or into the top layer of sediment. The basic grouting process involves drilling holes to a chosen depth and injecting the grout material. Materials used for grouting include Portland cement, bentonite, clay, alkali silicates, and silicate. Cement is the oldest grout material that sets and hardens. Cement can be applied underwater by mobile pump or by grouting preplaced aggregate that forces cement through piping to fill voids in aggregate. Bowen (1981), as cited in USEPA (1985), stated that cement cannot be used in fine-grained soils <0.1 mm diameter. Bentonite grouts can be used alone or with coarse sands of permeability greater than 10^{-1} cm/sec. Bentonite-chemical grouts can apply to medium-sized particles. Clays are common, inexpensive grouts that swell in the presence of water and gel at low solution concentrations. Chemical injection may use a cement-clay mixture or quicklime to stabilize bottom sediments prior to construction of harbor structures. Takenaka Doboku Company, Ltd., provides a Japanese method that places injection pipes onto a barge and connects the pipes to mixing pipes that enter the sediment (USEPA 1985).

In situ stabilization

627. Methods previously discussed for in situ stabilization of sediment in CDFs could also be applied to in situ sediments. Water quality issues would have to be addressed.

628. A small field application in Japan of the Sil-B process involved placement of a bottomless box frame (see discussion of caissons, paragraphs 51-52) in the river bottom such that river water trapped within the frame could be pumped out, followed by addition of Sil-B agent to the exposed bottom sediment and grab-bucket mixing of sediments with Sil-B agent. The thrust of Japanese implementation of solidification technology is to remove and physically improve bottom sediments for use as fill in creating new land. Analyses do not sufficiently address the extent of contamination prior to treatment or the chemical stability of treated sediments (Carusone and Hickman 1988).

No-Action Alternatives

629. The no-action alternative consists of leaving the contaminated sediment in place with the hope that environmental degradation will not worsen until future remedial actions are feasible. The lone alternative discussed in this section is monitoring.

630. In some cases, remedial actions at an area of concern may not be selected because of the unavailability of funds, because the impacts of removal and treatment/disposal exceed existing impacts, because contaminants are being degraded in situ, or because ongoing sedimentation processes are reducing impacts. For such sites, remedial actions may be inappropriate. However, to avoid long-term transport of contaminants or future unknown impacts, monitoring of the site may be an appropriate option. Monitoring could involve any one or all of the relevant migration pathways for contaminants, such as surface water, groundwater, aquatic organisms, air, and public health effects.

Restricted-Use Alternatives

631. Restricted-use alternatives are designed to lessen the opportunity of human contact and sediment resuspension. These alternatives include fencing and warning signs, navigation relocation, and seasonal restrictions.

Fencing and warning signs

632. Contaminated areas near the shore with access to the public can sometimes be fenced to prevent public access and potential contact with contaminated sediment. Fencing is often ineffective unless coupled with active patrolling, warning signs, and an aggressive public information program. Obviously, fish and wildlife assets are not protected by fencing. Warnings may include advisories not to eat certain species of fish due to contamination.

Navigation relocation

633. Some highly contaminated sediments situated in traffic areas for commercial shipping or recreational boating are disturbed by the navigation activities. Such disturbances may release and aggravate dispersion of contaminants. Use of alternate channels or alternate harbors can reduce the resuspension of sediment and release of contaminants. However, this will not provide a remediation alternative for the contaminated sediment.

Seasonal restrictions

634. Use of an area affected by contaminated sediments may be more hazardous to public health during certain seasons of the year, such as warmer weather when potential volatilization is highest. Restricted public use of the waterway during this time period may be a component of a restricted-use plan.