# ASSESSMENT AND REMEDIATION OF CONTAMINATED SEDIMENTS (ARCS) PROGRAM

# REMEDIATION GUIDANCE DOCUMENT

**Great Lakes National Program Office**
**U.S. Environmental Protection Agency**
**77 West Jackson Boulevard**
**Chicago, Illinois 60604-3590**

---

## *DISCLAIMER*

---

## *ACKNOWLEDGMENTS*

This report was prepared by the Engineering/Technology Work Group (ETWG) as part of the Assessment and Remediation of Contaminated Sediments (ARCS) Program. Dr. Stephen Yaksich, U.S. Army Corps of Engineers (Corps) Buffalo District, was chairman of the ETWG. Mr. Jan Miller of the Corps North Central Division coordinated the preparation of this report and was the technical editor. Mr. Ojas Patel, of the Corps North Central Division, contributed editing and technical support throughout the production of the document.

The ARCS Program was managed by the U.S. Environmental Protection Agency (USEPA), Great Lakes National Program Office (GLNPO). Mr. David Cowgill and Dr. Marc Tuchman of GLNPO were the ARCS Program managers. Mr. Stephen Garbaciak of GLNPO was the technical project manager and project officer for this project.

This report was drafted through the Corps support to the ARCS Program provided under interagency agreements DW96947581-0, DW96947595-0, and DW96947629-0.

Principal authors of chapters of this document were:

**Chapter 1** *Jan Miller*, Corps North Central Division
**Chapter 2** *Jan Miller*
**Chapter 3** *Michael Palermo*, Corps Waterways Experiment Station
**Chapter 4** *Donald Hughes*, Hughes Consulting Services/Great Lakes United
**Chapter 5** *Paul Zappi*, Corps Waterways Experiment Station
**Chapter 6** *Donald Hughes* and *James Allen*, Bureau of Mines Salt Lake City Research Center
**Chapter 7** *Daniel Averett*, Corps Waterways Experiment Station
**Chapter 8** *Jan Miller*
**Chapter 9** *Donald Hughes* and *Trudy Olin*, Corps Waterways Experiment Station

**Chapter 10** *M. Pamela Hoerner*, Corps Detroit District
**Chapter 11** *Jan Miller* and *Stephen Garbaciak*, GLNPO

Contributors to this document included:

Ron Church, Bureau of Mines Tuscaloosa Research Center, Chapter 9
Carla Fisher, Corps Detroit District, Chapter 10
Stephen Garbaciak, Chapter 7
Tommy Myers, Corps Waterways Experiment Station, Chapters 2-9
John Rogers, USEPA Environmental Research Laboratory-Athens, Chapters 3 and 7
H.T. (Dave) Wong, Corps Detroit District, Chapters 2-9

In addition to those provided by the principal and contributing authors, comments from the following reviewers aided greatly in the completion of this document:

Jack Adams, Bureau of Mines Salt Lake City Research Center
Jim Brannon, Corps Waterways Experiment Station
David Conboy, Corps Buffalo District
John Cullinane, Corps Waterways Experiment Station
Linda Diez, Corps Chicago District
Bonnie Eleder, USEPA Region 5
William Fitzpatrick, Wisconsin Department of Natural Resources
Norman Francinques, Corps Waterways Experiment Station
James Galloway, Corps Detroit District
Edward Hanlon, USEPA Region 5
Phil Keillor, Wisconsin Sea Grant Institute
Thomas Kenna, Corps Buffalo District
Charles Lee, Corps Waterways Experiment Station
Thomas Murphy, National Water Research Institute, Canada
Danny Reible, Louisiana State University
Roger Santiago, Environment Canada
Paul Schroeder, Corps Waterways Experiment Station
Jay Semmler, Corps Chicago District
Frank Snitz, Corps Detroit District
Dennis Timberlake, USEPA Risk Reduction Engineering Laboratory
Mark Zappi, Corps Waterways Experiment Station
Alex Zeman, National Water Research Institute, Canada

This report was edited and produced by PTI Environmental Services for Battelle Ocean Sciences under USEPA Contract No. 68-C2-0134.

---

## *ABSTRACT*

Contaminated sediments are present in many of the waterways in the Great Lakes basin and contribute to the impairment of the beneficial uses of these waterways and the lakes. This document presents guidance on the planning, design, and implementation of actions to remediate contaminated bottom sediments, and is intended to be used in conjunction with other technical reports prepared by the ARCS Program. This guidance was developed for application in Remedial Action Plans (RAPs) at Great Lakes Areas of Concern (AOCs), but is generally applicable to contaminated sediments in other areas as well.

Sediment remediation may involve one or more component technologies. *In situ* remedial alternatives are somewhat limited, and generally involve a single technology such as capping. *Ex situ* remedial alternatives typically require a number of component technologies to remove, transport, pretreat, treat, and/or dispose sediments and treatment residues. Some technologies, such as dredging and confined disposal, have been widely used with sediments. Most pretreatment and treatment technologies were developed for use with other media (i.e., sludges, soils, etc.) and have only been demonstrated with contaminated sediments at bench- or pilot-scale applications.

The feasibility of applying treatment technologies to contaminated sediments is influenced by the chemical and physical properties of the material. Bottom sediments commonly contain a variety of contaminants at concentrations far below those at which treatment technologies are most efficient. The physical properties of contaminated sediments, in particular their particle size and solids/water composition, may necessitate the application of one or more pretreatment technologies prior to the processing of the sediment through a treatment unit.

The evaluation of sediment remedial alternatives should consider their technical feasibility, contaminant losses and overall environmental impacts, and total project costs. This document provides brief descriptions of available technologies, examines factors for selecting technologies, discusses available methods to estimate contaminant losses during remediation, and provides information about project costs. The level of detail in the guidance provided here reflects the state of development and use of the various technologies.

This report should be cited as follows:

U.S. Environmental Protection Agency. 1994. "ARCS Remediation Guidance Document." EPA 905-B94-003. Great Lakes National Program Office, Chicago, IL.

---

## *LIST OF FIGURES*

---

## *LIST OF TABLES*

---

# *ACRONYMS AND ABBREVIATIONS*

**ADDAMS -** Automated Dredging and Disposal Alternatives Management System
**AOC -** Area of Concern
**APEG -** alkaline metal hydroxide/polyethylene glycol
**ARCS -** Assessment and Remediation of Contaminated Sediments
**ATP[reg.] -** Anaerobic Thermal Processor[reg.]
**BCI -** Building Cost Index
**B.E.S.T.[reg.] -** Basic Extractive Sludge Treatment[reg.]
**BOD -** biological oxygen demand
**CCI -** Construction Cost Index
**CDF -** confined disposal facility
**CERCLA -** Comprehensive Environmental Response, Compensation and Liability Act (Superfund)
**CFR -** Code of Federal Regulations
**COD -** chemical oxygen demand
**Corps -** U.S. Army Corps of Engineers
**COSTTEP -** Contaminated Sediment Treatment Technology Program (Canada)
**CSRP -** Contaminated Sediment Removal Program
**CTF -** confined treatment facility
**CZM -** Coastal Zone Management
**DAVES[reg.] -** Desorption and Vaporization Extraction System[reg.]
**DMSO -** dimethyl sulfoxide
**EA -** environmental assessment
**EDTA -** ethylenediaminetetraacetic acid
**EIS -** environmental impact statement
**ENR -** *Engineering News Record*
**ETWG -** Engineering/Technology Work Group
**FAR -** Federal Acquisition Regulation
**GLNPO -** Great Lakes National Program Office
**HDPE -** high-density polyethylene
**HELP -** Hydrologic Evaluation of Landfill Performance
**KOH -** potassium hydroxide
**KPEG -** potassium polyethyleneglycol
**LaMP -** Lakewide Management Plan
**MCACES -** Micro-Computer Aided Cost Engineering System
**NAAQS -** National Ambient Air Quality Standards
**NEPA -** National Environmental Policy Act
**NESHAPS -** National Emission Standards for Hazardous Pollutants
**NOAA -** National Oceanic and Atmospheric Administration
**NPDES -** National Pollutant Discharge Elimination System
**NPL -** National Priorities List
**OSHA -** Occupational Safety and Health Administration
**PAH -** polynuclear aromatic hydrocarbon
**PCB -** polychlorinated biphenyl
**PCDDF -** Primary Consolidation and Desiccation of Dredged Fill
**PEG -** polyethylene glycol
**PPE -** personal protective equipment
**QAPjP -** quality assurance project plan
**QAMP -** quality assurance management plan
**RAM -** Risk Assessment/Modeling Work Group
**RAP -** Remedial Action Plan
**RCRA -** Resource Conservation and Recovery Act

**ReTec -** Remediation Technologies, Inc.
**RI/FS -** remedial investigation/feasibility study
**RREL -** Risk Reduction Engineering Laboratory
**SARA -** Superfund Amendments and Reauthorization Act
**SEDTEC -** Sediment Treatment Technologies Database
**SITE -** Superfund Innovative Technology Evaluation
**TCLP -** toxicity characteristic leaching procedure
**TEA -** triethylamine
**TSCA -** Toxic Substances Control Act
**U.S.C. -** United States Code
**USACE -** U.S. Army Corps of Engineers
**USEPA -** U.S. Environmental Protection Agency
**UV -** ultraviolet
**VE -** value engineering
**VISITT -** Vendor Information System for Innovative Treatment Technologies
**Weston -** Roy F. Weston, Inc.
**WHIMS -** wet, high-intensity magnetic separation

---

# *GLOSSARY*

***a priori* -** a predictive technique for estimating losses that is also suitable for planning-level assessments.

**alternative -** a combination of technologies used in series or parallel to alter the sediment or sediment contaminants to achieve specific project objectives.

**bench-scale -** testing and evaluation of a treatment technology on small quantities of sediment (several kilograms) using laboratory-based equipment not directly similar to the full-sized processor.

**capping -** a disposal technology where the principle is to place contaminated sediments on the bottom of a waterway and cover with clean sediments or fill.

**component -** a phase of a remedial alternative.

**contaminant loss -** the movement or release of a contaminant from a remediation component into an uncontrolled environment.

**demobilization -** the process of removing construction equipment from a work site.

**desiccation limit -** a stage of drying where evaporation of any additional water from the dredged material will effectively cease.

**effluent -** dilute wastewaters resulting from sediment treatment and handling; this includes discharges, surface runoff, wastewater, etc. from a confined disposal facility or landfill.

**feasibility study -** a study that includes evaluation of all reasonable remedial alternatives, including treatment and nontreatment options.

***in situ* -** in its original place.

**leachate -** includes waters that specifically flowed through the sediment, or precipitation that has infiltrated sediments in a confined disposal facility or landfill.

**mobilization -** the process of bringing construction equipment to the work site.

**moisture content -** a measurement of the amount of moisture in a soil sample commonly used in engineering and geological applications, calculated (as a percentage) as follows:

Note: Moisture content is **not** the complement of solids content.

**passive dewatering -** dewatering techniques that rely on natural evaporation and drainage to remove moisture.

**pilot-scale -** when referring to the testing or demonstration of a sediment treatment technology, the use of scaled-down but essentially similar processors and support equipment as used in full-sized operation to treat up to several hundred cubic meters of sediment.

**pontoon -** a buoyant collar used to support a pipe section.

**pretreatment -** a component of remediation in which sediments are modified prior to treatment or disposal.

**process option -** a specific equipment item, process, or operation.

**remedial investigation -** the determination of the character of sediments and the extent of contamination for a Superfund site.

**solids content -** a measure of the mass of dry solids/mass of whole sediment or slurry in percent form.

**vadose -** the zone of soil above the groundwater level.

**value engineering (VE) -** a process where cost estimates are used to compare technically equivalent features during detailed design.

**water content -** also called moisture content, an engineering term which is determined as the mass of water in a sample divided by the mass of dry solids, expressed as a percentage.

**windrow -** a long row of material that has been left to dewater and air dry.

U.S. Environmental Protection Agency

Great Lakes Contaminated Sediments

Recent Additions | Contact Us | Search: GO

EPA Home > Great Lakes > Monitoring > Sediments > ARCS > EPA-905-B94-003 (Remediation Guidance Document) Chapter 1

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 1. INTRODUCTION

Although toxic discharges into the Great Lakes and elsewhere have been reduced in the last 20 years, persistent contaminants in sediments continue to pose a potential risk to human health and the environment. High concentrations of contaminants in bottom sediments and associated adverse effects have been well documented throughout the Great Lakes and associated connecting channels. The extent of sediment contamination and its associated adverse effects have been the subject of considerable concern and study in the Great Lakes community and elsewhere. For example, contaminated sediments can have direct toxic effects on aquatic life, such as the development of cancerous tumors in bottom-feeding fish exposed to polynuclear aromatic hydrocarbons (PAHs) in sediments. In addition, the bioaccumulation of toxic contaminants in the food chain can also pose a risk to humans, wildlife, and aquatic organisms. As a result, advisories against consumption of fish are in place in many areas of the Great Lakes. These advisories have had a negative economic impact on the affected areas.

To address concerns about the adverse effects of contaminated sediments in the Great Lakes, Annex 14 of the Great Lakes Water Quality Agreement (1978) between the United States and Canada (as amended by the 1987 Protocol) stipulates that the cooperating parties will identify the nature and extent of sediment contamination in the Great Lakes, develop methods to assess impacts, and evaluate the technological capability of programs to remedy such contamination. The 1987 amendments to the Clear Water Act, in section 118(c)(3), authorized the Great Lakes National Program Office (GLNPO) to coordinate and conduct a 5-year study and demonstration projects relating to the appropriate treatment of toxic contaminants in bottom sediments. Five areas were specified in the Act as requiring priority consideration in conducting demonstration projects: Saginaw Bay, Michigan; Sheboygan Harbor, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River, New York. To fulfill the requirements of the Act, GLNPO initiated the Assessment and Remediation of Contaminated Sediments (ARCS) Program. In addition, the Great Lakes Critical Programs Act of 1990 amended the section, now section 118(c)(7), by extending the program by one year and specifying completion dates for certain interim activities. ARCS is an integrated program for the development and testing of assessment techniques and remedial action alternatives for contaminated sediments. Information from ARCS Program activities will help address contaminated sediment concerns in the development of Remedial Action Plans (RAPs) for all 43 Great Lakes Areas of Concern (AOCs, as identified by the United States and Canadian governments), as well as similar concerns in the development of Lakewide Management Plans (LaMPs).

To accomplish the ARCS Program objectives, the following work groups were established:

- The **Toxicity/Chemistry Work Group** was responsible for assessing the current nature and extent of contaminated sediments in three of the five priority AOCs (i.e., Buffalo River, Indiana Harbor Canal, and Saginaw Bay) by studying the chemical, physical, and biological characteristics of contaminated sediments, and for demonstrating cost-effective assessment techniques that can be used at other Great Lakes AOCs and elsewhere. Superfund activities have provided good characterizations of Ashtabula River and Sheboygan Harbor, so the ARCS Program focused the assessment activities on the other three priority AOCs.
- The **Risk Assessment/Modeling (RAM) Work Group** was responsible for assessing the current and future risks presented by contaminated sediments to human and ecological receptors under various remedial alternatives (including the no-action alternative).
- The **Engineering/Technology Work Group** (ETWG) was responsible for evaluating and testing available removal and remediation technologies for contaminated sediments, for selecting promising technologies for further testing, and for performing field demonstrations at each of the five priority AOCs.

- The **Communication/Liaison Work Group** was responsible for facilitating the flow of information from the technical work groups and the overall ARCS Program to the interested public and for providing feedback from the public to the ARCS Program on needs, expectations, and perceived problems.

## APPLICABILITY OF GUIDANCE

This document is focused on the remediation of contaminated sediments in the Great Lakes, and will provide guidance on the selection, design, and implementation of sediment remediation technologies. This document has been written for use by professionals involved in the development or implementation of RAPs for Great Lakes AOCs. This report will describe the procedures for evaluating the feasibility of remediation technologies, testing technologies on a bench- and pilot- scale, identifying the components of a remedial design, estimating contaminant losses, and developing cost estimates for full-scale applications.

It is recommended that this document be used in conjunction with other reports prepared under the ARCS Program which provide detailed information on specific technologies (Averett et al., in prep.), contaminant loss estimation procedures (Myers et al., in prep.), and examples of full-scale remediation plans (USEPA, in prep.b). Also, the U.S. Environmental Protection Agency (USEPA) report *Selecting Remediation Techniques for Contaminated Sediment* (USEPA 1993d) is recommended as a reference, particularly for those sites involving the Superfund program.

The decision to remediate contaminated sediments in a waterway and the selection of the appropriate remediation technology(s) are part of a step- wise process using the guidance developed by the three ARCS technical work groups. The *ARCS Assessment Guidance Document* (USEPA 1994a) is used to characterize the chemical and toxicological properties of bottom sediments. The guidance herein provides tools for evaluating the feasibility of remediation technologies and estimating their costs and contaminant losses. The *ARCS Risk Assessment and Modeling Overview Document* (USEPA 1993a) provides a framework for integrating the information developed in the other two steps and evaluating the ecological and human health risks and benefits of remedial alternatives, including no action.

The procedures described herein can be used iteratively within a modeling and risk assessment framework to evaluate a series of remedial alternatives (which may consist of multiple remediation technologies) of varying costs and benefits. These procedures may also be used to determine the most economical option for cases where the scope and objectives for sediment remediation are already fully defined.

While the ARCS Program was specifically designed for the Great Lakes AOCs, most of the guidance provided herein is applicable to contaminated sediments in other waterways. However, marine and estuarine sediments may have some physicochemical differences from freshwater sediments that may affect the applicability of some remediation technologies. In addition, many of the technologies evaluated by the ETWG were originally developed for media other than bottom sediments, such as soils, sludges, water, mineral ores, and industrial waste streams. As a result, the guidance presented herein has some applicability to the remediation of other media, although the applicability to contaminated soils is the most direct.

---

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 2. REMEDIAL PLANNING AND DESIGN

This chapter presents general procedures for developing sediment remedial alternatives, evaluating their feasibility, estimating project costs, and estimating contaminant losses that may occur as a result of remediation activities. Before discussing these procedures, the decision-making strategies that may be applied to sediment remediation are examined. The chapter also summaries the various Federal laws and regulations that may be applicable to sediment remediation activities.

## DECISION-MAKING STRATEGIES

Decision-making strategies are pathways for approaching a complex issue or problem in a logical order or sequence. A strategy can be represented as a flow chart or framework of activities and decisions to be made. Decision-making strategies are usually developed for very specific applications. The management of contaminated sediments occurs for a variety of purposes other than environmental remediation and restoration. Other purposes include the construction and maintenance of navigation channels, the clearing of sediment deposits from water supply intakes, construction within waterways, and the operation and maintenance of reservoirs and impoundments for flood control, water supply, recreation, or other purposes. There is no single decision-making strategy for the management of contaminated sediments that suits all purposes. Two established strategies that have been applied to the management of contaminated sediments are 1) a technical management framework developed jointly by the U.S. Army Corps of Engineers (Corps) and USEPA and 2) the decision framework established for Superfund projects. These two strategies are discussed below.

### Corps/USEPA Sediment Management Framework

The Corps and USEPA have developed a management framework for determining the environmental acceptability of dredged material disposal alternatives (USACE/USEPA 1992). This framework, shown in Figure 2-1, is structured to meet the regulatory requirements of the Clean Water Act; Marine Protection, Research and Sanctuaries Act; and the National Environmental Policy Act (NEPA). This framework was developed for the management of clean as well as contaminated dredged material and has evolved from earlier decision-making strategies (Francinques et al. 1985; Lee et al. 1991).

The Corps/USEPA management framework is a tiered decision-making process. Information about the sediments to be dredged is evaluated to determine the suitability of disposal alternatives in order of increasing complexity. Sediments that are determined to be uncontaminated are suitable for a wider variety of disposal options, and decisions can be made early in the evaluation process. Sediments that are contaminated require a more extensive evaluation within the decision-making framework, have additional testing requirements, and usually have fewer disposal options.

Corps regulations (33 CFR 230-250) require that this framework be used in the management of dredged material from navigation projects and in the administration of the permit program for dredged material disposal under section 404 of the Clean Water Act. The Corps/USEPA framework may be applicable to many sediment remediation projects; however, the process does not fully address sediment treatment technologies.

### Superfund RI/FS Framework

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and Superfund Amendments and Reauthorization Act of 1986 (SARA) established and reauthorized the Superfund Program. The decision-making framework for Superfund projects is shown in Figure 2-2 and is described in detail in USEPA (1988a).

The Superfund decision-making framework has two major components: the remedial investigation and the feasibility study (RI/FS). For a Superfund site with contaminated sediments, the remedial investigation would identify the character of the sediments and the extent of contamination, among other information. The feasibility study would include an evaluation of all reasonable remedial alternatives, including treatment and nontreatment options.

## Comparison of Strategies

Either of the decision-making strategies discussed above might be applied to a sediment remediation project with equal success. These strategies represent two different approaches to the evaluation and selection of remedial alternatives. In the Superfund strategy, remedial alternatives are evaluated in a parallel fashion (Figure 2-3) (i.e., a wide range of possible alternatives are evaluated simultaneously, and then a selection is made among the leading candidates). Another possible strategy is a linear or sequential approach to evaluating disposal alternatives (Figure 2-3). Portions of the Corps/USEPA management framework use this approach, in which, for example, disposal options are examined in order of increasing complexity until a suitable alternative is found.

Each of these approaches has advantages and disadvantages. The advantages of the parallel approach over the sequential approach can be summarized as follows:

- The approach has been widely used for RI/FS efforts at Superfund sites contained in the National Priorities List (NPL) and at other non-Superfund sites
- Most environmental consultants and regulatory agencies are more familiar with this approach
- The approach is consistent with the requirements of NEPA
- The approach generally provides decision-makers with more than one option for consideration

The primary disadvantage of the parallel approach is that the evaluation of numerous alternatives may require significant resources and time.

Projects that are on the NPL are required to follow Superfund RI/FS procedures (the parallel approach). However, many (if not most) contaminated sediment sites, including the majority of AOCs in the Great Lakes, are not NPL sites. For projects where resources, funding, or time may not allow a detailed evaluation of numerous alternatives, a hybrid approach may be considered that incorporates elements of both the parallel and sequential approaches.

## Recommended Strategy for Sediment Remediation

A simple decision-making framework for evaluating sediment remedial alternatives is shown in Figure 2-4, and contains elements of both of the decision-making strategies discussed above. This framework contains four major activities (boxes) and one decision point (diamond). The first activity is to define the objectives and scope of the project. The next two activities involve the screening and preliminary design of remedial alternatives. The products of these activities are preliminary designs, cost estimates, and estimates of contaminant loss, which are used to determine if there is a feasible alternative that meets the project objectives. If there is more than one alternative that meets these objectives, the preferred alternative is selected. If there are no feasible alternatives that meet the project objectives, the evaluator must return to the first activity to reevaluate the project objectives and/or scope. The final major activity, once a preferred alternative has been selected, is implementation. The elements of this decision-making framework are described in the following sections, preceded by a brief definition of several relevant terms used throughout this guidance document.

A **sediment remedial alternative** is a combination of technologies that is used in series and/or in parallel to alter the sediments or concentrations of sediment contaminants in order to achieve specific project objectives (discussed below). The simplest alternative would employ a single technology, such as *in situ* capping. However, a more complex alternative, as shown in Figure 2-5, may involve several different technologies and, in the process, generate a number of separate residues or waste streams.

A **component** is a phase of a remedial alternative, such as removal, transport, pretreatment, treatment, disposal, or residue management. Chapters 4-10 of this report discuss the available technologies for each of these components. Nonremoval technologies (e.g., *in situ* containment), which could be considered components or complete remedial alternatives, are discussed in Chapter 3.

For each component, several **technology types** may be considered. For example, the removal component could involve the use of hydraulic or mechanical dredges. A subcategory of a technology type, referred to as a **process option**, is a specific equipment item, process, or operation. For example, a horizontal auger dredge is a process option under the hydraulic dredge technology type of the removal component.

***Project Objectives***

To simplify the use of this document, a key assumption is made that a decision to remediate contaminated sediments in some portion(s) of a river, channel, harbor, or lake has already been made. The reasons for that decision, although critical to the successful remediation of the impacted area, are not essential to the use of this guidance; however, the objectives of the remediation project will need to be established to guide the evaluation of remedial alternatives. In addition, the scope of the remediation effort will also have to be defined as clearly as possible.

The objectives of a sediment remediation project are usually designed to correct site-specific environmental problems. In some cases, the objective is in the form of a statement of the desired results to be achieved by remediation. In other cases, the objective may be defined in the authority under which the project is initiated. For example, the objective of the remedial action plans for the Great Lakes AOCs, as defined in the Great Lakes Water Quality Agreement, is to restore the beneficial uses of each area.

The objectives of a sediment remediation project can be quantitative, qualitative, or a combination of both. In some cases, the objectives are fully quantified, such as in the case of an enforcement action where the contaminated material is localized and its source is known (e.g., an illegal fill or spill). In such cases, the objective might be defined in quantitative terms, such as to remove sediments exceeding a specified level of contamination, or to remove a specific quantity of sediment. In this case, the objectives and scope of the project are virtually the same.

In many cases, however, sediment contamination is widely dispersed and the objectives of the remediation project are more qualitative. For example, an objective might be to reduce the human health risk caused by the consumption of fish contaminated by the sediments, or to enhance the diversity of aquatic life that is depressed by sediment contamination. Such objectives may become quantified by setting specific targets for remediation (e.g., fish tissue contaminant concentration).

The objectives of a sediment remediation project may be defined through risk analysis and modeling methods, as outlined in the *ARCS Risk Assessment and Modeling Overview Document* (USEPA 1993a). These methods can be used to determine the environmental impacts of the no action alternative as well as various remedial alternatives. When the objectives are established by risk assessment and modeling, the ability of remedial alternatives to meet these objectives can generally be determined using the same procedures.

Defining the objectives of a sediment remediation project is often a very complicated process, requiring coordination at many levels. It is not always possible to define specific, quantifiable objectives and proceed directly to the project design and construction stage. If there is more than one proponent for a remediation project, there may be different objectives, not all of which may be compatible or feasible. In this case, project objectives and scopes may need to be formulated in an iterative fashion, as shown in Figure 2-4. This approach is especially useful when the objectives are less certain or poorly quantified.

***Project Scope***

The scope of a sediment remediation project defines the extent of the remediation in terms of both space and time. The scope is generally an extension of the project objectives. The scope may be defined through detailed analysis, including risk assessment and modeling. It may be defined by statute or through a negotiated or adjudicated settlement. The scope may also be scaled to fit funding or other constraints through an iterative process, as shown in Figure 2-4.

The spatial scope of a sediment remediation project is typically defined as an area or reach of a river, channel, harbor, or lake. The scope may be defined in terms of sediment depth or thickness. For example, the project objective may be to decrease the level of contamination in fish to some threshold by reducing the exposure to sediment contaminants. The scope might then be defined as the creation, in a specific reach of river, of a new sediment surface with an acceptable level of contamination. This new sediment surface might be created by removing existing sediments, covering them, or treating them in place.

The objectives of a project may require that the scope include (or exclude) specific technologies. For example, project objectives may require the removal of contaminated sediments or the destruction of a particular contaminant. These restrictions may be mandated by authorizing legislation or applicable regulations.

The time element of a sediment remediation project may be fixed or open ended. Restrictions on the time to complete a remediation project can have significant effects on its feasibility and cost of implementation.

### *Screening of Technologies*

Once the project objectives and scope have been defined, the next step in the decision-making framework (Figure 2-4) is the screening of technologies. The purpose of this step is to eliminate from further consideration technologies that are not feasible or practicable, using available information. This is best done by first attempting to eliminate broad categories of options and then focusing on technology types. In the simplest context, there are two forms of remediation (containment and treatment) that can be performed on contaminated sediments under two possible conditions (in place or excavated). These options create the following four modes of sediment remediation:

- Containment in place
- Treatment in place
- Excavation and containment
- Excavation and treatment

A summary of the containment and treatment technology types for these four modes of remediation is shown in Table 2-1.

The state of development and experience with these modes of remediation are quite varied. The containment of contaminated sediments in place has been applied on a full or demonstration scale at a few locations, including the Sheboygan River and Waukegan Harbor Superfund sites on the Great Lakes. To date, the treatment of sediments in place has been demonstrated in the Great Lakes on a limited scale with a few technologies, but the results of these demonstrations are not yet available.

The containment of contaminated sediments dredged from navigation projects has been practiced for many years, and a significant amount of engineering and design information and guidance is available on this mode (Saucier et al. 1978; USACE 1980c, 1987b). The treatment of excavated sediments has been demonstrated on a pilot scale at a number of locations (including several ARCS AOCs) and implemented on a full scale at only one site on the Great Lakes. Much of the engineering and design information about treatment technologies for contaminated sediments has come from applications with materials other than sediments (e.g., soils, sludges).

The evaluator should begin the screening process by considering the four modes of sediment remediation listed in Table 2-1 in light of the objectives and scope of the project. It is possible that one or more of these modes might be eliminated categorically by the project objectives or scope. For example, if the project area is a navigation channel, and must be maintained at some depth for recreational or commercial navigation, in-place (nonremoval) options might be eliminated from further consideration. In some cases, the project objectives may require treatment of a specific contaminant. This would eliminate containment options (alone) from further consideration.

For the remaining modes of sediment remediation, the evaluator should next consider the technology types available for the critical components. In-place remediation is considered a single-component alternative. It is expected that the critical component of a remedial alternative involving sediment removal will either be the treatment or disposal component. In most remediation projects involving dredging, one or both of these components will largely determine if the alternative is ultimately feasible.

The evaluator should screen technology types for the critical components based on criteria developed by or with the project proponent. The criteria for screening remedial alternatives under Superfund are defined (USEPA 1988a) as:

- Overall protection of human health and the environment
- Compliance with applicable and relevant regulations
- Long-term effectiveness and permanence
- Short-term effectiveness
- Reductions in toxicity, mobility, and/or volume of contaminants
- Implementability
- Cost
- State and community acceptance

These criteria are appropriate for an RI/FS investigation, but require more detailed information than necessary for the screening level in the sediment remediation framework described herein. A shortened list of screening criteria for this framework might include:

- State of development and availability
- Compatibility with sediments and contaminants
- Effectiveness
- Implementability

- Cost

The initial screening of remediation technologies is conducted using readily available information on technologies and project-specific information on sediment conditions. No new data are collected. It is generally not necessary to identify specific process options at this point. If more than one remediation technology provides the same results, it may be possible to eliminate those technologies whose costs are greater by an order of magnitude (Cullinane et al. 1986a). After potential technology types for critical components have been evaluated based on the project-specific criteria, other components needed for each complete remedial alternative need only be identified to the extent necessary to determine the overall implementability and cost. Because of the importance of this initial screening step, and because the level of information on technologies varies greatly, screening should be conducted by persons experienced in such evaluations. This guidance document and the literature review of removal, containment, and treatment technologies prepared for the ARCS Program (Averett et al. 1990 and in prep.) may be used as primary sources for this effort.

At the conclusion of the screening step, the evaluator should have identified a limited number of technology types for the critical components of each remedial alternative. With the wide diversity of sediment remediation approaches available, it is recommended that at least one alternative be considered in the next step (preliminary design) for each of the remediation modes determined to be consistent with the project objectives and scope. For a majority of cases, at least one nonremoval technology, one confined disposal option, and one or more treatment technologies should be considered.

***Preliminary Design***

The next step in the decision-making framework (Figure 2-4) is the development of preliminary designs for those technologies that have passed the screening-level evaluation. This step involves the design of a limited number of remedial alternatives in sufficient detail to make a selection for implementation. Some additional data on the sediments, technologies, and locations for implementation may be collected during this step.

The preliminary design is a complex process that involves many separate decisions. A remedial alternative may include a number of components, and the preliminary design process must ensure that the process option selected for each component is technically feasible, compatible with other components, and capable of meeting applicable environmental regulations and project-specific constraints.

The following aspects of a sediment remedial alternative and the preliminary design analysis are discussed briefly below:

- Material characteristics
- Materials handling
- Compatibility of components/technologies
- How to begin the design phase
- Information requirements

***Material Characteristics***--Sediments are soil and water mixtures transported by and deposited in aquatic environments. In most cases, the relative amounts of gravel, sand, silt, clay, and organic matter in a sediment reflect the particle size characteristics of the soil in the watershed and the sorting that occurred during transport. In a limited number of waterways, sediment physical characteristics are more influenced by the nature of the anthropogenic discharges to the system. Chemical contaminants in the sediments represent only a small portion of its mass and do not, with few exceptions, significantly alter the grain size distribution. Sediment contaminants tend to be associated more with silt and clay fractions and less with sand and gravel fractions, because fine-grained sediments, particularly those with significant organic carbon content, have a higher affinity for some contaminants. In addition, sand and gravel deposits are usually present in areas of high energy (i.e., erosion and scouring) where fine-grained sediments and contaminants have been washed away.

The physical and chemical characteristics of the sediments in a waterway are site specific and may vary both laterally and vertically. Some sediment deposits have layers with distinct physical and chemical properties. In other areas, the sediment properties may be relatively homogeneous. The distribution of contaminants in a sediment deposit may reflect activities over many years or decades. Evaluators should not expect to be able to develop contaminant distribution profiles in sediments with as high a level of resolution as for other environmental media.

Most fine-grained, contaminated sediments have been deposited in recent (geologic) time and are not well consolidated, particularly in navigation channels that have been dredged in the past. Sediments may have significant amounts of oversized materials and debris. Cobbles, gravel, coal, and other bulk commodities may have been spilled from adjacent docks or passing ships. Bottles, cans, tires, bicycles, shopping carts, and entire car bodies have been recovered in dredging operations.

The amount of water in sediments is one of its most important physical properties, but there is considerable confusion about the terminology for this property (see *Glossary* for definitions). This manual will refer to the solids content of a sediment and avoid using the terms moisture or water content, which have a layman definition at odds with their engineering definition.

Site-specific analysis of the physical and engineering properties of sediments should always be obtained before even the most preliminary design is begun. Recommended physical and engineering properties for analysis are shown in Table 2-2 (detailed analytical procedures are available in USACE 1970). Also shown are typical values for contaminated sediments in Great Lakes tributaries.

A general rule-of-thumb is that in-place, predominantly fine-grained, contaminated sediments have a solids content of approximately 50 percent, and that dry sediment solids generally have a density between 2.5 and 2.7 g/cm[3]. Using these values, a unit of sediment (in place) is roughly one-third solids by volume. With this solids content, sediments are only slightly fluid, and would not readily flow. The physical properties of a sediment can be altered by components of a remedial alternative. In some cases, this is done intentionally to facilitate handling or treatment. In other cases, changes to sediment physical properties by a component may increase material quantities and greatly affect costs.

***Materials Handling***--Each component of a sediment remedial alternative (except nonremoval) involves a significant amount of materials handling. The removal component involves the excavation of the sediment from the bottom of the waterway. The transportation component involves moving excavated sediment to a location where the material may be placed into a holding area, moved into pretreatment units, and then carried into treatment units. In addition to the solids, there are other materials that must be handled. For example, the residual water from dewatering, effluent, and leachate systems must be collected and routed. In addition, some treatment technologies create residues other than solids and water that must be handled.

One of the most important factors that affects materials handling is how the sediments are removed. Sediments that are dredged mechanically are generally removed at or near their *in situ* solids content. In contrast, hydraulic dredging entrains additional water with the sediments and produces a slurry that may have a solids content ranging from 10-20 percent. In creating this slurry, the total material volume increases 3-6 times. This increase in volume affects all subsequent components of the remedial alternative. For example, the use of hydraulic dredging may eliminate certain transportation options, increase the size requirements of a disposal area, and necessitate larger and more sophisticated effluent treatment systems.

A common goal of most sediment remedial alternatives is to separate the solids from the water fraction of the sediment (i.e., dewater) to the maximum extent possible. This is done to minimize disposal costs for the solids and is a requirement of some treatment technologies. Sediments may be dewatered through a variety of processes to a solids content greater than 50 percent. Depending on the process used, there may be little or no volume reduction, because water is replaced by air in the voids between the sediment solids.

Contaminated sediments may be handled and rehandled a number of times during the implementation of a remedial alternative. The costs and contaminant losses of each of these handling operations may be significant.

***Compatibility***--The need for and compatibility of components and technologies is determined by a number of factors, including physical requirements, material characteristics, rate of processes, and logistical considerations.

The consideration of these factors is best illustrated by example. Assume that the critical component is treatment, and the technology type being considered is solvent extraction. Most process options of this technology have similar requirements on the feed material. Process options could be constructed that are capable of treating 100-500 tonnes per day, generating three residues: solids, water, and extracted organic compounds. These process requirements will have the following effects on other components:

- The process, even with multiple units, cannot keep pace with dredging. An area for temporary storage of sediments is necessary.

- The feed material must have a high solids content. This can be accomplished by restricting dredging to mechanical methods or using hydraulic dredging followed by one or more dewatering steps.

- The feed material must have oversized material (i.e., larger than 5 mm) removed. A pretreatment component, involving screening or other technologies, must be applied.
- The water from the treatment process and the water from sediment dewatering must be treated and discharged. Different water treatment technologies may be needed for these residues, depending on the nature and concentrations of contaminants present.
- Disposal methods must be identified for the solid and organic residues. Additional treatment may be required for one or both of these residues prior to disposal.

As illustrated above, the development of a sediment remedial alternative begins by describing a single component and identifying its requirements and limitations. The other components can then be identified and technology types can be considered and evaluated for compatibility. There is no particular sequence for evaluating components. In most cases, they must be considered concurrently.

***How to Begin the Design Phase***--Although subsequent chapters in this document discuss remediation components in a logical process sequence (i.e., removal is followed by transport, which is followed by pretreatment, etc.), the formulation of an overall remedial alternative is not as simple as following this linear sequence to select the optimal technology for individual components. The preliminary design phase usually begins with the disposal component because it represents the terminal point of two components (removal and transport) and the disposal facility location may be used to implement other components (pretreatment, treatment, and residue treatment). Most treatment technologies will require a disposal facility and some form of pretreatment to support the treatment process. The disposal facility (or a secure land area) is needed for storing, pretreatment, and handling of dredged sediments; as a base for treatment operations; and possibly for long-term disposal of residues. While it is possible to perform these functions at different sites, there would be increased difficulties associated with obtaining lands for managing contaminated materials.

The availability and location of lands for handling or disposing of sediments can often influence the selection of remediation technologies. For example, if the only available lands for a disposal site are several kilometers from the removal site, hydraulic dredging and pipeline transport technologies may not be feasible. Some technologies, such as confined disposal, gravity dewatering, and land application of sediments, require a great deal of land. In contrast, most technologies that rely on process equipment (e.g., mechanical dewatering, solvent extraction, thermal treatment) are relatively compact and have smaller land requirements.

Selection of disposal and/or treatment sites for contaminated sediments may be the most controversial and time-consuming decision of the entire project. In fact, the public and agency acceptability of a project may be determined largely by this decision. In areas adjacent to urban waterways, land is a limited resource. It is therefore recommended that preliminary design begin with the identification of suitable lands. A technically feasible alternative without a site for implementation is of limited value.

***Information Requirements***--Specific types of information are required to prepare a preliminary design, evaluate its feasibility, and develop estimates of project costs and contaminant losses. A list of the most basic information required to initiate an evaluation of sediment remedial alternatives is provided in Table 2-3. Potential sources of historical information are also provided.

Additional information needed to evaluate the feasibility of specific technologies and estimate their costs and contaminant losses is discussed in subsequent chapters on each technology type. To obtain this information may require analysis of the physical and engineering properties of sediments, bench- or pilot-scale evaluations of treatment and/or pretreatment technologies, laboratory tests to determine contaminant losses, laboratory tests that simulate dewatering and residue treatment, and surveys and geotechnical explorations of lands to be used. Some of these data collection activities may be postponed until the detailed design phase of the project. Best professional judgment must be exercised in making this decision.

### Implementation

Ideally, more than one remedial alternative will be identified that is feasible and meets the project objectives. In this case, the project proponent must decide which alternative to recommend and support. The implementation of the selected remedial alternative may involve a number of activities, including:

- Securing funding

- ✍ Development of detailed design, plans, and specifications
- ✍ Acquiring real estate and rights-of-way
- ✍ Obtaining appropriate permits
- ✍ Contract advertisement, negotiation, and award
- ✍ Construction, operation, and maintenance

These activities are discussed briefly below.

***Funding***--While discussion of the sources and methods for securing funding for implementation is beyond the scope of this guidance document, a few consequences of the timing of funding are worth mentioning. For large remediation projects, funding may not be available all at one time but in increments, perhaps coinciding with budgetary cycles. It may therefore be appropriate to plan the implementation of remediation in increments. The challenge is to divide the project into increments that can stand alone from environmental and engineering feasibility perspectives should the next funding increment be delayed or unavailable. For additional information on funding opportunities for RAP activities, the reader is referred to the series of Apogee Research, Inc. reports on this subject (Apogee Research, Inc. 1992a,b, 1993a,b).

***Detailed Design***--This step of implementation involves the detailed design of the remedial alternative and preparation of plans and specifications for construction. During this step, extensive data collection may be conducted, including pilot- or full-scale testing of process equipment, detailed surveys, and geotechnical explorations of lands to be acquired. It is not uncommon for significant changes in the project design to occur at this stage as a result of the new data collected and the application of more sophisticated design analytical methods. It is quite possible that the alternative recommended by the preliminary design/feasibility study is determined to be infeasible. By the completion of this step, virtually every aspect of the construction and operation of the remedial alternative should be designed and thoroughly reviewed to ensure the technical accuracy and engineering feasibility of the alternative.

***Real Estate***--The acquisition of real estate, easements, and rights-of-way for project construction and operation need to be completed before a construction contract is advertised. These acquisitions may include land for pretreatment, treatment, and disposal operations; easements for an area to mobilize dredging equipment; or a right-of-way for construction equipment and sediment transportation. Easements or rights-of-way may also have to be obtained from riparian property owners along the waterway.

***Permits***--Applicable permits and certifications for project construction and operation should be obtained before a construction contract is advertised. A detailed discussion of the legal and regulatory requirements for sediment remediation is provided later in this chapter.

***Contracting***--Contracting mechanisms and regulations are organization-specific and are beyond the scope of this guidance document. Parts of the remediation project, or the entire effort, may be contracted. Superfund remedial planning and design are often contracted separately from the remediation construction. The most common contracting approach for remediation construction is to advertise the entire remediation project as a single contract for a turn-key operation. In this case, a prime contractor would be responsible for obtaining the necessary subcontractors with the specialized equipment or experience required. An alternative approach is for the project proponent to purchase some of the equipment and contract for its operation. This approach may be advantageous if the project is large and must be conducted in a number of operational cycles, or if there are several project areas that can be remediated using the same equipment. Modifications are often required in the design and operation of a project after construction has been initiated because of changes in site conditions, changes in materials, or the failure of a component to operate as expected. These design and operational modifications should always be coordinated with the designers and with regulatory agencies.

***Construction, Operation, and Maintenance***--These activities are discussed in detail in Chapter 10.

## ESTIMATING PROJECT COSTS

This section discusses the development of cost estimates for sediment remedial alternatives to support the decision-making and implementation processes. There is no existing guidance on estimating costs specifically for sediment remediation projects; however, there is considerable guidance on estimating costs for general construction and some guidance for hazardous waste remediation projects. This discussion presents the cost estimating procedures used by the Corps for civil works projects and those used by the USEPA for Superfund projects. The appropriate guidance for most sediment remediation projects would include a combination of these approaches. Additional guidance for estimating the costs of specific components of sediment remedial alternatives is provided in subsequent chapters of this document.

## Purpose of Cost Estimates

Project cost estimates are required during all phases of a sediment remediation project, from initial planning, through detailed design, and during construction and operation. The purpose of the cost estimates will change as the project progresses. During the planning stages, cost estimates are used as a criterion for screening technologies and selecting the preferred alternative. At the detailed design stage, cost estimates are often used to compare technically equivalent features and identify those that may be suitable for value engineering (VE) studies. Following detailed design and preparation of plans and specifications, cost estimates are used to evaluate bids on project construction and operation. During construction, cost estimates are used for scheduling payments, contract negotiation, and dispute resolution.

The reliability of a cost estimate depends largely on the level of detail available at the time it is prepared. It also depends on the predictability of variables and factors used to develop the cost estimate. A thorough knowledge and understanding of the scope of work and all components associated with site remediation is necessary for the development of a reliable cost estimate, including a clear understanding of the construction operations and techniques that would be used.

Cost estimates should complement the decision path. For civil works projects, such as maintenance dredging, there are two types of cost estimates in the decision-making process: the current working estimate and the government estimate. The current working estimate is an estimate that is prepared and updated periodically during the planning and design of a project. The level of detail and reliability of this estimate reflect the current state of project evaluation and design (USACE 1980c). The current working estimate is a total project cost estimate, which includes all reasonable costs that will be required during project implementation (i.e., the estimated costs of construction and operation contracts, engineering and design efforts, construction management and real estate easements, and land acquisition). The current working estimate is used as a tool to support the decision-making process and control costs, and should be prepared with as much accuracy as possible, so that the total project cost estimate for site remediation can be relied upon at the earliest possible stage in the decision-making process.

For virtually all projects that are funded by the Federal government, and for most projects funded by other governmental agencies, a government estimate or equivalent is developed at the end of detailed design and immediately prior to the advertisement of the contract(s) for construction and operation (USACE 1982). The government estimate is used to evaluate construction contract bids, control negotiations, establish a pricing objective for procurement and contracting purposes, and serve as a guide in developing progress payment schedules. It is a detailed construction cost estimate and does not include the other noncontract items of the current working estimate. The development of a government estimate for a Federal project must follow the procedures and guidelines of the Federal Acquisition Regulation (FAR) (48 CFR Chapters 1-99).

## Elements of a Cost Estimate

A sediment remediation project has capital, operation, and maintenance costs. Capital costs include expenditures that are initially incurred to develop and implement a remedial action (e.g., dredging and transportation, construction and operation of a treatment system, construction of a disposal facility) and major capital expenditures anticipated in future years (e.g., capping a confined disposal facility [CDF] or decontamination of treatment equipment) (Burgher et al. 1987). The following elements should be considered in developing estimates of capital costs (Cullinane et al. 1986a; Burgher et al. 1987):

- Relocation costs
- Costs of lands, easements, and rights-of-way
- Land and site development costs
- Costs for buildings and services
- Equipment costs
- Replacement costs
- Disposal costs
- Engineering expenses
- Construction expenses
- Legal fees, licenses, and permits
- Contingency allowances
- Startup and shakedown costs
- Costs of health and safety requirements during construction

Operation and maintenance are post-construction activities needed to ensure the effectiveness of a remedial action (Burgher et al. 1987). These activities might include treatment plant operations, surface water and leachate management at a disposal facility, and monitoring and routine maintenance at disposal sites. The following elements should be considered in developing estimates of operation and maintenance costs (Cullinane et al. 1986a; Burgher et al. 1987):

- Operating labor costs
- Maintenance materials and labor costs
- Costs of auxiliary materials and energy
- Purchased service costs
- Administrative costs
- Insurance, taxes, and licensing costs
- Maintenance reserve and contingency fund

The capital, operation, and maintenance cost data needed for preparing estimates are divided into two categories, direct costs and indirect costs. The direct costs are those that are directly attributable to a unit of work. They are generally referred to as labor, equipment, and material/supply costs. The labor rate, equipment rate, and material/supply quotes are readily available from many sources, some of which are discussed in later chapters. However, production rates, hours of work, size of crew, selection of equipment and treatment plants, and schedules are estimated largely from site-specific data.

There are some differences between the civil works and Superfund guidance for estimating indirect costs. The Corps approach considers indirect costs, sometimes referred to as distributed costs, to include all costs that are not directly attributable to a unit of work, but are required for the project. These costs might include field office and home office operations, permits, and insurance. The USEPA guidance for hazardous waste remediation (Burgher et al. 1987) includes these costs, plus engineering expenses, startup/shakedown costs, and contingency allowances, as indirect costs. Indirect costs are typically estimated as a fixed percentage of the total direct costs.

For preliminary cost estimates, indirect costs (as defined by the Corps) may be estimated as 10-15 percent of direct costs. The USEPA guidance (Burgher et al. 1987) offers the following numbers for estimating specific indirect costs:

- Engineering expenses (7-15 percent of direct capital costs)
- Legal fees, licenses, and permits (1-5 percent of total project costs)
- Startup and shakedown costs (5-20 percent of capital costs)
- Contingency allowances (15-25 percent of total capital costs)

When screening-level construction cost estimates are prepared, there are generally few details available that would warrant a detailed analysis of direct and indirect costs; total unit price data are often used instead. However, when a detailed construction cost estimate is required in the later stages of design and implementation, direct and indirect cost data are estimated separately.

The level of confidence of a cost estimate depends on the level of detail available at the time it is prepared. One method to improve the confidence in the cost estimate is to assess and include appropriate contingencies in the estimate. A contingency is a form of allowance to cover unknowns, uncertainties, and/or unanticipated conditions that are not possible to adequately evaluate from the available data. Computer software, such as HAZRISK (Diekmann 1993) and REP/PC (Decision Sciences Corp. 1992), is available to perform a more formal assessment and assign contingencies. If these programs are not available, the contingency rates shown in Table 2-4 may be used instead. These rates are empirical and are only a guide. USEPA contingency allowances for feasibility studies (between 15 and 25 percent of capital costs) are in general agreement with the numbers shown in Table 2-4.

## Development of Cost Estimates

### Technology Screening

Cost estimates are one of the criteria used to screen remediation technologies for further consideration. The screening cost analysis for an RI/FS investigation involves order-of-magnitude costs to eliminate alternatives with costs that are 10 times or higher than costs for other alternatives (Burgher et al. 1987). The accuracy of costs at the screening level for RI/FS investigations should be between +100 and -50 percent (Burgher et al. 1987).

At the screening level, the project cost analysis is very crude and limited to available information on the sediments, site conditions, and technologies being considered. Because the level of detail is minimal at this phase, historical data and parameters of similar past projects are recommended for the development of the cost estimate. Substantial amounts of historical cost data for some components of sediment remediation (i.e., removal, transport, disposal, and residue management) are available and are summarized in later chapters of this document. The USEPA has developed a Remedial Action Cost Compendium (Yang et al. 1987) that shows the range of actual costs at Superfund projects.

Historical cost data on the pretreatment and treatment components are very limited, and in some cases the only data available are projections made by technology vendors based on bench- or pilot-scale applications. Cost projections for technologies that do not already have full-scale equipment with some operating history should be approached with a certain amount of skepticism. One of the major factors in the cost of many innovative treatment technologies is the investment required for the development, scaleup, construction, and testing of full-scale equipment. The amortization of these development costs greatly affects their unit costs and the degree of uncertainty associated with those costs. Very few remediation projects are able to bear these development costs alone, and few companies are willing to make this investment unless there is a clear indication that there will be a dependable market for the technology at several remediation sites. One potential solution to this handicap is for interests from several AOCs having similar sediment contamination problems to join forces in financing the development or acquisition of a remediation technology.

### *Preliminary Design*

During the preliminary design phase, a limited number of remedial alternatives are evaluated in sufficient detail to make a selection for implementation. This phase is comparable to the feasibility study for Superfund projects. The preliminary design should contain sufficient engineering and design information that could readily lead into the next phase (the detailed design). The cost estimate should be prepared based on the latest information available and should include all reasonable costs required in the implementation phase. The estimate should incorporate costs for additional engineering and design, real estate easements and land acquisition, and construction costs. This cost estimate will serve as a baseline current working estimate for project management through the implementation phase.

The process for evaluating costs during a Superfund feasibility study includes the following steps (Burgher et al. 1987):

- Estimation of costs
- Present worth analysis
- Sensitivity analysis
- Input to alternatives analysis

The accuracy of cost estimates for feasibility studies for Superfund projects should be within the range of +50 to -30 percent (Burgher et al. 1987).

### *Implementation*

This phase should include preparation of a detailed design and the plans and specifications for contracting the construction and operation of the remedial alternative. During the detailed design, cost estimates can be used to compare technically equivalent features in a process known as VE. VE is directed at analyzing the function of construction, equipment, and supplies for the purpose of achieving these functions at reduced life-cycle cost without sacrificing quality, aesthetics, or operations and maintenance capability (USACE 1987f).

During the development of plans and specifications, a detailed government estimate is prepared. This government estimate is used to evaluate bids on project construction and operation contracts. Bids are evaluated for balance as well as dollar amount. Corps regulations for civil works projects will not allow a contract award if the low bid exceeds the government estimate by more than 25 percent. During construction, cost estimates are used for scheduling payments, contract negotiations, and dispute resolution.

## Sources of Information

The accuracy of a cost estimate depends on the reliability of the information used in its development. For some of the components of a sediment remedial alternative there are a large number of sources of cost data available. A list of a few sources that could be consulted for cost estimates is shown in Table 2-5.

Construction costs may vary significantly from one region of the country to another. To convert approximate costs, area adjustment factors may be applied. Some Federal agencies, such as the U.S. Departments of Labor and Energy, maintain regional cost information. The Corps maintains a Civil Works Construction Cost Index System (CWCCIS), which may be used as a guide for regional construction cost adjustments.

Several computer software programs have been developed for cost estimating and are in general use. The Corps has developed a Micro-Computer Aided Cost Engineering System (MCACES) that is being used worldwide for construction cost engineering. This software is available commercially from Building Systems Design (1992). The U.S. Department of Energy has developed a summary of available cost estimating software applicable to environmental remediation projects (Youngblood and Booth 1992), and the reader is referred to this document for more information on how to obtain these software packages. Software has been developed by or for the USEPA (CORA and RACES), the U.S. Air Force (ENVEST and RACER), and the U.S. Department of Energy (FAST, MEPAS, and RAAS). If computer software is not available, manual estimating techniques are readily available (USACE 1980c, 1982).

Cost information provided on sediment remediation technologies in this document has been adjusted to January 1993 price levels using the indices in the *Engineering News Record* (ENR).

## ESTIMATING CONTAMINANT LOSSES

No remedial alternative for contaminated sediments is without some environmental consequence. The balancing of environmental benefit vs. cost is a critical part of the evaluation of sediment remedial alternatives. Ideally, the alternative that maximizes this benefit:cost relationship would be selected. However, the costs, as well as social, legal, and political considerations, all have important roles in the final decision.

Environmental damages and benefits are not easy to quantify in measures that are readily comparable. Risk assessment is one of the methods to quantify the environmental effects of a project or condition. Risk assessment procedures determine the potential harm caused by exposing humans or other organisms to contaminants. Contaminant exposures may be measured directly or predicted using mathematical models, and may occur through various media (e.g., air, water, solids, biota) and exposure routes (e.g., inhalation, ingestion, dermal contact). A detailed discussion of risk assessment and modeling in relation to contaminated sediment remediation is provided in the *ARCS Risk Assessment and Modeling Overview Document* (USEPA 1993a).

To evaluate risks to human health or the environment, the exposure conditions must be fully characterized. To use mathematical models to predict the exposure conditions, the loadings of contaminants must be estimated and used as input to the model(s). The losses of contaminants from sediment remedial alternatives may be estimated through a number of techniques that were evaluated by the ARCS Program.

### Contaminant Loss Pathways

Contaminant loss is the movement or release of a contaminant from a remediation component into an uncontrolled environment. Examples of loss include spillage or leakage during dredging and transport, seepage from a capped *in situ* site or from a CDF, and residual contamination in the treated discharges from a disposal facility or sediment treatment unit. Contaminants that remain within a controlled area or process stream, or are modified or destroyed by a process, are not considered losses. The term loss is reserved for the uncontrollable or unintentional discharge of contaminants.

Contaminant loss can occur during each component of a sediment remedial alternative through one or more pathways. For example, the potential pathways for contaminant loss from a CDF include surface runoff, effluent, seepage, leachate, volatilization, dust, and uptake by plants and animals (Figure 2-6). The contaminant loss from a component is the sum of the individual losses through the various pathways, and the contaminant loss from a remedial alternative is the sum of the losses from each component.

The magnitude of contaminant loss may vary greatly between remedial components and pathways and is influenced by the type of contaminant being considered. The losses through one pathway may be thousands or hundreds of thousands of times greater than the losses through other pathways in the same component. The losses through some pathways or from some components may be considered insignificant for specific evaluations. As a result, it is worthwhile to assess the relative importance of different pathways of contaminant loss before proceeding with detailed estimates. The contaminant losses discussed in this document are not meant to be the final determinant in the complete environmental efficacy of a particular sediment remedial alternative, however. The losses are intended to be used as loadings in the implementation of a contaminant fate model as described in the *ARCS Risk Assessment and Modeling Overview Document* (USEPA 1993a).

### Estimating Techniques

A detailed investigation of contaminant losses from sediment remediation components was conducted for the ARCS Program (Myers et al., in prep.). This study identified contaminant migration pathways, examined existing predictive techniques for estimating contaminant losses, and evaluated their applicability and reliability. ***This study (Myers et al., in prep.) should be used as the primary reference for developing contaminant loss estimates for sediment remedial alternatives.*** Key points from this study are summarized below.

Predictive techniques for estimating contaminant losses generally fall into one of two categories: *a priori* techniques and techniques based on pathway-specific laboratory testing. *A priori* techniques are suitable for planning-level assessments. Techniques that use pathway-specific test data provide state-of-the-art loss estimates.

The state of development of predictive techniques for estimating contaminant losses from remediation components varies with the component and the loss pathways. For some remediation components there are no pathway-specific tests available. In these cases, *a priori* techniques may be the only techniques available; however, *a priori* techniques are not always available for all pathways of all components.

The confidence and accuracy of the contaminant loss estimates depend on the state of development and the amount of field verification data available. In some cases, there may be a substantial amount of field data available, but predictive techniques are not designed to produce data that are directly comparable to field data. In this case, confidence is low and accuracy is unknown. For the prediction of contaminant losses during dredging, field data on turbidity and suspended solids downstream of dredging operations may be available; however, predictive techniques are used to estimate contaminant flux in the water column at the point of dredging. In some cases, predictive techniques (e.g., prediction of leachate losses) have a sound theoretical basis, but few field verification data exist. In this case, confidence is high and accuracy is unknown.

### *Losses During Dredging*

Predictive techniques for sediment losses during hydraulic and mechanical dredging are available for conventional dredging equipment. Predictive techniques are not available for innovative dredging equipment options. The available predictive techniques provide estimates of sediment losses in terms of mass loss per time at the point of dredging. Exposure concentrations are not estimated. To estimate exposure concentrations, the predicted fluxes of sediments and the associated chemical contaminants must be incorporated into water quality or exposure assessment models. Techniques for estimating contaminant losses during dredging are still in the early development stage. Techniques have been proposed, but field validation data are scarce. The available techniques are inherently *a priori*, although laboratory tests have been considered. Efforts are ongoing in the Great Lakes to develop predictive techniques for estimating contaminant losses during dredging, at the point of dredging. As previously discussed, confidence is low for the prediction of losses during dredging, and accuracy is unknown.

### *Losses During Transportation*

Techniques for estimating losses of sediments and the associated chemical contaminants during the transportation of dredged material are not available for most transportation modes. Pipeline breaks, scow spillage, and truck accidents can be expected to occur, but the frequency of such occurrences associated with dredged material transportation has not been documented, and there has been little effort to quantify the associated losses. Predictive techniques for losses from scows due to volatilization of contaminants are available, but have not been field verified.

### *Losses During Treatment*

The limited database for treatment of contaminated sediments and the strong influence of sediment characteristics on treatability preclude the use of *a priori* loss estimates for most treatment technologies. Laboratory techniques are available for estimating losses for most treatment technologies. Most treatment technologies will generate waste streams that, unless decontaminated, constitute a loss pathway. Even destruction technologies will have some estimable loss because no treatment process is perfect. Treatment process losses can be in the form of contaminated solid residuals requiring disposal (with attendant losses) or in the form of contaminated fluids. Fluid losses include gaseous emissions, discharged process wastewater, and other liquid releases.

Predictive techniques for contaminant losses during treatment are based on a materials balance of the process treatment train. A process flow chart should identify waste streams through which contaminants can escape treatment or control. However, detailed information is not usually available until after treatability studies have been completed. The technical basis for using data from treatability studies to estimate contaminant losses is well developed, but there are few verification data for full-scale dredged material treatment processes.

Loss estimates based on treatability studies are anticipated to be reliable and accurate. A high degree of confidence is expected for those treatability studies with good materials balance. If the materials balance is poor, then confidence will be low.

### *Losses During Disposal*

Predictive techniques are available for most of the key pathways by which contaminants are lost from CDFs and confined aquatic disposal sites. Predictive techniques vary in their stage of development, depending on the disposal alternative and pathway. *A priori* techniques are available for estimating losses from confined aquatic disposal sites; however, there are few field verification data for these techniques. *A priori* and test-based techniques for estimating effluent losses during hydraulic filling of confined disposal sites are well developed, but techniques for estimating losses during mechanical disposal at in-water and nearshore CDFs are more crude and have only been conducted at a few sites (USACE Chicago District 1986).

Scientifically sound *a priori* and test-based techniques are available for estimating losses from CDFs by leaching. Predictive techniques for leachate loss have not been field verified. Well-developed, test-based techniques are available for estimating runoff losses at CDFs, but there are no *a priori* predictive techniques available for runoff. The only predictive techniques available for estimating volatile losses from CDFs are *a priori* techniques. Estimation techniques for volatile losses from dredged material are available, but have not been field verified.

Confidence and accuracy for *a priori* loss estimates from CDFs and confined aquatic disposal sites are low. Confidence and accuracy for test-based loss estimates vary with the stage of development of the test and interpretation procedures. Confidence and accuracy are high for estimating effluent loss during hydraulic filling of CDFs. Confidence is high for test-based estimates of leachate losses, but accuracy is unknown. Confidence and accuracy are high for estimation of test-based runoff loss.

## Preparing Loss Estimates

### *Level of Effort Required*

*A priori* techniques require less effort than the test-based techniques for estimating contaminant losses. The computational frameworks for both types of techniques are similar so that computations performed using *a priori* techniques usually do not have to be reconstructed for the test-based techniques. The major difference in effort is the time and money required for test-based loss estimates. *A priori* loss estimates can be used to guide resource allocation for pathway- and remediation component-specific testing.

Most *a priori* techniques can be implemented using spreadsheet software for desktop computers. Some aspects of leachate loss estimation require running the Hydrologic Evaluation of Landfill Performance (HELP) computer model (Schroeder et al. 1984). This model runs on desktop computers and is required for both *a priori* and test-based estimates of leachate losses. Obtaining appropriate coefficients for the *a priori* equations can be a significant effort. A standardized default database for model coefficients is not currently available.

Test-based predictive techniques require substantial time and money if a full suite of tests are conducted. Resource requirements are relatively small for some key pathways such as effluent losses. Other pathways, such as runoff losses, currently require a large volume of sediments and the tests take several months to complete.

### *Type of Data Required*

The minimum data required for most *a priori* techniques are bulk sediment chemistry and project-specific design information. The project-specific design information needs are numerous, but this information is usually available at the preliminary design phase. For CDFs, for example, a dredging schedule, dredge production rates, site geometry, foundation conditions, dike design, disposal mode (hydraulic or mechanical), and other similar types of information are needed.

For remedial alternatives involving treatment, data from bench- or pilot-scale treatability studies are needed. If sediment-specific treatability data are not available, the data for a similar sediment and treatment process can be used. Pilot-scale data should be considered, if available. Information on anticipated processing rates and pretreatment and/or storage facility designs will also be needed.

Protocols for pathway-specific tests identify data requirements. A complete program for estimating contaminant losses for an array of alternatives and components should be carefully planned and coordinated to reduce replication of effort and ensure comparability among the various pathways evaluated.

## REGULATORY AND LEGAL CONSIDERATIONS

When conducting a sediment remediation project, it may be necessary to obtain various permits or certifications as required by existing environmental laws and regulations, from appropriate Federal, State, or local agencies. For example, permits may be required for specific remedial activities or for discharges that may result from these activities. A summary of activities and discharges that may require a permit or other form of authorization under Federal law are listed in Table 2-6.

The discussion that follows focuses on Federal environmental regulations. For some of these regulations, the permitting and enforcement authority has been transferred or delegated to the State. In addition, many states have other laws and regulations that may be applicable to one or more sediment remediation activities. The regulations discussed herein and listed in Table 2-6 are not all inclusive, and the proponent of a sediment remediation project should ensure that the requirements of all applicable Federal, State, and local laws and regulations are addressed.

## Construction in Waterways

Any structure or work that affects the course, capacity, or condition of a navigable water of the United States must be permitted under section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 403). This permit program is managed by the Corps, and the regulations addressing this program are contained in 33 CFR Parts 320-330 (Regulatory Programs of the Corps of Engineers). Activities associated with a particular sediment remedial alternative that would likely require a section 10 permit include the placement of an *in situ* cap on contaminated sediments in a waterway, dredging activities, the mooring of vessels, and the construction of any structure in the waterway. Permits issued under the authority of section 10 of the Rivers and Harbors Act of 1899 and section 404 of the Clean Water Act (see below) are typically handled concurrently by Corps district offices. The Corps coordinates section 10 permits with the U.S. Coast Guard, which issues a notice to navigation of when and where the construction activities will take place.

Any development activities in an approved State coastal zone must be consistent to the maximum extent practicable with the State plan developed under the Coastal Zone Management Act of 1972 (16 U.S.C. section 1455b et. seq.). Federal funds for Coastal Zone Management (CZM) plan development are administered by the National Oceanic and Atmospheric Administration (NOAA). Activities associated with a sediment remediation project likely to require a CZM consistency determination by the State include dredging, *in situ* capping, and construction and operation in the coastal zone of facilities for sediment rehandling, treatment, and disposal. Four Great Lakes states (Michigan, New York, Pennsylvania, and Wisconsin) have approved CZM plans.

## Discharge of Dredged or Fill Materials

The disposal of dredged or fill materials to waters of the United States is regulated under the Clean Water Act (33 U.S.C. section 1251 et. seq.). Clean Water Act section 404 in particular designates the Corps as the lead Federal agency in the regulation of dredged and fill discharges, using guidelines developed by the USEPA in conjunction with the Corps. Regulations addressing this permit program are again contained in 33 CFR Parts 320-330 (Regulatory Programs of the Corps of Engineers). Activities associated with a particular sediment remedial alternative that would likely require a permit under Clean Water Act section 404 authority include the placement of an *in situ* cap on contaminated sediments in a waterway or wetland, the discharge of any dredged sediments or treatment residues into a waterway or wetland, and the discharge of effluent, runoff, or leachate from a disposal facility for sediments.

As noted above, Clean Water Act section 404 permits for the disposal of dredged or fill materials into waters of the United States are issued through Corps district offices. Some nationwide and regional permits have been issued to cover specific types of discharges. Only one state (Michigan) has been delegated Clean Water Act section 404 permitting responsibilities as provided under Clean Water Act section 404(g). Permit applicants must provide sufficient information for the permitting office to complete an evaluation of the discharge under the authority of section 404(b)(1) of the Clean Water Act. The Clean Water Act section 404(b)(1) evaluation considers the overall impacts of the proposed discharge, including ecological, social, and economic effects.

Finally, Clean Water Act section 401 authorizes states to issue a water-quality certification for proposed dredged and fill disposal activities. Issuance of this certification indicates that the proposed dredged or fill disposal will not violate State water quality standards, after allowance for dilution and dispersion of contaminants. A dredged or fill discharge section 404 permit may not be processed without a Clean Water Act section 401 certification or waiver.

## Discharges of Water

Water discharges resulting from a sediment remedial alternative may be regulated under various sections of the Clean Water Act. The administration of regulations developed pursuant to the Clean Water Act is the responsibility of the USEPA, the Corps, or the State, depending on the applicable section of the act.

Clean Water Act section 307 directed the USEPA to develop pretreatment standards for industries. The National Pretreatment Program was subsequently established to ensure that major industrial and commercial users of municipal sewer systems pretreat their discharges so that the discharges from publicly owned treatment works remain in compliance with their discharge permits. Technology-based standards were developed by the USEPA (40 CFR 403) to be implemented at municipal publicly owned treatment works.

The responsibility for the administration of the pretreatment program has been delegated by the USEPA to four of the Great Lakes states (Michigan, Minnesota, Ohio, and Wisconsin). Local municipalities and sanitary districts are responsible for the management of pretreatment programs for their wastewater systems and must issue pretreatment permits to significant users. One activity associated with a sediment remedial alternative that could require a pretreatment permit would be a discharge of water from a sediment disposal facility or treatment system into a municipal wastewater treatment facility through a sanitary sewer.

Clean Water Act section section 404 and 401 apply to the discharge of effluent, runoff, or leachate from a disposal facility for sediments. These regulations were discussed above.

Clean Water Act section 402 is the National Pollutant Discharge Elimination System (NPDES). This is the principal program for the regulation of point-source discharges of pollutants and is managed by the USEPA. The responsibility for NPDES permitting has been delegated by the USEPA to all of the Great Lakes states (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin). Activities associated with a sediment remedial alternative that would likely require an NPDES permit include a continuous point-source discharge of water from a sediment treatment system and the storm water discharge from a sediment disposal or treatment site. As discussed above, the discharge of water from a dredged material disposal facility is regulated under Clean Water Act section section 404 and 401. The USEPA Region 5 has stated that a point-source discharge of leachate from a CDF should be regulated under the NPDES program.

Storm water discharges from disposal and treatment sites during initial construction would also be regulated under the NPDES program. Most states have general permits that may cover these construction activities. The storm water runoff inside an operating CDF or treatment site would most likely have to be captured, routed, and treated before discharge. This runoff might be combined with other water discharges from pretreatment and treatment processes or effluent or leachate collection. In this case, the storm water discharge would be regulated as part of these other discharges under the NPDES program or section section 404 or 401 of the Clean Water Act.

## Solid Waste Disposal

The Resource Conservation and Recovery Act (RCRA; 42 U.S.C. section 6901 et. seq.) broadly defines solid waste as:

> . . . any garbage, refuse, sludge from a waste treatment plant, water supply plant or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities, but does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges which are point sources subject to permits under section 402 of the Federal Water Pollution Control Act, or source, special nuclear, or byproduct material as defined by the Atomic Energy Act of 1954, as amended.

Subtitle D of RCRA authorizes states to issue solid waste disposal permits. As illustrated above, the RCRA definition of solid waste is very general, and few states have regulations that specifically identify sediments or dredged material as a category or class of solid waste. The Corps has a policy that dredged material is not a solid waste and is not subject to solid waste regulations. However, some Federal and State agencies do not concur with this policy. As a result, the application of solid waste regulations to contaminated sediments is still open to question.

A technical framework for designing disposal facilities for dredged material has been developed jointly by the Corps and USEPA and is discussed in Chapter 8 (USACE/USEPA 1992). This framework identifies potential pathways for contaminant loss and migration and uses testing procedures developed specifically for sediments to evaluate the contaminant losses or impacts through these pathways. Environmental controls, such as barriers, caps/covers, and leachate collection systems are used only when sediment-specific testing and site-specific evaluation demonstrate a need. This strategy is quite different from the minimum technology approach that is used under RCRA and most State solid waste regulations. The minimum facility requirements for solid waste disposal identified in RCRA (40 CFR 257-258) were structured for municipal solid waste. These requirements include a minimum design for liners, caps, and leachate collection. They also include restrictions on disposal of liquids in landfills that may be difficult to apply directly to dredged sediments containing substantial amounts of water.

Because of the uncertainty about the applicability of State solid waste regulations to contaminated sediments, most disposal site designs will reflect a compromise between a sediment-specific design and the design dictated by a State's municipal solid waste requirements.

## Hazardous and Toxic Waste Disposal

RCRA and the Toxic Substances Control Act (TSCA; 15 U.S.C section 2601 et. seq.) provide for the regulation of materials that are classified as hazardous and toxic, respectively. Regulations developed pursuant to RCRA address the storage, treatment, and disposal of hazardous wastes (40 CFR 260-270). The USEPA is responsible for the administration of RCRA and has established three lists of hazardous wastes under Subtitle C. If a waste is not listed as hazardous, it may still be covered by RCRA if it exhibits one of four hazardous waste characteristics: ignitability, corrosivity, reactivity, or toxicity.

A low percentage of contaminated sediments will meet the regulatory definitions of hazardous or toxic materials. In some remediation projects, isolated areas or hot spots of sediments containing TSCA- or RCRA-regulated materials may be located and require different handling than the remainder of the less-contaminated sediments. Contaminated sediments, except for sediments and sludges from specific industrial processes, are not listed as hazardous wastes under RCRA. The USEPA policy is that sediments containing one or more listed hazardous wastes require handling as a hazardous waste. The Corps policy is that dredged material is not a solid waste and is not subject to RCRA regulations. As a result of this policy disagreement, there is some confusion about the application of RCRA regulations to contaminated sediments. The USEPA Region 5 and the Corps are currently preparing guidance for the construction of disposal facilities for contaminated sediments that will address the regulatory intent of RCRA and TSCA.

Sediment remedial activities that might require a RCRA permit include the storage, treatment, and disposal of contaminated sediments (or the residue from a pretreatment or treatment process) that are defined or characterized as hazardous under RCRA. The owner/operator of a facility that generates RCRA-hazardous materials must obtain a permit. States are delegated RCRA permitting authority by the USEPA in a piecemeal fashion as the State regulations are adopted. Some Great Lakes states do not have the authority to issue RCRA corrective actions.

RCRA and its amendments include a ban on the land disposal of specific wastes (including dioxin), requiring adequate treatment prior to land disposal. The design and operating requirements for a RCRA-hazardous landfill are defined in 40 CFR 264, Subpart N and in USEPA (1989d).

TSCA regulates the manufacture, use, distribution, handling, and disposal of a very limited number of materials defined as toxic substances. In effect, this Act regulates the disposal of only two substances, asbestos and polychlorinated biphenyls (PCBs). The latter of these is generally more relevant to contaminated sediment remediation. TSCA is applicable to any material, specifically including dredged material, that contains 50 ppm or greater PCBs. Sediment remedial activities that are regulated under TSCA include the handling, transport, treatment, and disposal of a sediment or treatment residue that contains 50 ppm or greater PCBs.

TSCA is managed by the USEPA, and this authority cannot be delegated. TSCA regulations (40 CFR 761.60) specifically identify three disposal alternatives for PCB-contaminated sediments and municipal sewage sludges: incineration, disposal in a licensed chemical waste landfill (40 CFR 761.75), or other alternatives accepted by the USEPA Regional Administrator. Some states have additional regulations addressing PCB-contaminated materials independent of TSCA.

The permitting requirements of TSCA vary with the remediation technology to be applied. Some technologies have been preapproved for treatment of PCBs, and no additional permitting may be necessary. The remediation target for treatment technologies under TSCA is to reduce the levels of PCB contamination to less than 2 ppm.

## Atmospheric Discharges

The 1970 amendments to the Clean Air Act (44 U.S.C. section 7401 et. seq.) directed the USEPA to establish National Ambient Air Quality Standards (NAAQS) that would provide safe concentrations of specific pollutants. NAAQS have been established for six pollutants: sulfur dioxide, particulate matter, ozone, carbon monoxide, nitrogen dioxide, and lead. In addition, National Emission Standards for Hazardous Pollutants (NESHAPS) have been established for seven pollutants: beryllium, mercury, vinyl chloride, asbestos, benzene, radionuclides, and arsenic. The USEPA regulations for the air program are codified in 40 CFR 52-61.

Under the 1990 amendments to the Clean Air Act, 189 hazardous air pollutants are to be regulated. Sources of these pollutants will be identified and regulations developed according to source categories. These sources will be required to use the maximum achievable control technology. Maximum achievable control technology standards for air emissions from solid waste storage and disposal facilities are to be developed in 1994.

The development of discharge regulations and permitting of point-source emissions are the states' responsibilities. States are required to develop State implementation plans, which assess the extent of air quality degradation and include plans for meeting the NAAQS in nonattainment areas (areas that are not in compliance with the standards) and for maintaining the NAAQS is areas that are in compliance. Regional plans for improving air quality in nonattainment areas are typically developed and managed by county or municipal governments, in cooperation with State regulatory agencies. However, the USEPA can enforce an approved State implementation plan. Sediment remedial activities likely to be subject to these regulations would be the point-source emissions from a pretreatment or treatment process to the atmosphere. Area emissions from disposal facilities may become regulated in the near future.

## Health and Safety

The Occupational Safety and Health Act (OSHA; 29 U.S.C. section 651 et. seq.) authorized the Secretary of Labor to set mandatory occupational safety and health standards. The secretary directed OSHA to develop these standards and administer their compliance. OSHA has established minimum safety and health requirements for general construction (29 CFR 1926). The Corps has developed a *Safety and Health Requirements Manual* (USACE 1987e), which is used to assure that Corps personnel and contractors maintain compliance with OSHA regulations. These include requirements for personnel training, medical surveillance, allowable exposure limits, and personal protective equipment (PPE).

Section 126 of SARA directed that standards be developed to protect the health and safety of workers engaged in Superfund remediation activities. OSHA standards for hazard communication, set forth in 29 CFR 1910.1200, require employers to provide information to workers exposed to hazardous chemicals. This information consists of lists of all hazardous chemicals at the site (workplace) and material safety data sheets. Workers at sites with hazardous wastes are also required to be trained to recognize the health effects, proper handling, spill control, PPE, and emergency procedures.

## Environmental Assessments/Impact Statements

Section 309 of the 1970 amendments to the Clean Air Act and the NEPA of 1970 (42 U.S.C. section 4321 et. seq.) require preparation of a detailed statement when a Federal action may significantly impact the quality of the human environment. One of two types of NEPA documents must be prepared for any major Federal action: an environmental assessment (EA) or an environmental impact statement (EIS). The more detailed EIS is required when significant impacts to an important resource are anticipated.

The USEPA administers the NEPA program, but the agency that has the lead in the Federal action is responsible for preparing and coordinating the NEPA document. The NEPA document is filed with the USEPA, which publishes a notice of availability in the Federal Register.

A sediment remediation project conducted by a Federal agency or with Federal funds would require NEPA compliance. In addition, the issuance of a permit under a Federal regulatory program requires NEPA compliance. The permittee is required to provide the information and data required for a NEPA document to the permitting agency, which then prepares the EA or EIS.

## Other Regulations

There are many State and local regulations that may have to be addressed as part of a sediment remediation project. These regulations include, but are not limited to:

- Zoning ordinances
- Transportation restrictions
- Riparian authorities
- Right-of-way restrictions
- Utility easements
- Water withdrawal regulations
- Floodplain/floodway construction restrictions

The applicability of these and other State and local regulations would need to be addressed on a site-specific basis.

For example, the owners of properties adjacent to a waterway may have certain riparian rights, which can impact sediment remediation activities. These may include the rights to any lands or fill constructed in the waterway, the rights to water withdrawal, and the ownership of any materials below the ordinary high water mark. The riparian doctrine, a development of English common law, is followed in most Great Lakes states. The permission of all riparian owners would be required for virtually any sediment remedial alternative.

View the graphical version of this page at: http://www.epa.gov/grtlakes/arcs/EPA-905-B94-003/B94-003.ch2.html

**U.S. Environmental Protection Agency**

**Great Lakes Contaminated Sediments**

Recent Additions | Contact Us | Search: GO

EPA Home > Great Lakes > Monitoring > Sediments > ARCS > EPA-905-B94-003 (Remediation Guidance Document) Chapter 3

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 3. NONREMOVAL TECHNOLOGIES

Nonremoval technologies are those that involve the remediation of contaminated sediments *in situ* (i.e., in place). Nonremoval technologies for contaminated sediments include *in situ* capping, *in situ* containment, and *in situ* treatment.

Nonremoval technologies are single-component remedial alternatives. They do not require sediment removal, transport, or pretreatment. As a result, nonremoval technologies are often less complex and have lower costs than multicomponent alternatives (e.g., combinations of removal, transport, treatment, and disposal). In some cases (e.g., *in situ* treatment), nonremoval technologies may be similar to the treatment and disposal technologies used with dredged sediments.

This chapter provides descriptions of sediment remediation technologies that have been demonstrated, designed, or considered for application *in situ*. Discussions of the factors used to select from the available technology types and techniques for estimating costs and contaminant losses are also provided.

## DESCRIPTIONS OF TECHNOLOGIES

### *In situ* Capping

*In situ* capping is the placement of a covering or cap over an *in situ* deposit of contaminated sediment. The cap may be constructed of clean sediments, sand, or gravel, or may involve a more complex design using geotextiles, liners, and multiple layers. An annotated bibliography prepared for the Canadian Cleanup Fund (Zeman et al. 1992) summarizes most of the capping projects and studies that have been completed to date.

Capping is also a viable alternative for disposal of contaminated sediments that have been dredged and placed in another aquatic location (this type of capping is discussed in Chapter 8). Much of the technical information and guidance provided herein has been adapted from that developed for dredged material capping in ocean waters. The guidance provided in this section focuses on *in situ* capping of contaminated sediments in riverine and sheltered harbor environments such as those commonly found in the Great Lakes region.

A limited number of *in situ* capping operations have been accomplished in recent years under varying site conditions. *In situ* capping has been applied in riverine, nearshore, and estuarine settings. Conventional dredging and construction equipment and techniques can be used for *in situ* capping projects, but these practices must be precisely controlled. The success of projects to date and available monitoring data at several sites indicate that *in situ* capping may be an effective technique for long-term containment of contaminants.

*In situ* capping of contaminated sediments with sand has been demonstrated at a number of sites in Japan (Zeman et al. 1992). Demonstration projects conducted at Hiroshima Bay evaluated various types of placement equipment. More recent studies have examined the efficiency of sand caps in reducing the diffusion of nutrients.

At the Denny Way project in Puget Sound, a layer of sandy sediment was spread over a contaminated nearshore area, with water depths of 6 18 m, using bottom-dump barges with provisions for controlled opening and movement of the barges (Sumeri 1989). This was accomplished by slowly opening the conventional split-hull barge over a time frame of 30 60 minutes, allowing the gradual release of the material in a sprinkling manner. A tug was used to slowly move the barge laterally during the release, and the material was spread in a thin layer over the desired area.

At the Simpson-Tacoma Kraft mill project in Puget Sound, an *in situ* capping project involved spreading hydraulically dredged sediment with surface discharge through a spreading device (Sumeri 1989). Hydraulic placement is well-suited to placement of thin layers over large surface areas. Specialized equipment and placement techniques developed for dredged material capping and *in situ* capping are shown in Table 3-1 (Palermo 1991b).

*In situ* capping using an armoring layer has also been demonstrated at a Superfund site in Sheboygan Falls, Wisconsin. This project involved placement of a composite cap, with layers of gravel and geotextile, to cover PCB-contaminated sediments in the shallow water (<1.5 m) and floodway of the Sheboygan River. The cap was placed using land-based construction equipment and manual labor. A typical cross section of the *in situ* cap for this project is shown in Figure 3-1.

A variation of *in situ* capping would involve the removal of contaminated sediments to some depth, followed by capping the remaining sediments in place. This method is suitable when capping alone is not feasible because of hydraulic or navigation restrictions on the waterway depth. It may also be used where it is desirable to leave the deeper, more contaminated sediments capped in place (vertical stratification of sediment contaminants is common in many Great Lakes tributaries).

## ***In situ* Containment**

While *in situ* capping isolates the contaminated sediments from the water column immediately above the sediments, *in situ* containment involves the complete isolation of a portion of the waterway. Physical barriers used to isolate a portion of a waterway include sheetpile, cofferdams, and stone or earthen dikes. The isolated area can be used for the disposal of other contaminated sediments, treatment residues, or other fill material. The area may have to be modified to prevent contaminant migration (e.g., slurry walls, cap and cover).

Perhaps the largest sediment remediation project undertaken to date has been at Minamata Bay, Japan, where 58 hectares of the bay with the highest levels of mercury-contaminated sediments was isolated using cofferdams, and 1.5 million m[3] of contaminated sediments from other areas of the bay were hydraulically dredged and placed into the enclosed area (Hosokawa 1993). The contaminated sediments were capped with volcanic ash, sand, and geotextile, and the area has been filled to grade.

On a far smaller scale, remediation at the Waukegan Harbor Superfund site included the isolation of a boat slip containing the highest levels of PCB-contaminated sediments. The slip was isolated using a double bentonite-filled sheetpile cutoff wall across the open end and a bentonite slurry wall around the landward perimeter. About 15,000 m[3] of contaminated sediment was hydraulically dredged from other areas of the harbor, placed into the isolated slip, and capped with clay and topsoil. A series of drawdown wells were installed around the perimeter of the isolated slip, and will be operated indefinitely to maintain an inward hydraulic gradient.

## ***In situ* Treatment**

Some treatment technologies have been developed specifically for *in situ* application, while others have been adapted from *ex situ* treatment applications, including some of the technologies discussed in Chapter 7, *Treatment Technologies*. Most *in situ* treatment technologies could also be applied to sediments that have been dredged and placed in a disposal area.

*In situ* treatment has several limitations. One such limitation is the lack of process control. Process control is contingent upon effectively monitoring conditions at the site, typically by performing sampling and analysis at appropriate frequencies, before and after treatment. The efficacy of *in situ* treatment of sediments is difficult to determine because of the nonhomogeneous distribution of contaminants, sediment physical properties, and treatment chemicals. One of the limitations of *in situ* treatment is the difficulty in ensuring uniform dosages of chemical reagents or additives throughout the sediments to be treated. Areas of sediment within the site may receive varying levels of treatment, with some areas of sediment being untreated while others are overtreated relative to the intended treatment goal. *In situ* treatment may be less cost effective than *ex situ* treatment when these factors are considered.

Among the most significant limitations to *in situ* treatment is the impact of the process on the water column. Processes that would release contaminants, reagents, or heat, or produce other negative impacts on the overlying water column, are not likely to be acceptable for *in situ* sediment remediation. A suitable *in situ* treatment technology is, in most cases, one that can be applied with minimal disturbance of the sediment-water interface or one in which the process is physically isolated from the water column. There are two general methods of applying *in situ* treatment that address this limitation: surface application and isolation of the sediments prior to treatment. Several types of treatment processes might be used within these applications.

Surface application is the introduction of one or more materials (e.g., reagents, additives, nutrients) onto the sediments by spreading and settling, or injecting them into the sediments through tubes, pipes, or other devices. Researchers at the Canadian National Water Research Institute have developed and demonstrated equipment that is capable of injecting solutions of oxidizing chemicals into uncompacted sediments at a controlled rate (Murphy et al. 1993). A schematic of this apparatus is shown in Figure 3-2.

The second method for applying sediment treatment in place is by isolating the sediment from the surrounding environment. This method allows the use of reagents or process conditions that might otherwise cause deleterious effects to the waterway. Various types of equipment might be used for isolating the sediments, including a caisson, sheetpile cell, tube, or box. A hypothetical application using a sheetpile caisson is shown in Figure 3-3. Within the enclosing caisson, the water may be removed or left behind (if needed to support the process). One proprietary system (MecTool, Millgard Environmental Corp.) uses a bladder to isolate the sediments (and the treatment process) from the overlying water. Within the enclosed caisson, sediments can be mixed and treatment reagents can be added. After the treatment is completed, the caisson can be removed and reset at an adjacent area.

Three types of sediment treatment technologies that have been demonstrated or at least considered for *in situ* application will be discussed below: chemical, biological, and immobilization.

### ***In situ*** **Chemical Treatment**

Sediments in lakes and reservoirs have been treated *in situ* to control eutrophication or other conditions (USEPA 1990i). Aluminum sulfate (alum) has been used to control the release of phosphorus from bottom sediments and thereby limit algal growth (Kennedy and Cooke 1982). The alum is typically spread over a large area of the lake, and allowed to settle through the water column and deposit on the sediment surface. Alum treatment is recommended for lake restoration in well-buffered, hard-water lakes (USEPA 1990i).

The injection of calcium nitrate into sediments to promote the oxidation of organic matter has been demonstrated in conjunction with lime and ferric chloride additions to promote denitrification and phosphorus precipitation (USEPA 1990i). Calcium nitrate injection is discussed below as part of a bioremediation application.

A detailed discussion of treatment technologies for toxic contaminants is provided in Chapter 7. Perhaps because of the limitations associated with *in situ* treatment, development in this area of treatment has been limited.

### ***In situ*** **Biological Treatment**

Effective *in situ* bioremediation of fine-grained, saturated soils and sediments (as opposed to more porous groundwater aquifers or soils within the vadose zone) poses a major challenge. While delivery and transport of nutrient and electron acceptor amendments to and through groundwater aquifers is a demonstrated technology, movement of these materials through fine-grained sediments is difficult.

Contaminated sediments removed from the Sheboygan River Superfund site have been evaluated for biodegradation of PCBs in a confined treatment facility (CTF). These experiments as well as efforts to measure PCB dechlorination in sediments capped *in situ* in the Sheboygan River have been inconclusive as of early 1994.

A form of bioremediation has been demonstrated on PAH-contaminated sediments in Hamilton Harbor, Ontario (Murphy et al. 1993). Dissolved calcium nitrate was injected into sediments over 1.4 hectares using the system shown in Figure 3-2. The chemical injection oxidized about 80 percent of the hydrogen sulfide and stimulated the subsequent biodegradation of low molecular weight organic compounds (79-percent reduction). More moderate reductions in PAHs (25 percent) were shown.

### ***In situ*** **Immobilization**

Immobilization alters the sediment's physical and/or chemical characteristics to reduce the potential for contaminants to be released from the sediment to the surrounding environment (Myers and Zappi 1989). The principal environmental pathway affected by *in situ* immobilization for sediments is leaching of contaminants from the treated sediment to groundwater and/or surface water. Solidification/stabilization is a commonly used term that covers the immobilization technologies discussed herein.

Binders used to immobilize contaminants in sediment or soils include cements, pozzolans, and thermoplastics (Cullinane et al. 1986b). Many commercially available processes add proprietary reagents to the basic solidification process to improve effectiveness of the overall process or to target specific contaminants. The effectiveness of an immobilization process for a particular sediment is difficult to predict and can only be evaluated by laboratory tests conducted with that sediment.

*Ex situ* solidification/stabilization processes are readily implemented using conventional mixing equipment. However, injection of a reagent to achieve a complete and uniform mix with *in situ* sediments is considerably more difficult and has not been demonstrated on a large scale. Reagents for the solidification process can be injected into the sediment in a liquid or slurry form. Porous tubes are sometimes used to distribute the reagents to the required depth. Available commercial equipment includes a hollow drill with an injection point at the bottom of the shaft. The drill is advanced into the sediment to the desired depth. The chemical additive is then injected at low pressure to prevent excessive spreading and is blended with the sediment as the drill rotates. The treated sediment forms a solid vertical column. These solidified columns are overlapped by subsequent borings to ensure sufficient coverage of the area (USEPA 1990e). *In situ* solidification/stabilization has been demonstrated in sediments at Manitowoc Harbor in Wisconsin, where a cement/fly ash slurry was injected through a hollow-stem kelly bar using a proprietary mixing tool (MecTool) and slurry injector. This process formed treated vertical columns 6 ft (1.8 m) in diameter to a depth of 6 m below the river bed, using a 6x25-ft (1.8x7.6-m) steel cylinder placed 1.5 m into the sediments in 6 m of water (similar to the setup shown in Figure 3-3). This demonstration experienced difficulties in solidification of some sediments and management of liberated pore water (Fitzpatrick 1994).

## SELECTION FACTORS

The nonremoval technologies discussed in this section represent single-component remedial alternatives, and are not as comparable as different technology types or process options of a multicomponent alternative (e.g., different types of dredges). Most nonremoval technologies are in the development stage and have only been applied at a small scale at a limited number of sites. As a result, guidance on their feasibility, design, and implementation is very limited. Factors for selecting nonremoval technologies, shown in Table 3-2, are not intended for comparison purposes, but to screen these technologies for overall feasibility at a particular project site.

### *In situ* Capping

The primary technical considerations that affect the feasibility of *in situ* capping are the physical and hydraulic characteristics and the existing and future uses of the waterway. The suitability of *in situ* capping to a contaminated sediment site is less affected by the type or level of contaminants present, because it physically isolates the sediments and their associated contaminants.

The ideal area for *in situ* capping would be sheltered and not exposed to high erosive forces, such as currents, waves, or navigation propeller wash, or to upwelling from groundwater. Depending on the erosive forces present at a site, an *in situ* cap may have to be armored with stone or other material to keep the cap intact. Areas on five tributaries of the Great Lakes were examined under the ARCS Program in developing guidance on the hydraulic design of *in situ* caps (Maynord and Oswalt 1993). River currents were the dominant erosive force in only one of five areas. The scour caused by navigation (recreational as well as commercial) was the dominant force in the other areas studied. The potential scour caused by large commercial vessels would necessitate very large armor stone, making *in situ* capping difficult in or near most active navigation channels (Environmental Laboratory 1987; Maynord and Oswalt 1993).

For some waterways, *in situ* capping may not be consistent with local or regional plans for waterway use. For example, if a reach of a river with contaminated sediment deposits is already shallow, an *in situ* cap may further reduce water depths to levels that are not safe for existing and planned recreational boating. Removal of some contaminated sediments and *in situ* capping for the remaining portion may be an option in this case. In all cases, the construction of an *in situ* cap represents a deliberate modification to the morphology of the bottom of a waterway. Future uses of the waterway may be limited by this modification.

**Design Process for *In situ* Capping**
Capping is a dredged material disposal technology that has been used by the Corps for over 10 years (discussed in detail in Chapter 8). Although there are many differences between *in situ* capping and dredged material capping, some of the design guidance for this disposal technology (Palermo et al., in prep.) is appropriate to *in situ* capping and is presented herein.

An *in situ* capping operation should be treated as an engineering project with carefully considered design, construction, and monitoring to ensure that the design is adequate. The basic criterion for a successful *in situ* capping operation is simply that the cap required to isolate the contaminated material from the environment be successfully placed and maintained. The elements of *in situ* capping design are listed in Table 3-3. The design considerations for *in situ* capping include selection and evaluation of capping materials, cap thickness, equipment and placement techniques for the cap, cap stability, and monitoring.

***Data Collection***--A variety of information about the project site and sediments is needed to prepare an *in situ* capping design. The areal extent and thickness of the contaminated sediment deposit should be defined by surveys of the area. The site conditions should also be defined to include bathymetry, currents, water depths, bottom sediment characteristics, type and draft of adjacent navigation, and flood flow. The contaminated sediment deposit to be capped must be characterized for both physical and chemical parameters.

Physical characteristics are important in determining the suitability of placement of various capping materials. *In situ* density (or solids content), plasticity, shear strength, consolidation, and grain size distribution are needed for evaluations of resistance to displacement.

***Capping Material***--Various types of capping material may be used for *in situ* capping. If available, dredged sediment from navigation projects can be used. This option could be considered a beneficial use of material that might otherwise require disposal elsewhere. In other cases, removal of bottom sediments from areas adjacent to the capping site may be considered. Material other than sediments is also an option for the cap, such as clean fill from offsite sources, geotextiles, stone/gravel, and grout mattresses. In general, sandy sediments are suitable for use as a cap at sites with relatively low erosive energy, while armoring materials may be required at sites with high erosive energy.

***Cap Thickness***--The cap must be designed to chemically and biologically isolate the contaminated material from the aquatic environment. For sediment caps, the determination of the minimum required cap thickness is dependent on the physical and chemical properties of the contaminated and capping sediments, the potential for bioturbation of the cap by aquatic organisms, the potential for consolidation and erosion of the cap material, and the type(s) of cap materials used. Laboratory tests have been developed to determine the thickness of a capping sediment required to chemically isolate a contaminated sediment from the overlying water column (Sturgis and Gunnison 1988). The minimum required cap thickness for chemical isolation is on the order of 30 cm for most sediments tested to date. Bioturbation depths are highly variable; however, in Great Lakes sediments they are typically on the order of 10 cm. The minimum thickness of capping sediment for most projects will therefore be determined by constructability constraints. Conventional equipment and placement accuracies will dictate minimum cap thicknesses of 50-60 cm.

Geotextiles may be incorporated into *in situ* caps for a number of purposes, including: stabilizing the cap, promoting uniform consolidation, and reducing erosion of the granular capping materials.

Geotextiles and synthetic liners might also be incorporated into the cap design to limit bioturbation and provide contaminant isolation (Palermo and Reible, in prep.). A geotextile was incorporated into the cap used at the Sheboygan River (Figure 3-1), and a geotextile has been used as part of a contaminated sediment cap in Sorfjord, Norway (Zeman 1993).

An armoring layer for resistance to erosion can also be considered in the cap design (Environmental Laboratory 1987; Maynord and Oswalt 1993). For caps composed of armoring layers, the chemical isolation would be dependent on a filter, while the armor layer would normally prevent any disturbance of the cap by bioturbation and would be designed to resist erosion. Consideration must be given, however, of the potential attraction to benthic species of the new surface provided by the armoring layer.

***Equipment and Placement Techniques***--For sediment caps, the major consideration in the selection of equipment and placement of the cap is the need for controlled, accurate placement of the capping material (and the associated density and rate of application of the capping material). In general, the capping material should be placed so that it accumulates in a layer covering the contaminated material. The use of equipment or placement rates that would result in the capping material displacing or mixing with the contaminated material must be avoided.

Pipeline and barge placement of dredged material for *in situ* capping projects is appropriate in more open areas such as harbors or wide rivers. Specialized equipment and placement techniques developed for dredged material capping that might be considered for *in situ* capping are shown in Table 3-1 (Palermo 1991b). In constricted areas, narrow channels, or shallow nearshore areas, conventional land-based construction equipment may be considered.

Once the equipment and placement techniques for the cap are selected, the need for land-based surveys or navigation and positioning equipment and controls can be addressed. The survey or navigation controls must be adequate to ensure that the cap can be placed (whether by land-based equipment, bargeload, hopperload, or pipeline) at the desired location in a consistently accurate manner.

***Monitoring***--A monitoring program should be considered as a part of any capping project design (Palermo et al. 1992). The main objectives of monitoring for *in situ* capping would normally be to ensure that the cap is placed as intended and the required capping thickness is maintained, and that the cap is effective in isolating the contaminated material from the environment.

Intensive monitoring is necessary at capping sites during and immediately after construction, followed by long-term monitoring at less frequent intervals. Based on Corps experience at dredged material capping sites in New England, long-term monitoring should include bathymetric surveys, camera profiles, and occasional core samples (Fredette 1993). In addition to physical and chemical monitoring, biological monitoring may be conducted to track recolonization of benthos and evaluate contaminant migration. In all cases, the objectives of the monitoring effort and any remedial actions to be considered as a result of the monitoring should be clearly defined as a part of the overall project design.

### *In situ* Containment

The technical feasibility of using *in situ* containment is determined primarily by the physical conditions of the site. Areas that may be suitable for *in situ* containment include backwater areas, slips, turning basins, and some wide areas of rivers. Areas within active navigation channels are generally not suitable.

The primary factors limiting the feasibility of *in situ* containment are the potential impacts of the new fill on flow patterns, flooding, navigation, and habitat. Slips and turning basins are especially well suited, because they only need to be isolated at one end and can generally be filled without reducing the hydraulic capacity of the adjacent river channel.

*In situ* containment will require structural measures and environmental controls to isolate the containment area from the adjacent waterway and prevent unacceptable contaminant migration. Testing and evaluation to determine the appropriate controls is discussed in Chapter 8, *Disposal Technologies*.

It may also be possible to completely reroute waterways with contaminated sediments. The waterway can then be dewatered, and the sediments removed, treated in place, or confined in place. This is an extreme measure and is only likely to be feasible for small waterways with limited flows.

### *In situ* Treatment

There are three primary considerations in evaluating the suitability of *in situ* treatment. The first consideration is whether the treatment process can work effectively under the physical conditions of *in situ* sediments (i.e., saturated, anaerobic, and ambient temperatures). Treatment technologies that require greatly different conditions are less likely to be feasible for *in situ* application. Bench-scale testing of proposed treatment technologies should be performed to determine if the process can operate effectively under *in situ* conditions. Treatment technology testing is discussed further in Chapter 7.

The second consideration is the level of control needed to apply the treatment technology. Some technologies require well-mixed systems in order for reagents and sediment contaminants to react effectively. Specialized equipment may be needed to introduce reagents and manipulate the sediments. The development of such equipment may require pilot- or full-scale testing. Technologies that require greater levels of sediment manipulation are less likely to be feasible for *in situ* applications.

The third consideration is the environmental impact on the water column and aquatic environment. Suitable treatment technologies must be able to operate without dispersing the sediments, releasing toxic reagents or contaminants, or creating conditions more harmful to aquatic life than already exist. Examples of specialized equipment to isolate the treatment process from the water column are shown in Figures 3-2 and 3-3.

## ESTIMATING COSTS

There is little detailed cost information in the literature about *in situ* remediation technologies, even for those that have been implemented. Available information about applications that have been implemented or proposed is summarized in Table 3-4 [part i] [part ii].

### *In situ* Capping

Capital costs for *in situ* capping include costs of capping materials, construction equipment, and labor. These costs will be influenced by the complexity of the cap design, accessibility of the capping site, water depth, and other factors. If clean dredged material (e.g., from a navigation project) can be used in a capping application, capital costs could be greatly reduced.

Operation and maintenance costs include monitoring and periodic cap replenishment. Based on the experience of the Corps' New England Division with dredged material capping, the costs for a routine long-term monitoring cycle (bathymetric surveys and camera profile) are about $30,000 (Fredette 1993). This basic physical monitoring cycle is conducted every 2 3 years. More extensive monitoring (including sediment cores and biological monitoring) is conducted on a less frequent cycle.

### ***In situ* Containment**

Capital costs for *in situ* containment include the materials, equipment, and labor needed to construct the caisson, bulkhead, dike, or revetment, which isolates a portion of the waterway. Typical costs for marine sheetpile construction in the Great Lakes are \$12-17/ft[2] (\$130-180/m [2]) (Wong 1994). Additional capital costs may be related to the filling of the enclosed area with contaminated sediments (or other materials) and the environmental controls necessary for the enclosed site. These dredging and confined disposal costs are discussed in Chapter 4 (*Removal Technologies*) and Chapter 8 (*Disposal Technologies*). Operation and maintenance costs for *in situ* containment include monitoring and routine maintenance of the structure.

### ***In situ* Treatment**

Capital costs for *in situ* treatment include the costs of equipment, materials, reagents, and labor necessary to treat the sediments. The development and fabrication costs for the application equipment may be significant. A substantial amount of development cost may also be required for the treatment process itself, if it has not been applied *in situ*.

## ESTIMATING CONTAMINANT LOSSES

The loss of contaminants from sediments *in situ* is a primary rationale for remediation. The amounts of sediment contaminants lost during and after remediation need to be estimated to determine the benefits of remediation and to evaluate the impacts of remedial alternatives. The mechanisms for contaminant losses associated with nonremoval technologies are summarized in Table 3-5.

Estimating contaminant losses for nonremoval technologies is difficult because of the lack of field monitoring data and standard procedures for assessing nonremoval technologies. Predictive models based on diffusion are conceptually applicable to most nonremoval technologies. The seepage/leaching losses from an enclosed area constructed for *in situ* containment can be estimated using the predictive models developed for CDFs (see Chapter 8, *Disposal Technologies*). However, predictive techniques are not available that account for any of the other mechanisms of contaminant loss associated with nonremoval technologies.

Contaminant losses during placement of a cap, construction of an isolation wall, or the injection of reagents or additives for chemical treatment or immobilization can result in highly localized, but transient disturbances of contaminated sediment. For example, during *in situ* immobilization, contaminant losses occur at the point of additive injection, and injection-related losses last only as long as additives are being injected. These highly localized and transient disturbances can be as important as long-term diffusion losses. At present, highly localized, transient contaminant losses associated with the implementation of nonremoval technologies cannot be predicted. In addition, nonremoval technologies involving several processing steps, especially those involving mixing of the contaminated sediments, will have more contaminant loss mechanisms to consider than simpler nonremoval technologies, such as *in situ* capping.

Once the implementation phase of a nonremoval technology is completed, diffusion is the major contaminant loss pathway. Advection, bioturbation, and biodegradation can also be important in some cases, but can be avoided by careful planning, design, preproject testing, and monitoring. For example, sites with significant groundwater movement through the sediment (and associated significant contaminant losses) are not good candidates for nonremoval technologies. Controls for bioturbation should be part of engineering design, and the potential for biodegradation of solidified matrices following immobilization processing should be evaluated in a laboratory testing phase.

The application of diffusion models to certain nonremoval technologies, such as *in situ* capping and *in situ* immobilization, is better established than the application of these models to other nonremoval technologies, such as *in situ* chemical treatment. The diffusion models are described in detail in Myers et al. (in prep.). Cap thickness, sorption properties of the cap, contaminant chemical/physical property data, and sediment chemical/physical property data are variables needed to evaluate *in situ* capping effectiveness. For *in situ* immobilization, process-specific physical and chemical data are needed, including bulk density, contaminant concentration after processing, effective diffusion coefficients, and durability data. For other nonremoval technologies, there may be additional information needs.

EPA Home | Privacy and Security Notice | Contact Us

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 4. REMOVAL TECHNOLOGIES

The removal or excavation of sediments from a water body, commonly known as dredging, is a process that is carried out routinely around the world. The term environmental dredging has evolved in recent years to distinguish dredging operations for the primary purpose of environmental restoration from those operations for the purpose of simply removing sediments. The most common purpose of dredging is to construct or maintain channels for navigation or flood control (Hayes 1992). Environmental dredging operations usually involve relatively small volumes of sediment, with the objective of effectively removing contaminated material in a manner that minimizes the release of sediments and contaminants to the aquatic environment. Other objectives may be established for specific projects.

As noted by Hayes (1992):

> The primary purpose of routine dredging operations is usually to remove large volumes of subaqueous sediments as efficiently as possible within specified operational and environmental restrictions. Environmental dredging operations, on the other hand, would attempt to remove sediments with some known contamination as effectively as possible. An effective method would include complete removal of the desired sediment with as little environmental risk and consequence as possible. The important distinction is that economics play a secondary role to environmental protection in environmental dredging operations.

The loss of contaminants to the surrounding waters, or into the atmosphere, is of particular concern when dredging contaminated sediments. Because contaminants are generally bound to the fine particles, which are most easily resuspended, most efforts are focused on minimizing the amount of resuspension through innovative equipment design and operational controls. Further reductions in the transport of contaminants can be accomplished with barriers such as silt curtains, silt screens, and oil booms.

The various types of mechanical and hydraulic dredges, as well as barriers, are described in this chapter. Discussions of the factors used to select dredging equipment and techniques for estimating costs and contaminant losses (e.g., via resuspension) are also provided.

Different types of dredges were reviewed in the literature review prepared for the ARCS Program (Averett et al., in prep.). Other general references on the subject of dredging include the *Handbook of Dredging Engineering* (Herbich 1992), *Fundamentals of Hydraulic Dredging* (Turner 1984), and *Dredging and Dredged Material Disposal* (USACE 1983).

## DESCRIPTIONS OF TECHNOLOGIES

Dredging involves mechanically penetrating, grabbing, raking, cutting, or hydraulically scouring the bottom of the waterway to dislodge the sediment. Once dislodged, the sediment is lifted out of the waterway either mechanically, as with buckets, or hydraulically, through a pipe. Thus, dredges can be categorized as either mechanical or hydraulic depending on the basic means of moving the dredged material. A subset of the hydraulic dredges employs pneumatic systems to pump the sediments out of the waterway. These are termed pneumatic dredges.

The most fundamental difference between mechanical and hydraulic dredging equipment is the form in which the sediments are removed. Mechanical dredges offer the advantage of removing the sediments at nearly the same solids content as the *in situ* material. That is, little additional water is entrained with the sediments as they are removed, meaning that the volume of the sediments is essentially the same before and after dredging. In contrast, hydraulic dredges remove and transport sediment in slurry form. The total volume of material is greatly increased, because the solids content of the slurry is considerably less than that of the *in situ* sediments. (The relationship between the volume of *in situ* sediment with various slurries is discussed in Chapter 6 in the *Dewatering Technologies* section.)

The two general types of dredges most commonly used to perform navigation maintenance and construction-related dredging, mechanical and hydraulic, are shown in Figure 4-1. Both dredges are available in a wide variety of sizes, including small, portable hydraulic dredges. The various types of dredges and dredging equipment, vessel positioning systems, contaminant barriers, and monitoring requirements applicable to sediment removal technologies are discussed below.

## Mechanical Dredges

Mechanical dredges remove bottom sediment through the direct application of mechanical force to dislodge and excavate the material. The dredged material is then lifted mechanically to the surface at near-*in situ* densities (Averett et al., in prep.). As noted above, this feature is significant because it minimizes the amount of contaminated material to be handled. Mechanical dredges can be particularly effective for those locations where dredged sediment must be transported by a barge to a disposal or treatment facility (Zappi and Hayes 1991).

Production rates for mechanical dredges are typically lower than those for comparably sized hydraulic dredges. However, high productivity is typically not the main priority for environmental dredging projects. Mechanical dredges can operate in constricted areas and do not interfere with shipping to the same extent as hydraulic dredges (Zappi and Hayes 1991). Mechanical dredges are often selected for small dredging projects in confined areas such as docks and piers. They provide one of the few effective methods for removing large debris (Averett et al., in prep.) and are adaptable to land-based operations.

Major types of mechanical dredges include the following:

- Clamshell bucket
- Backhoe
- Bucket ladder
- Dipper
- Dragline

Although it has not been proven by field or laboratory measurements, it is commonly thought that the bucket ladder, dipper, and dragline dredges operate in a manner that would lead to high sediment resuspension rates, making them unsuitable for dredging contaminated material (Zappi and Hayes 1991). The clamshell bucket and backhoe dredges are described below.

### *Clamshell Bucket Dredges*

The clamshell bucket dredge, also known as the grab dredge, is the most commonly used mechanical dredge in the United States, if not the world (Zappi and Hayes 1991). This dredge may consist simply of a crane mounted on a spud barge, although most bucket dredges have a crane/barge system specifically designed and constructed for dredging (Figure 4-1) (Zappi and Hayes 1991). Buckets are classified by their capacities, which range from <1 to 50 yd[3] (<0.8 to 40 m[3]), with 2-10 yd[3] (1.5-7.5 m[3]) being typical. Bucket dredges are available from a wide variety of sources throughout North America.

A bucket dredge is operated similarly to a land-based crane and bucket. The crane operator drops the bucket through the water column, allowing it to sink into the sediment on contact. The loaded bucket is then lifted, causing the jaws to close, and raised through the water column. Once above the water surface, the operator swings the bucket over the receiving container (usually a barge) and lowers the bucket to release its load (Zappi and Hayes 1991). The bucket dredge usually leaves an irregular, cratered sediment surface (Herbich and Brahme 1991). The bucket has been used at numerous sites throughout the Great Lakes for removing both contaminated and clean sediments. It is estimated that 77 bucket dredges are stationed in Great Lakes ports.

A variation of the conventional dredge bucket, the enclosed dredge bucket, has been developed to limit spillage and leakage from the bucket. Although originally designed by the Japanese Port and Harbor Institute and produced in Japan by Mitsubishi Seiko Co., Ltd., variations of this design have been produced by several U.S. manufacturers (Zappi and Hayes 1991). The operation and deployment of the enclosed dredge bucket is identical to that of the conventional clamshell bucket discussed above.

The original enclosed dredge bucket (Figure 4-2) features covers designed to prevent material from spilling out of the bucket while it is raised through the water column. The design also employs rubber gaskets or tongue-in-groove joints that reduce leakage through the bottom of the closed bucket. An alternative design, developed by Cable Arm, Inc. (Figure 4-2), offers several advantages over the standard clamshell design, including the ability to remove sediment in layers, leaving a flat sediment surface.

Enclosed bucket dredges have been used routinely in various Great Lakes ports for the maintenance of navigation channels. They have also been used in sediment remediation projects in the Black River near Lorain, Ohio, in 1990, and in the Sheboygan River, Wisconsin, in 1990 and 1991. The Cable Arm bucket was demonstrated by the Contaminated Sediment Removal Program (CSRP) on contaminated sediments in the Toronto and Hamilton Harbors in Canada in 1992 (Environment Canada 1993) and has been used for navigation maintenance dredging in the Cuyahoga and Fox Rivers.

***Backhoes***

Backhoes, although normally thought of as excavating rather than dredging equipment, can be used for removing contaminated sediments under certain circumstances. Backhoes are normally land based, but may be operated from a barge, and have been used infrequently for navigation dredging in deep-draft (20-ft [6-m]) channels. Backhoes have received limited use for removing PCB-contaminated sediments from the Sheboygan River. A backhoe was recently used to remove 13,000 m[3] of contaminated sediments from Starkweather Creek in Madison, Wisconsin. Sediment resuspension from the dredging was monitored and found to be no greater than that expected with other types of dredging equipment (Fitzpatrick 1994).

Specialized backhoes include closed-bucket versions and a pontoon-mounted model especially adapted to dredging applications (see WaterMaster described in St. Lawrence Centre 1993). The latter may be equipped with a suction pump as well.

## Hydraulic Dredges

Hydraulic dredges remove and transport sediments in the form of a slurry. They are routinely used throughout the United States to move millions of cubic meters of sediment each year (Zappi and Hayes 1991). The hydraulic dredges used most commonly in the United States include the conventional cutterhead, dustpan, and bucket-wheel. Certain hydraulic dredges, such as the modified dustpan, clean-up, and matchbox dredges, have been specifically developed to reduce resuspension at the point of dredging.

Hydraulic dredges provide an economical means of removing large quantities of contaminated sediments. The capacity of the dredge is generally defined by the diameter of the dredge pump discharge. Size classifications are: small (4-14 in., 10-36 cm), medium (16-22 in., 41-56 cm), and large (24-36 in., 61-91 cm) (Averett et al., in prep.). The dredged material is usually pumped to a storage or disposal area through a pipeline, with a solids content of typically 10-20 percent by weight (Herbich and Brahme 1991). Souder et al. (1978) indicated that slurry concentrations are a function of the suction pipeline inlet velocity, the physical characteristics of the *in situ* sediment, and effective operational controls. The slurry uniformity is controlled by the cutterhead (if one is employed) and suction intake design and operation. The cutterhead (both conventional and innovative) should be designed to grind and direct the sediment to the suction intake with minimal hydraulic losses. Water jets can also be used to loosen the *in situ* material and provide a uniform slurry concentration. The dredgehead and intake suction pipeline should be designed to maintain velocities that are capable of breaking the *in situ* sediment into pieces that the pump can handle while minimizing entrance and friction losses.

The dredge pump and dredgehead (e.g., cutterhead) should work in tandem so that the entire volume of contaminated sediment comes into the system, while maintaining a slurry concentration that the dredge pump is capable of handling. The pump must impart enough energy to the slurry so that the velocities in the pipeline prevent the solids from settling out in the line prior to reaching the next transport mode or remediation process. A properly designed and operated dredgehead, suction intake and pipe, pump, and discharge pipeline system can minimize sediment resuspension while significantly reducing system maintenance and the likelihood of pump failure.

Fundamentally, there are four key components of a hydraulic dredge:

- The **dredgehead** is the part of the dredge that is actually submerged into the sediment
- The **dredgehead support** is usually a ladder as shown in Figure 4-1, but may instead be a simple cable or a sophisticated hydraulic arm
- The **hydraulic pump** provides suction at the dredgehead and propels the sediment slurry through a pipeline (It may be submerged or deck-mounted.)
- The **pipeline** carries the sediment slurry away from the dredgehead to the receiving area (e.g., CDF, lagoon)

### Dredgeheads

Various types of dredgehead configurations are used to facilitate the initial loosening and gathering of bottom sediment. Most hydraulic dredges are usually identified by the type of dredgehead (e.g., bucket wheel dredge). Various types of dredgeheads are discussed below.

***Cutterhead Dredges***--Conventional cutterhead dredges are the most common hydraulic dredges in the United States. According to Averett et al. (in prep.), there are 300 such dredges operating in the United States today. A conventional open basket cutterhead is shown in Table 4-1.

Cutterhead dredges are usually operated by swinging the dredgehead in a zig-zag pattern of arcs across the bottom, which tends to leave windrows of material on the bottom (Herbich and Brahme 1991). Innovative operating techniques, including overlapping dredge or step cuts, can reduce or eliminate windrows. Cutterhead dredges can be operated to reduce resuspension or losses of volatile contaminants using additional equipment such as sediment shields, gas collection systems, underwater cameras, and bottom sensors.

Innovative dredgehead designs have been developed specifically for removing contaminated materials. Such dredgeheads put a premium on minimizing sediment resuspension and on accurate control of the depth of sediments removed. Two such dredgeheads, the Clean-up and the Refresher, are shown in Table 4-1.

***Suction Dredges***--This category includes those hydraulic dredges that do not employ a cutterhead. Such dredges may use water jets to help loosen sediments. Examples of three dredgehead designs used for such dredges are provided in Table 4-2.

***Hybrid Dredges***--These dredges use a combination of mechanical action and hydraulic pumping, but would not be considered cutterhead dredges. Examples of dredgehead designs used by hybrid dredges are shown in Table 4-3, and include the bucket wheel, screw impeller, and disc-bottom dredgeheads.

### Dredgehead Support

The physical support for the dredgehead, or ladder, is largely interchangeable among the various dredges and will not be discussed further in this document.

### Hydraulic Pumps

The three main applications of hydraulic pumps in the dredging process are:

- Dredge plant pumps used to remove *in situ* sediments
- Booster pumps used to maintain slurry velocities
- Pumpout stations used to rehandle sediment from hoppers, barges, and railcars

Dredge plant pumps are discussed in this section. The other two types of pump applications are discussed in Chapter 5, *Transport Technologies*.

Fundamentally, pumps are used to convert mechanical or pumping energy into slurry energy. Usually they are driven by electric or diesel motors, although air-driven (pneumatic) pumps have also become popular. Energy put into a slurry by a pump is used to maintain pipeline velocities while overcoming elevation heads and friction and entrance losses.

The two general classes of dredge plant pumps are kinetic and positive displacement (Lindeburg 1992). A summary of the characteristics of selected examples of these pump types is provided in Table 4-4 [part i] [part ii] [part iii].

### Pipelines

Details on slurry pipelines are provided in Chapter 5, *Transport Technologies*.

### Portable Hydraulic Dredges

Portable hydraulic dredges are relatively small machines that can be transported over land. They are convenient for isolated, hard-to-reach areas and are economical for small jobs. These dredges are also capable of operating in very shallow water (approximately 0.5 m). Two such dredges are the horizontal auger dredge and the Delta dredge (Delta Dredge and Pump Corp.). These two dredges are shown in Table 4-5. Two examples of horizontal auger dredges are the Mudcat, manufactured by Ellicott Machine Co. and the Little Monster, manufactured by the H & H Pump and Dredge Co. A Mudcat dredge with several equipment modifications was demonstrated by the CSRP in November 1991 at the Welland River, Ontario (Acres International Ltd. 1993).

A third type of portable dredge is the hand-held hydraulic dredge. This dredge can be as simple as a hose connected to a vacuum truck, such as the one used to remove PCB-contaminated sediments from the Shiawasee River in Michigan (USEPA 1985b). In another example, diaphragm sludge pumps were used by the USEPA's Inland Response Team to remove PCB-contaminated sediments from the Duwamish River Waterway in Seattle, Washington (Averett et al., in prep.). The primary application of such dredges is the removal of small volumes of contaminated materials that can be easily accessed from the surface or by divers.

### *Self-Propelled Hopper Dredges*

A self-propelled hopper dredge operates hydraulically, but it is often described as a separate type of dredge because the dredged material is retained onboard rather than being discharged through a pipeline (Figure 4-1). Self-propelled hopper dredges are well suited for dredging large quantities of sediments in open areas. They are not well suited for small dredging projects, especially in close quarters. For these reasons, they are not likely to be used for sediment remediation projects around the Great Lakes and will not be discussed in further detail in this document.

## Vessel or Dredgehead Positioning Systems

A critical element of sediment remediation is the precision of the dredge cut, both horizontally and vertically. Technological developments in surveying and positioning instruments have improved both aspects of dredging. Vertical control is particularly important where contamination occurs as a relatively thin or uneven layer. Video cameras can be used to continuously monitor dredging operations. The depth of the dredgehead can be measured using acoustic instrumentation and by monitoring dredged slurry densities. In addition, surveying software packages can be used to generate pre- and post-dredging bathymetric (water depth) charts, determine the volume dredged, locate obstacles, and calculate surface areas (St. Lawrence Centre 1993). A digital dredging method, which enables dredge operators to follow a complex sediment contour, has been developed in the Netherlands (van Oostrum 1992).

The horizontal position of the dredge may be continuously monitored during dredging. Satellite- or transmitter-based positioning systems (e.g., global positioning system, SATNAV, LORAN C) may be used to define the dredge position. In some cases, however, the accuracy of these systems is inadequate for precise dredging control. Very accurate control is possible through the use of optical (laser) surveying instruments set up at one or more locations onshore. These techniques, in conjunction with on-vessel instruments and control of spud placement, can enable the dredge operator to target specific sediment deposits.

The positioning technology described above may enhance the accuracy of dredging in some circumstances. However, planners and designers should not develop unrealistic expectations of dredging accuracy. Contaminated sediments cannot be removed with surgical accuracy even with the most sophisticated equipment. Equipment is not the only factor affecting the accuracy of a dredge. Site conditions (e.g., weather, currents), sediment conditions (e.g., bathymetry, physical character), and the skill of the dredge operator are all important factors. In addition, the distribution of sediment contaminants can, in many cases, only be resolved at a crude level and with a substantial margin for error. The level of accuracy required for environmental dredging should reflect the accuracy at which the sediment contamination distribution is resolved.

## Containment Barriers

When dredging contaminated sediments, it may be advisable to limit the spread of contaminants by using physical barriers around the dredging operation. Such barriers may be appropriate when contaminant concentrations are high or site conditions dictate the need for minimal adverse impacts. A number of physical barriers commonly used in the construction industry may be adapted to this purpose. Structural barriers, such as cofferdams, are not generally applicable as temporary barriers, but are options for *in situ* containment (see Chapter 3, *Nonremoval Technologies*). The determination of whether these types of barriers are necessary, aside from regulatory requirements, should be made based on a thorough evaluation of the relative risks posed by the anticipated release of contaminants from the dredging operation, the predicted extent and duration of such releases, and the long-term benefits gained by the overall remediation project. The *ARCS Risk Assessment and Modeling Overview Document* (USEPA 1993a) and the *Estimating Contaminant Losses from Components of Remediation Alternatives for Contaminated Sediment* (Myers et al., in prep.) should be used to make this determination. More commonly, nonstructural barriers, such as oil booms, silt curtains, and silt screens, have been used to reduce the spread of contaminants during dredging. Oil booms are appropriate for sediments that are likely to release oils when disturbed. Such booms typically consist of a series of synthetic foam floats encased in fabric and connected with a cable or chains. Oil booms may be supplemented with oil absorbent materials (e.g., polypropylene mats).

Silt curtains and silt screens are flexible barriers that hang down from the water surface. Figure 4-3 shows a typical design of a silt curtain. Both systems use a series of floats on the surface, and a ballast chain or anchors along the bottom. Although the terms silt curtain and silt screen are frequently used interchangeably, there are fundamental differences. Silt curtains are made from impervious material such as coated nylon and primarily redirect flow around the dredging area rather than blocking the entire water column. In contrast, silt screens are made from synthetic geotextile fabrics, which allow water to flow through but retain a fraction of the suspended solids (Averett et al., in prep.).

Silt curtains have been used at many locations with varying degrees of success. For example, silt curtains were found to be ineffective during a demonstration in New Bedford Harbor, primarily as a result of tidal fluctuation and wind (Averett et al., in prep.). Similar problems were experienced when Dokai Bay (Japan) was dredged in 1972 (Kido et al. 1992). Barriers consisting of a silt curtain/silt screen combination were effectively applied during dredging of the Sheboygan River in 1990 and 1991. Water depths were generally 2 m or less. A silt curtain was found to reduce suspended solids from approximately 400 mg/L (inside) to 5 mg/L (outside) during rock fill and dredging activities in Halifax Harbor, Canada (MacKnight 1992). A silt curtain was employed during a dredging demonstration at Welland, Ontario (Acres International Ltd. 1993). The curtain minimized flow through the dredging area, although there were problems in the installation and removal.

### Monitoring

Monitoring may be conducted during environmental dredging for a number of purposes, including:

- Measure contaminated sediment removal efficiency
- Determine dredged volumes
- Measure sediment resuspension at dredge
- Track contaminant transport
- Check performance of barriers and other controls

During maintenance dredging, monitoring is generally focused on the quantity of material dredged because the contractor is paid according to this quantity. The quantity of dredged material may be estimated from bathymetric surveys conducted before and after the dredging, or from other measurements, such as barge counts or pumping rates and duration.

Measurements of turbidity or suspended solids are made during sediment remediation and during some maintenance dredging operations to monitor the level of sediment resuspension caused by the dredge. Water samples are typically collected at one location upstream and several locations downstream from the dredging site. Additional water quality monitoring around the dredging site may be required by the State or other regulatory agencies. Monitoring programs for tracking contaminant transport and checking the efficiency of barriers and other controls are site-specific. During remedial dredging projects, sediment samples may be collected and analyzed after dredging to monitor the removal efficiency and to determine if additional passes by the dredge are needed.

## SELECTION FACTORS

A number of publications on the selection of dredges for environmental applications have been published, including the *Guide to Selecting a Dredge for Minimizing Resuspension of Sediment* (Hayes 1986) and *Selecting and Operating Dredging Equipment: A Guide to Sound Environmental Practices* (St. Lawrence Centre 1993). Generally one of the key considerations in any dredging project involving contaminated sediments is the minimization of sediment resuspension. While this subsection focuses on the selection of dredging equipment, it should be noted that the operation of the dredge also has a profound effect on the rate of sediment resuspension (Hayes 1986). Selection of specialty dredges designed for minimal sediment resuspension does not guarantee superior results. The keys to an effective and environmentally safe dredging operation are:

- Selection of equipment compatible with the conditions at the site and the constraints of the project
- Use of highly skilled dredge operators
- Close monitoring and management of the dredging operation

Conventional dredging equipment, employed in a careful and efficient manner, can achieve results comparable to specialty dredging equipment.

### Dredge Selection

The operational characteristics of selected dredges are summarized in Table 4-6. These characteristics may be used to help narrow the range of dredges potentially suited to a given remediation project. Other factors that can be used to guide the selection of an appropriate dredge for a site are discussed below.

***Solids Concentration***

There are two major factors that affect the desired solids concentration:

- **Compatibility with Other Components** In most cases, it is preferable to use a dredging system that is capable of delivering material at high solids concentrations. This tends to minimize the costs of handling, treating, and disposing of sediments. Mechanically dredged sediments do not require intensive dewatering, which is an expensive pretreatment process (see Chapter 6). Mechanical dredging keeps the volume of dredged material to a minimum and greatly reduces the costs of water treatment (see Chapter 9).

- **Distance to Treatment/Disposal Site** The feasibility of pipeline transport to the treatment/disposal site is discussed in Chapter 5, *Transport Technologies*. The ability to deploy pipelines, even temporarily, in highly urbanized areas can be limited. If access is unlimited, slurried sediments can be transported by pipeline several kilometers with the use of booster pumps. If pipeline transport is not feasible, sediments can be transported at high solids concentrations (e.g., as produced with mechanical or pneumatic dredges) by scows or barges.

***Production Rate***

For navigation dredging, the size of the dredge (and number of dredges) is largely dictated by the volume of sediments to be removed and the time allowed. The quantities of sediments dredged at remediation projects are small in comparison to navigation dredging, and factors other than sediment volume may influence the dredge size and production rates. Production rates may be deliberately reduced to minimize sediment resuspension or because of constraints caused by sediment transport, pretreatment, treatment, or disposal components.

***Dredging Accuracy***

Precise control of operational dredging depth is particularly important when dredged sediments are to be handled in expensive treatment and disposal facilities (Averett et al., in prep.). The vertical and lateral accuracy of the dredge is important to ensure that contaminated sediments are removed, while minimizing the amount of clean sediments removed. The accuracy of a dredging operation is only partially influenced by the type of dredge selected. Conditions of the site and sediments, the proficiency of the operator, and the rate of production all influence the accuracy of the dredge cut.

***Dredging Depth***

Dredges are limited to dredging areas with an adequate depth of water to accommodate the draft of the dredging vessel. This factor becomes important when contaminated sediments are located outside of navigable waterways. Some dredging equipment can be operated from land to access sediments in shallow waterways. The maximum depth to which dredges can reach is also limited. Some dredges are limited by the length of the dredging arm or ladder. Hydraulic dredging in very deep water (>20 m) may require submerged pumps or remotely operated dredges.

***Ability to Handle Debris***

Sediment, especially in urban areas, often contains large rocks, concrete, timber, tires, and other discarded materials. In cargo loading/unloading areas, pockets of coal, iron ore pellets, or other bulk materials may occur from spillage. Very large debris (e.g., greater than 0.5 m in any dimension) can only be removed mechanically (further discussion of specialized debris removal equipment is provided in Chapter 6). Mechanical dredges will generally remove large debris with the sediments, but are likely to produce greater turbidity in the process. Dredgeheads equipped with cutters are able to reduce the size of some debris such as wood. Although debris that is larger than the diameter of the suction pipe and not cut by the cutter simply cannot be removed by hydraulic dredges, smaller debris can also clog hydraulic pipelines and damage pumps.

***Other Factors***

In addition to the selection factors shown in Table 4-6, there are a number of other factors that may be significant in the selection of a dredge for a remediation project, including sediment resuspension, dredge availability, and site restrictions. These factors are discussed below.

> ***Sediment Resuspension***--In areas where sediments have high contaminant concentrations, toxicity, mobility, or a combination thereof, extraordinary care and expense may be required to minimize sediment resuspension or spillage. In such cases, releases of contaminants to the water are a primary concern, and may override other factors in selecting a dredge. As noted above, the degree of resuspension is influenced by both the type of dredge and its operation. Resuspension characteristics of dredges are discussed later in this chapter in regard to estimating contaminant losses.
>
> ***Dredge Availability***--A wide variety of dredging equipment is available throughout North America and in the Great Lakes region. A summary of dredges stationed in the Great Lakes is shown in Table 4-7. A summary of the availability of specialty dredges is provided in Table 4-8. As shown, many of the specialty dredges

developed in Japan and Europe are not readily obtainable in the United States. The *International Dredging Review* publishes an annual directory of dredge owners and operators, which should be consulted for an up-to-date listing of dredging contractors and available equipment. ***Site Restrictions***--Channel widths, surface and submerged obstructions, overhead restrictions such as bridges, and other site access restrictions may also limit the type and size of equipment that can be used. For example, hopper dredges are ships that require navigable depths, cutterhead dredges require anchoring cables for operation, while bucket dredges can operate in confined areas. In some cases, it may be more appropriate to remove material from shore, as was done with contaminated sediments from Starkweather Creek in Madison, Wisconsin (Fitzpatrick 1994).

## Containment Barriers

The effectiveness of nonstructural containment barriers at a sediment remediation site is primarily determined by the hydrodynamic conditions at the site. Conditions that will reduce the effectiveness of barriers include:

- Strong currents
- High winds
- Changing water levels
- Excessive wave height (including ship wakes)
- Drifting ice and debris

As a generalization, silt curtains and screens are most effective in relatively shallow, quiescent water. As water depth increases, and turbulence caused by currents and waves increases, it becomes increasingly difficult to effectively isolate the dredging operation from the ambient water. The St. Lawrence Centre (1993) advises against the use of silt curtains in water deeper than 6.5 m or in currents greater than 50 cm/sec.

The effectiveness of containment barriers is also influenced by the quantity and type of suspended solids, the mooring method, and the characteristics of the barrier (JBF Scientific Corp. 1978). Typical configurations for silt curtains and screens are shown in Figure 4-4. To be effective, barriers are deployed around the dredging operation and must remain in place until the operation is completed at that site. For large projects, it may be necessary to relocate the barriers as the dredge moves to new areas. Care must be taken that the barriers do not impede navigation traffic. Containment barriers may also be used to protect specific areas (e.g., valuable habitat, water intakes, or recreational areas) from suspended sediment contamination.

## Monitoring

A monitoring program for environmental dredging should be designed to meet project-specific objectives. Monitoring can be used to evaluate the performance of the dredging contractor, equipment, and the barriers and environmental controls in use. Monitoring may also be integrated into the health and safety plan for the dredging operation to ensure that exposure threshold levels are not exceeded.

The monitoring program must be designed to provide information quickly so that appropriate changes to dredging operations or equipment can be made to correct any problems. Simple, direct, and preferably instantaneous measurements are most useful. Measurements of turbidity, conductivity, and dissolved oxygen can be used as real-time indicators of excessive sediment resuspension. Project-specific guidelines for interpreting monitoring results should be developed in advance, as well as potential operational or equipment modifications.

## ESTIMATING COSTS

The basic principles of cost estimating, and the use of cost estimates to support the decision-making process are discussed in Chapter 2. More detailed guidance specific to estimating the costs of dredging operations is provided in this section. This guidance is applicable to feasibility studies, but is not adequate for preparing a detailed dredging cost estimate.

This document discusses the removal (Chapter 4) and transport (Chapter 5) components of a sediment remedial alternative separately. However, these components are likely to be part of a single contract, and their costs would, in most cases, be estimated together. Virtually all costs associated with the removal component of a sediment remediation project are capital costs (direct and indirect). The elements of environmental dredging costs include:

- Mobilization/demobilization
- Dredge operation

- Contaminant barriers
- Monitoring
- Health and safety
- Equipment decontamination

Each of these elements is discussed below, and available unit prices are presented. Although many of these unit prices are obtained from navigation dredging experience, only the operational costs are likely to be increased significantly during sediment remediation dredging as a result of the more slowed operation and decreased production.

Cost information is available from some historical sediment remediation projects. A total of 13,000 m[3] of sediments was excavated from Starkweather Creek in Wisconsin by backhoe at a cost of approximately $10.00/m[3] (Fitzpatrick 1994). The Waukegan Harbor Superfund project in Illinois removed 23,000 m[3] by dredging at a cost of $1.1 million (Albreck 1994). However, these and other unit dredging costs from historical remediation projects should only be used when all cost items are known.

## Mobilization/Demobilization

The first cost incurred in any dredging project is that of bringing the dredging equipment to the dredging site and preparing it for operation. This process is referred to as mobilization. Demobilization occurs at the end of the project operation and typically costs one-half the mobilization expense. Typical mobilization/demobilization costs for the Great Lakes region (provided by USACE Detroit District) are as follows:

| | Cost (per 100 km)* |
|---|---|
| Mechanical dredge (clamshell) | $37,500 |
| Hopper dredge (<4,000 m[3]) | $75,000 |
| Hydraulic (pipeline) dredge | $18,750 |

* Distance the dredge must be transported to the project site.

Mobilization costs for backhoes (without the requirement for a floating platform) are typically less than $400 (USEPA 1985a). Portable dredges are often leased or purchased outright.

Mobilization/demobilization may represent the largest single cost element in the dredging project, especially for projects with small dredging quantities. Additional costs will be incurred if specialized pumps or unconventional dredgeheads are employed. Generally, specialty dredging equipment may be transported separately to the site and used with the conventional dredging equipment. The costs for specialty dredging equipment must be developed on a site-specific basis.

## Dredge Operation

The costs of a dredging operation depend on the size of the dredge employed and the amount of time that the equipment is onsite (i.e., the cost of dredging is largely a function of the production rate). In conventional dredging, the rate of production is fairly predictable, based on the consistency of the sediments and the size of the dredge employed. Algorithms for predicting the production rates of different dredge types are provided in Church (1981).

During environmental dredging, additional time must be allowed for other factors, such as:

- Greater precision of cut
- Slower production rates to minimize resuspension
- Multiple passes needed to achieve cleanup goals
- Use of contaminant barriers
- Restrictions posed by other remedial components

In most cases, additional costs will be incurred as the production rates are lowered.

One of the goals of environmental dredging is to remove only those sediments that are contaminated. Because of the costliness of treating or disposing of contaminated sediments, the quantity of clean sediments removed must be minimized. The production rate of the dredge may be deliberately slowed so that downstream components such as sediment handling and transport, pretreatment, treatment, disposal, and/or effluent treatment are not overwhelmed. This is particularly true for hydraulic (pipeline) dredging, in which adequate time must be allowed for sediments to settle out in the receiving basin (see Chapter 8). In fact, it may be more cost effective, in such instances, to select a smaller dredge that can be operated at a constant rate close to its capacity, rather than a large dredge with an operating schedule that is frequently interrupted.

Typical unit costs for various types of maintenance dredges are provided in Table 4-9. They reflect the costs of dredge operation for rates of production typical of maintenance dredging in the Great Lakes. These costs should be adjusted to account for the lower production rates anticipated with environmental dredging. The adjustment for environmental dredging production rates may be as much as 2 3 fold (or more) for specific applications. For example, the hydraulic dredging of 23,000 m[3] of sediments during the Waukegan Harbor Superfund cleanup cost $1.1 million, or roughly $48/m[3] (Albreck 1994). This cost included the deployment of a contaminant barrier (silt curtain).

## Containment Barriers

Several types of containment barriers are available to contain contaminants released during dredging. Current unit costs for oil booms and silt curtains and screens are summarized in Table 4-10.

## Monitoring

The costs of a monitoring program for an environmental dredging operation may be significant. However, these costs are project specific, and few generalizations can be made. Among the potentially more costly items of a monitoring program are detailed bathymetric surveys (before and after dredging), post-dredging sediment contaminant analysis, and sediment resuspension monitoring. The cost of sediment analysis will depend on the contaminants analyzed and the turnaround time requested of the laboratory. The primary costs for resuspension monitoring are for field sampling, as turbidity and suspended solids analyses are relatively inexpensive.

## Health and Safety

The removal of contaminated materials from a waterway can be a hazardous activity, especially if contaminant concentrations are high. Depending on the types of contaminants present, the concentrations expected, and the degree of contact workers may have with the sediment, it may be necessary to provide workers with special PPE, such as respirators and Tyvek coveralls. Such gear can decrease the productivity of workers and thereby greatly increase operating costs. This is particularly true if workers are required to wear respirators or use supplied air. However, in most cases sediment contaminants are not volatile, and therefore respiratory protection is rarely needed.

Another health and safety consideration is the training of site workers. Workers at all Federal Superfund sites, as well as other hazardous waste sites, are required to undergo 40 hours of health and safety training (29 CFR 1910.120). This requirement may represent an additional expense not anticipated by the dredging contractor.

## Equipment Decontamination

Reusable equipment that comes into contact with contaminated materials may have to be decontaminated prior to leaving the site. This is an expense not normally included with demobilization costs. The level of decontamination required will depend on the nature of the sediment contaminants and the laws and regulations governing the remediation. Large equipment such as dredges may have to be steam-cleaned or washed with detergents, unless it can be shown that contamination can be effectively removed using less intensive methods. It may be possible to clean pumps and pipelines by pumping clean water or clean sediment through them. All wash water from these operations would have to be captured and probably treated before being released.

# ESTIMATING CONTAMINANT LOSSES

The loss of contaminants during dredging may need to be estimated for a number of reasons, including:

- Comparison and selection of dredging equipment
- Evaluation of the overall losses from remedial alternatives
- Determination of compliance with water quality requirements
- Determination of short-term impacts on sensitive resources

Factors that potentially affect contaminant losses from dredging are listed in Table 4-11.

A study conducted under the ARCS Program examined the available predictive tools for estimating contaminant losses from dredging (Myers et al., in prep.). The three mechanisms of contaminant loss from dredging are:

- Particulate contaminant releases
- Dissolved contaminant releases
- Volatile contaminant releases

## Particulate Contaminant Releases

Methods for predicting sediment resuspension have been developed for cutterhead and mechanical (bucket) dredges. These methods predict the resuspension of particulates as a function of dredging equipment, operation, and sediment properties. These techniques have not been field verified, and are therefore not fully developed (Myers et al., in prep.).

Limited field studies have indicated that the type of dredging equipment used may have less effect on sediment resuspension than how it is used. The care with which a dredge operator excavates material has a significant effect on sediment resuspension (Hayes 1992). For example, variables such as cutter speed, swing speed, and degree of burial (bank factor) have been incorporated into models for cutterhead dredges (Myers et al., in prep.). Decreasing each of these parameters can reduce the resuspension caused by hydraulic dredging. Similarly, smooth and controlled hoisting can limit resuspension during clamshell dredging (McClellan et al. 1989).

Sediment properties are site-specific variables that cannot be controlled. In general, fine-grained, less-cohesive sediments have the greatest potential for resuspension and will travel further before resettling to the bottom.

The resuspension characteristics of numerous dredge types have been measured at various locations. A summary of resuspension tests is provided in Table 4-12, as compiled by Herbich and Brahme (1991), Zappi and Hayes (1991), and others. The comparability of sediment resuspension results from different sites is highly limited due to differences in the monitoring programs, sediment types, site conditions, and other factors. As indicated above, the type of dredge used is not always the most significant factor affecting sediment resuspension.

## Dissolved Contaminant Releases

Resuspension of sediment solids during dredging can impact water quality through the release of contaminants in dissolved form. Dredging exposes sediments to major shifts in liquid/solids ratio and reduction/oxidation potential (redox). Initially upon resuspension, the bulk of the contaminants are sorbed to particulate matter. As the resuspended particles are diluted by the surrounding waters, sorbed contaminants may be released, increasing the fraction of dissolved contaminants in the water. Changes in redox potential (i.e., from an anaerobic to an aerobic environment) can affect metal speciation. This may increase the solubility of metals (e.g., oxidation of mercury sulfides) or decrease metal concentrations (e.g., metal scavenging by oxidized iron flocs) (Myers et al., in prep.). Organic contaminants are largely unaffected by redox shifts.

Methods for predicting the release of dissolved contaminants during dredging are less developed than those for sediment resuspension. A method using equilibrium partitioning concepts has been proposed for estimating the concentrations of dissolved organic contaminants, and a laboratory elutriate-type test has also been evaluated (Myers et al., in prep.).

## Volatile Contaminant Releases

Dissolved organic chemicals are available at the air-water interface where volatilization can occur. Although the dissolved phase concentrations and therefore the evaporative flux are highest near the dredge, the mass release rate (flux times area) may be dominated by the lower concentration region away from the dredge.

Methods for predicting the rate of volatilization across the sediment-water interface are fairly well developed. To apply these methods at a dredging site requires the application of a mixing model to define both the area of the contaminant plume and the average dissolved-phase contaminant concentrations within that plume (Myers et al., in prep.).

---

View the graphical version of this page at: http://www.epa.gov/grtlakes/arcs/EPA-905-B94-003/B94-003.ch4.html

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 5. TRANSPORT TECHNOLOGIES

Transport technologies are used to move sediments and treatment residues between components of a remedial alternative. In most cases, the first element of the transport component is to convey sediments dredged during the removal process to the disposal or rehandling site. Sediments may then be transported for pretreatment and then treatment, and treated residues may be transported to a disposal site. Transport is the component that links the other components of a remedial alternative, and may involve several different technologies or modes of transport.

Transport modes can include waterborne, overland, or a combination of these technologies. Waterborne transport modes include pipeline transport, hopper dredges, and barge systems. Overland transport modes include pipeline, railcar, truck trailer, and conveyor systems. In most cases, contaminated sediments are initially moved using a waterborne transport mode (pipeline or barge) during the removal process (one exception is when land-based dredging is used). Hydraulic removal technologies produce contaminated, dredged material slurries that are typically hauled by pipeline transport to either a disposal or rehandling site. Mechanical removal technologies typically produce dense, contaminated dredged material or excavated basin material for rehandling, which is hauled by barge, railcar, truck trailer, or conveyor systems.

Averett et al. (in prep.) provide a literature review of dredged material transport technologies. Other key resources for information on transport technologies include Churchward et al. (1981), Souder et al. (1978), Turner (1984), and USEPA (1979). Much of the information on transport technologies in the literature cited herein was developed for application to municipal sewage sludge, dredged material, and mining materials. The intended applications were generally scaled for very large quantities of materials. In many instances, these materials were transported over long distances, using permanently installed systems as part of long-term operations. In contrast, sediment remediation projects will typically move relatively small quantities of material over short distances and are often short-term operations. The feasibility and costs of transportation modes will be influenced by the scale of the remediation project.

This chapter provides a brief description of the pipeline, barge, railcar, truck trailer, and conveyor transport technologies. Discussions of the factors for selecting the appropriate transport technology and techniques for estimating costs and contaminant losses during transport are also provided. When transport modes are compared and contrasted with each other, the volumes of material being discussed are in-place cubic yards or cubic meters of sediment.

### DESCRIPTIONS OF TECHNOLOGIES

### Pipeline Transport

Temporary dredge pipelines are the most economically feasible mode for hauling contaminated dredged material slurries and water. For a sediment remedial alternative, pipelines may be used for the discharge from a hydraulic dredge; with the hydraulic pumpout from a tank barge, railcar, or truck trailer; and in routing process water, effluent, or leachate to treatment systems.

The amount of dredged material slurry generated during sediment removal is greatly affected by the contaminated sediment characteristics, removal equipment design, and removal equipment operation. Pipeline transport systems should be hydraulically designed and operated to minimize downtime while effectively moving this slurry. Equipment durability and pipeline routing greatly affect system downtime. Effective slurry transport consists of moving the slurry with minimal particle sedimentation in the line and with good line connections and minimal line wear and corrosion. Other factors being equal, fine-grained dredged material can be less costly to move (i.e., require less energy) than coarse-grained material (Denning 1980; Souder et al. 1978; USEPA 1979).

It is periodically necessary to halt dredging operations to add or remove sections of the pipeline to permit vessel passage or dredge advance, repair leaks, or reroute the line. Therefore, pipeline sections should be quick and easy to assemble, maintain, and dismantle. Although leaks can be welded, extra pipe sections should be readily available onsite to replace both land- and water-based pipeline sections that are clogged or leaking. Frequent monitoring helps to prevent excess leakage (Cullinane et al. 1986a).

### *Discharge Pipeline*

Hydraulic dredge discharge pipelines can be identified by their properties (i.e., construction material, internal diameter, relative strength or schedule number, length, wall thickness, or pressure rating) or method of deployment (i.e., floating, submerged, or overland). Discharge pipelines typically range in length from <3 to >15 km (with boosters) (Cullinane et al. 1986a; Souder et al. 1978; Turner 1984). Souder et al. (1978) indicate that during commercial land reclamation projects slurries have been moved through pipelines of up to 24 km in length, and that a well-designed hydraulic dredge system can theoretically move some slurries >200 km using multiple booster pumps.

Discharge pipe sections are available in a variety of wall thicknesses and standard section lengths. The internal diameter, which is slightly larger than the diameter of the dredge suction line, ranges from 6 to 42 in. (15 to 105 cm; Turner 1984). Internal pipe section linings of cement, plastic, or glass can reduce the abrasion caused by slurry-entrained gravel, sand, and site debris; metal corrosion caused by sediment-bound contaminants and saline transport water; and the internal pipe roughness. In addition, internal abrasion and corrosion can be evenly distributed by periodically rotating each pipe section. External metal pipe corrosion can be controlled with coatings and/or cathodic protection.

Several types of discharge pipelines available for use are discussed below.

***Rigid Pipeline***--Rigid pipe sections can be constructed of steel, cast and ductile iron, thermoplastic, and fiberglass-reinforced plastic; the steel and iron sections are most commonly used. These sections can be joined by ball, sleeve, or flange joints to form discharge lines of varying lengths. The rigid nature of these sections permits longer, unsupported line spans and reduces the potential for damage while handling. Standard steel and iron pipe section lengths are 20, 30, and 40 ft (6.1, 9.1, and 12.1 m).

***Flexible Pipeline***--Flexible discharge pipe sections are constructed of either high-density polyethylene (HDPE) or rubber. The flexibility of the materials allows these sections to naturally adjust to wave action and shore contours. Therefore, these pipelines are easier to route than rigid pipelines. In addition, the flexible nature of these pipelines allows long-sweeping and more hydraulically efficient routing. However, flexible pipelines are far less commonly used than rigid pipelines.

***Floating Pipeline***--Discharge pipelines typically include a floating pipeline connected to the dredge pump(s) at the stern of the dredge hull. The floating pipeline can subsequently be run to a shore-based pipeline routed to the disposal or rehandling site. Because of concerns about obstructions in these pipelines and their overall stability, their use is typically limited to sections that connect the dredge pump to the land-based line. These sections provide for easy dredge movement (i.e., swing and advance). The dredge pump is connected to a floating rigid pipeline by either a rubber hose, swivel elbow, or ball joint(s). These lines are typically anchored at various locations.

Pipeline flotation is accomplished using pontoons or buoyant collars. Pontoons are typically constructed of metal cylinders with tapered ends, mounted to each end of a pipe section. The pontoons are joined together by rigid, wooden or steel beams. The rigid pipe section is attached to wooden pontoon saddles. Tender boats are used to move floating pipeline sections.

Obstruction of the waterway can be minimized by routing the pipeline to and along the shoreline. However, these pipelines should be placed in waters of adequate depth and distance from the shoreline to prevent the lines from dragging on the bottom and/or ramming the shoreline. When obstruction of the waterway is of little concern, the pipeline should be floated in a wide arc so that the dredge can advance without frequent stops to add additional pipe sections (Huston 1970).

***Submerged Pipeline***--Submerged pipelines can be used in place of floating pipelines in waterways where vessel traffic would require frequent dredge downtime to disconnect the line and permit passage. Submerged pipelines require two stationary points where the ends of the line can be fixed as they rise out of the water. For temporary lines, these points are typically well-moored barges (Huston 1970). Although less susceptible to damaging wave action, submerged pipelines should be used conservatively because inspection for plugs and leakage is difficult.

***Shore Pipeline***--Relative to floating and submerged pipelines, shore pipelines are made up of shorter (10-15 ft [3-5 m]) and generally lighter pipe sections. Pipe sections are joined and placed aboveground or on a cribbing. These lines should only be covered to protect the line from damage (i.e., traffic crossings, freezing/thaw conditions) because detection of leakage is difficult. Shore pipelines generally flow into a disposal or rehandling site.

### *Booster Pump*

Booster pumps (kinetic or positive displacement) supplement the dredge pump(s) by increasing the distance a slurry can be pumped without particle sedimentation. Booster pumps are used when the output of the dredge pump(s) is so reduced by line routing that the cost of a booster pump is justified by the increased productivity it achieves. Although easier to design, booster pumps do not have to be identical to the dredge pump(s). For dredges that operate with long discharge lines and require booster pumps, Turner (1984) indicated that installing a booster pump on the dredge hull would reduce labor and maintenance costs. This layout would lower the labor costs typical of line booster pumps but would increase material costs for pipelines necessary to withstand increased pressures.

Booster pumps are installed to form a series of identical pumping stations (barge- or land-based) generally spaced uniformly from the dredge to the disposal or rehandling site. At each pumping station, two essentially similar pumps are arranged in series. However, if deemed necessary to optimize the reliability of the operation, an auxiliary spare pump and motor with all pertinent piping, valves, and connections can be provided for emergency use in the event of a major breakdown in the primary equipment. Positive displacement booster pumps used in combination with a centrifugal dredge pump would require a booster pump holding facility because it is practically impossible to match positive displacement pumping rates to centrifugal pumping rates (USEPA 1979).

## Barge Transport

Transport barges or scows can be defined as cargo-carrying craft that are towed or pushed by a powered vessel on both inland and ocean waters (McGraw-Hill 1984). Barge transport is the most common means of transport for mechanically dredged material. Features of barge transport that are discussed in this section are barge types, tow operations, and loading/unloading operations.

### *Barge Types*

Three types of barges that are applicable to sediment remediation projects are the tank, hopper, and deck barges. The features of these barges are provided in Table 5-1. Tank barges are most frequently used to haul coal, petroleum and petroleum products, agricultural products, iron, steel, and chemicals. Sectionalized compartments provide structural stability to the barge hull, distribute cargo loads more evenly, help prevent cargo from shifting while in tow, and allow each section to carry different types of cargo.

Hopper barges are designed specifically to deliver bulk material to open-water disposal sites, and are the most commonly used barges for transporting dredged material. Early hopper barge designs used mechanically driven chain, cable, sheave, and releases to open the cargo compartment door(s). Recent designs use high-pressure hydraulic systems. Split-hull and continuous compartment bottom and side-dump hopper barges are simultaneously dumped, whereas bottom and side-dump hopper barge sections can be dumped individually.

The Buffalo District studied the leakage from hopper barges and concluded that all hopper barges leak to some degree. They concluded that all hull seams should be carefully shut and stabilized with sandbags, hay bales, and/or plastic liners to help minimize hull leakage.

Deck barges are simply a flat work surface and may be used as a work barge (i.e., anchor, derrick, jack-up, mooring, office, pontoon, quarterboat, service, shop, store, or survey barges) or the platform for the dredge. During a sediment remediation project on the Black River in Lorain, Ohio, a single deck barge was used as the platform for a bucket dredge and several dumpsters that were used to contain the dredged sediments. After the dumpsters were filled, the barge was brought to the shore, where the dumpsters were offloaded to flatbed trucks and hauled to a nearby disposal site.

Barge hulls can be of either single- or double-walled construction. The bow and/or stern of a barge hull is either vertical (box-shaped) or raked (angled). Raked hulls provide less tow resistance, thereby resulting in fuel savings, while box-shaped hulls are typically limited to barges on the interior of an integrated tow of multiple barges. Barges operated in moderately high wave areas can be constructed with a notched stern in which the towboat bow fits. This connection provides greater resistance to longitudinal movement along the vessel interface and enhances control under adverse conditions (Churchward et al. 1981).

### *Tow Operations*

In the absence of significant wave action, the best position for a towboat is at the barge stern (Churchward et al. 1981). While the main factor in selecting a towboat is its ability to maneuver and push or tow the barges, the towboat's draft is also an important factor. The towboat draft should be consistent with site and transport route water depths to prevent sediment resuspension from propwash and hull dragging. Towboats are also used to move the dredge floating plant (when not self-propelled).

Although grain- or coal-filled barges are typically moved in large, integrated tows (up to 40 barges), dredged material-filled barges are generally hauled individually. A typical maintenance dredging operation might use two barges (one is filled by the dredge while the other is being transported to or from the disposal or rehandling site). If the distance between the dredging and disposal or rehandling site is long, additional barges and towboats may be used. The objective is to have sufficient barges and towboats available to keep the dredge operating continuously.

Spillage during transport can result from overfilling the barge or from a leaky hull. Risks of spillage are especially great when moving through rough waters. Overfilling can be prevented by filling the barge only to the bottom of the barge coaming. Spillage while in tow can be prevented by placing removable covers over the barge coaming. Barge hulls should be inspected regularly to ensure that they are completely sealed.

### *Loading/Unloading Operations*

Tank and hopper barges are typically loaded by first pulling the barge adjacent to the dredge floating plant. Dredged sediment is frequently splashed or dropped onto the deck of a barge during loading operations. Spillage can be reduced by minimizing the height from which the bucket releases its load. Dredge operators should place the bucket into the cargo compartment before releasing the load and not drop it with any freefall. In addition, tank barges should be loaded uniformly to prevent excessive tilting or overturning.

During maintenance dredging of uncontaminated sediments, supernatant is allowed to overflow during filling to increase the barge's payload (i.e., reduce the amount of water hauled). Because of the potential for contaminant release and the inefficiency of barge overflow for fine-grained sediment, supernatant overflow should not be permitted on contaminated sediment dredging projects. Methods to remove free-standing water from barges, including the use of polymer flocculants, have been investigated by some Corps districts to produce more economical loads with contaminated dredged material (Palermo and Randall 1990).

Most barges can be unloaded using a variety of mechanical equipment, including cable, hydraulic, or electrohydraulic rehandling buckets (Hawco 1993). Backhoes and belt conveyors or bucket line dredges can also be used to unload barges. All unloading facilities should be equipped with drip pans or aprons to collect material spilled while unloading the barge and loading the material onto a railcar, truck trailer, or conveyor or directly into a disposal or rehandling facility.

Mechanically dredged sediments have been unloaded from barges to CDFs using a modified hydraulic dredge or submerged dredge pump. Water from the rehandling site or disposal facility (where available) is added to the barge and mixed in with the sediment to provide a uniform slurry for the rehandling dredge pump.

## Railcar Transport

Railcar transport is widely used in the transport of sewage sludge, but has not been used for the transport of dredged material (according to available literature). However, railcar transport of contaminated sediments may be feasible when travel distances are especially long (i.e., >160 km).

Railcar designs can include tank, hopper, deck, and box cars (Churchward et al. 1981). Mechanically filled tank and hopper railcars are most likely the only economical means of hauling contaminated dredged material. The features of tank and hopper railcars are summarized in Table 5-2. Tank cars might also be used to haul liquid treatment residues. Souder et al. (1978) indicate that railcars of the 70- to 100-net ton class are preferable for hauling bulk materials such as dredged sediment. Tank and hopper railcars can be constructed with permanent or hatched covers to prevent weather effects and spilling or leaking of material or water from the car. Like barges, railcars should be uniformly loaded.

Railcars are pulled by either diesel- or electric-powered locomotives. However, with the exception of switching facilities, railcars must be hauled by a railroad company locomotive, requiring a contract that can take several months to obtain (USEPA 1979). Larger trains (railcar capacity and number of cars) are limited by track system designs and crossing times.

***Tank Railcars***

Rectangular tank railcars are typically used to haul dense materials. They are unloaded by moving them off the mainline track to an elevated loop track, disassembling the train, and dumping each car using rotary car unloading equipment. The rotary car technique turns the railcar upside down to allow gravity drainage. Swivel tank car connections can be used to avoid disassembling the train during rotary dumping. Rotary dumping equipment is very expensive and generally works best for non-cohesive materials (Souder et al. 1978). Shaker units can be used to help unload the typically cohesive contaminated dredged material.

Cylindrical railcars are typically used for hauling liquid cargo and could be used for hauling dredged material slurries. These cars are hydraulically filled and are unloaded by moving them to an elevated track to allow gravity drainage through a hatch or valve opening(s) on the car body. Tank cars can also be pumped out.

***Hopper Railcars***

Similar to tank railcars, hopper railcars are typically unloaded by moving them to an elevated loop track. Hopper railcars are unloaded by opening the bottom-mounted hopper door(s) or hatch(es) to allow gravity drainage (Souder et al. 1978). Unlike rotary unloading, bottom dumping of hopper railcars does not require disassembly from the train prior to unloading and, depending on the material cohesion, the train may not even have to come to a complete stop.

## Truck Trailer Transport

Truck trailer transport is the most common mode of transportation for hauling mechanically dredged material to upland disposal sites. Truck cargo compartments can include van (open and closed tops), flat, tank (liquid or pneumatic cargo), dump, depression deck, rack, or refrigerated (van or tank) types (Churchward et al. 1981). However, only tank and dump compartments are suitable for hauling dredged material and liquid treatment residues. The features of these types of trailers are summarized in Table 5-3.

Tank and dump compartments can be mounted on a single diesel- or gas-powered tractor chassis or mounted on a trailer chassis and towed by a tractor over both paved and unpaved roads. To minimize the number of drivers required and to allow loading to continue while other trucks are en route, it is desirable to use excess trailers. As with barge and railcar transport, mechanically filled trailers are the only economical means of hauling contaminated dredged material by truck. Liquid treatment residues (e.g., contaminated oil residue from solvent or thermal extraction processes) can be hauled in cylindrical tank trailers.

Trailer gates and hatches can be sealed with rubber gaskets, straw, or other materials to prevent leakage or spillage. During a dredging operation at Michigan City, Indiana, the bottom of dump truck flap gates were lined with sand, and a street sweeper was used to clean any drippage on public roads. Dump truck gates fitted with neoprene seals and double redundant locking latch mechanisms were used to haul dredged material during the Starkweather Creek cleanup in 1992 (Fitzpatrick 1993). Like barges and railcars, trailer covers can be installed to minimize odor releases during transport, to prevent spillage from sudden stops or accidents, and to prevent weather damage. Trailers should also be uniformly loaded.

## Conveyor Transport

Conveyor systems have been widely used for the transport of sewage sludge and for material transport in mining and mineral processing (USEPA 1979). Within a sediment remedial alternative, conveyors might be used to transport mechanically dredged sediments from barges to disposal or rehandling sites, from rehandling sites to pretreatment and/or treatment systems, between process units of a pretreatment/treatment system, and, for solid residues, from treatment systems to disposal sites or to other transport modes.

Conveyor transport systems include belt, screw, tabular, and chute systems. The features of the belt and screw conveyor systems are summarized in Table 5-4. These conveyor systems typically require a loading or feeder bin from which the material is placed on the conveyor. An unloading or feedout bin may also be required, depending on whether the material is going to a disposal/rehandling site, a pretreatment or treatment unit, or another mode of transport.

Commercially available conveyor systems can be permanently installed or portable. Portable conveyors provide system flexibility and allow material to be placed over a wider area. These systems are most practical for handling small volumes of mechanically dredged material (USEPA 1979; Souder et al. 1978). For example, a small conveyor system was used to transport materials in the pilot-scale demonstration of sediment washing technologies conducted for the ARCS Program at Saginaw Bay, Michigan (USACE Detroit District, in prep.).

Conveyors have low operating costs and move high volumes with minimal noise and air pollution. However, they can be expensive to purchase and very labor intensive and, like pipelines, may require right-of-way permission. Chute systems that lead from one flight to another can become clogged by oversized pieces. Like pumps and pipelines, conveyors are a continuous system; therefore, if one segment fails the whole system fails (Souder et al. 1978).

Chute or inclined plane conveyors or slides have no mechanical parts. Chutes have been used to move mechanically dredged sediments from barges into CDFs adjacent to navigable waterways. Examples of chutes used at the Chicago Area CDF are shown in Figure 5-1. Sediments were unloaded from the barges using a crane and small bucket and placed onto the chute, which carried the sediments into the CDF. In some cases, water was sprayed onto the chute to help move the material. Based on the use of chutes for sewage sludge, it is recommended that the incline be greater than 60deg. for dewatered material and greater than the material's natural angle of repose for dried material. These systems can be open or covered to prevent spillage (USEPA 1979). Relatively shallow slopes (30deg. and less) have been used with slides transporting wet dredged material.

## SELECTION FACTORS

The limitations of each transport technology should be considered prior to selecting the contaminated sediment transport mode(s). These limitations might include legal, political, sociological, environmental, physical, technical, and economic practicality. Souder et al. (1978) developed a generalized sequence for selecting alternatives for inland transport of clean dredged material. The selection factors for contaminated sediment transport adapted from Souder et al. (1978) include: compatibility with other remedial components, equipment and route availability, compatibility with environmental objectives, and costs.

### Compatibility with Other Remedial Components

The selection of transport modes should be among the last decisions in the planning of a sediment remedial alternative. In many cases, the selection of other remedial components will eliminate all but one or two transport modes for consideration. For example, a remedial alternative involving hydraulic dredging will, with few exceptions, necessitate pipeline transport. Mechanically dredged sediments, on the other hand, can be transported using any of the modes discussed, including pipeline transport (although sediments will have to be slurried).

Some disposal/rehandling facilities can accommodate both hydraulically or mechanically transported sediments. Others, because of limited size or design features, cannot accommodate loadings by hydraulic slurry. Many treatment and pretreatment technologies have rigid restrictions on both the character and rate of feed material delivery. Residues from pretreatment or treatment systems may require continuous handling to subsequent components, or may be stockpiled for bulk handling. Transport modes must therefore be compatible with all components of a remedial alternative.

### Equipment and Route Availability

#### *Equipment Availability*

Availability is rarely a limiting factor in the selection of transportation equipment. Most contaminated sediment sites are in urban areas, with transportation equipment available from several sources. At worst, equipment will have to be brought in from a greater distance, increasing the mobilization and demobilization costs.

> ***Pipeline and Barge Transport***--Equipment for waterborne transport is readily available for leasing from dredging and marine construction contractors. The availability of specific equipment, including pipelines and barges, will reflect regional markets for their use and the dimensional restrictions (e.g., vertical clearance, width, draft) of regional waterways. Dredging/marine construction trade journals, such as *International Dredging Review*, *Terra et Aqua*, *World Dredging, Mining and Construction*, and *The Waterways Journal*, contain the names of contractors and advertisements for equipment lease or purchase.
>
> ***Railcar Transport***--Railcars filled with sediments or treatment residues may be added to an existing train route or transported as an entire trainload of railcars or "unit train." Single-car transport can require that a railcar be switched from train to train several times, resulting in increased costs. A unit train operation, commonly applied to hauling coal, is negotiated with a railroad company and is dedicated to carrying only one commodity from one point to another on a tightly regulated and continuing schedule.
>
> A unit train operation could haul from 70 to 140, 100-ton (91 tonne) railcars (approximately 10,000 tonnes of contaminated dredged material) over distances of 80-2,400 km. Souder et al. (1978) recommended haul volumes of greater than 380,000 m[3] and haul distances greater than 80 km to support a unit train operation. A shorter haul distance increases the cost significance of loading and unloading.

***Trailer Transport***--A variety of truck trailer rigs may be leased or contracted through most large construction companies. There are numerous State and Federal restrictions on the size (vehicle width, height, and length) and weight of truck trailer rigs. Some regulations limit the number of trailers in tow by a tractor. Some weight regulations provide for the maximum weight that can be carried on single and multiple tandem (two grouped) axle groupings. However, most weight restrictions relate the overall or gross weight to the vehicle's wheel base. Most State regulations limit truck trailer loads to about 25 tons (23 tonnes). Other regulations include speed limits; requirements for safety features such as speedometers, brakes, horns, lights, windshield wipers, mirrors, and bumpers; and requirements for liability insurance. Some local ordinances even restrict truck operations to certain hours of the day and to certain routes (Souder et al. 1978).

***Conveyor Transport***--Conveyor systems are widely used in wastewater treatment and mining applications. Conveyor equipment may be purchased from suppliers to these industries identified in trade journals, including *Water and Waste Digest* and *Waterworld Review*. Some types of conveyor equipment may also be available for lease from the manufacturers or from dredging and construction contractors. Chutes and slides are typically fabricated by the dredging/transport contractor from purchased or available material. One dredging contractor split two abandoned railroad tank cars in half lengthwise and welded them into an open slide for transporting dredged material into the Chicago Area CDF (Figure 5-1).

### *Route Availability*

Factors associated with transport routing include route constraints and scheduling. Route constraints include the availability of existing routes, rights-of-way for access, size and weight limits, and site obstructions. Transportation routes should run through areas that would be the least sensitive to accidental releases, where possible. The entire route should be easily accessible for maintenance, monitoring, and spill response. Site obstructions can affect the transport modes, or the transport modes can block traffic flow on existing routes. Scheduling difficulties may result from traffic interruption, overloads, and shutdowns due to harsh weather conditions (Souder et al. 1978). Routing difficulties can result in lengthy transport times, decreased efficiency, and increased costs.

***Pipeline Transport***--To deploy pipelines for a sediment remediation project, easements and rights-of-way must be obtained for the entire route. The ability to obtain even temporary easements for pipelines will be complicated because of the contaminated nature of the sediments. Pipeline crossings at roads and railroads may require special construction or excavation. Because sediment remediation projects are most likely in highly urbanized/industrialized areas, routing may be a major limitation in the use of pipelines.

***Barge Transport***--Barge selection, routing, and transit time are greatly affected by channel dimensions, site obstructions, other channel and seasonal conditions, speed limits and other restrictions, traffic congestion, and user fees. In addition to the length, width, and depth of a channel, other factors affecting barge access include lock sizes, bend radii, and structures (e.g., piers, jetties). Barge and tow boat drafts (loaded) should be less than the shallowest channel depth in the dredging area and on the tow route. Site obstructions can include height limitations caused by bridges or power lines and submerged objects such as cables, pipelines, piles, and rock. Transient or seasonal conditions that can affect barge access include water depths, currents, tidal influence, wave action, and icing. The number of barges required for a project will depend on the dredge production rate, haul volume, and travel time (distance, routing, unloading).

The majority of barge traffic in the Great Lakes area is limited to relatively short hauls that run close to lake shorelines. However, barge dimensions allowed in the Great Lakes area are typically larger than those of other inland barges because of larger lock dimensions (Churchward et al. 1981). The potential for substantial wave action generally demands that ocean-going barges (self-propelled or towed) or ships traverse the Great Lakes.

The *U.S. Coast Pilot* (a National Ocean Service annual report) contains detailed information about navigation regulations and channel restrictions for the Great Lakes and connecting channels. Navigation charts are available from NOAA. Additional information about channel restrictions, traffic, and user fees can be obtained from local harbor authorities, the Corps, or the U.S. Coast Guard.

***Railcar Transport***--With the exception of short spurs constructed to provide access to a disposal site, economic railcar transport typically demands the use of existing railroad track lines. These track lines are readily available in most industrialized areas. Mainline spur construction, if permitted, would be too expensive for low-volume dredged material transport. In addition, efficient railcar loading and unloading (bottom or rotary dump) facilities are required to make the unit train concept work and to realize the benefits derived from reduced rates on a large haul.

***Truck Trailer Transport***--There are about 5.6 million km of paved roads in the United States, of which about 912,000 km (25,600 km of interstate) can be considered for a transport system route (Souder et al. 1978). However, unpaved roads can be constructed relatively quickly at nearly any project site. Therefore, truck routes are more flexible and faster to construct than either waterway or railroad track routes. Because terminal points and routes can be changed readily at little cost, truck trailer transport provides a flexibility not found with other modes of transportation.

### Compatibility with Environmental Objectives

Transport technologies are inherently designed to contain their cargo during transport. With the exception of volatilization, contaminant losses (e.g., leakage during transport or spillage during loading or unloading) are generally the result of poorly maintained or operated equipment. Most transport modes have one or more controls that can be applied to limit leakage occurring as a result of transport and spills during loading and unloading (e.g., covers, gate seals, splash aprons); however, these controls are only a few of the necessary steps to minimize contaminant losses. Transport equipment should be tested for leaks prior to hauling contaminated material and should be carefully monitored during operation. As with dredging operations, the amount of spillage during rehandling is greatly affected by the time and care taken by equipment operators.

The exteriors of barges, railcars, and truck trailers should be cleaned prior to leaving the loading or unloading facilities. These loading/unloading areas should be designed so that cleaning and runoff water can be collected at a central location and treated as necessary. After final use, barge, railcar, truck trailer, and conveyor interiors can be decontaminated using high-pressure water sprays. Pump/pipeline systems can be decontaminated by pumping several pipeline volumes of clean water through the system.

The applicability of Federal, State, and local environmental laws and regulations on the transport of contaminated sediments and treatment residues should be investigated on a case-specific basis. Federal regulations on the transport of hazardous and toxic materials include the Hazardous Materials Transportation Uniform Safety Act, RCRA, and TSCA. Specific requirements exist for transport, including registration, labeling, packaging, placarding, and material handling (UAB 1993).

Waterborne transport of contaminated materials may also be regulated by the International Maritime Dangerous Goods Code, which identifies some materials as "marine pollutants" with specific stowing requirements (Currie 1991). Federal regulations generally address interstate transport, and State and local regulations covering intrastate transport may differ from the Federal regulations (UAB 1993).

Virtually all transport modes have environmental effects unrelated to their cargo. Towboats, trucks, trains, and conveyors all have exhaust from their diesel- or gas-powered engines or generators. Towboats used to transport barges may cause sediment resuspension along the route, especially at locations where the barge accelerates, decelerates, or changes directions. A number of studies have been conducted to evaluate the physical, biological, and chemical effects of commercial navigation traffic in large waterways (Miller et al. 1987, 1990; Way et al. 1990; Miller and Payne 1992, 1993a,b).

## ESTIMATING COSTS

The transport component of a sediment remedial alternative may incorporate several modes of transport to connect different components. For example, the remedial alternative shown schematically in Figure 5-2 uses pipeline transport between the hydraulic dredge and the rehandling facility. Dewatered sediments are removed from the rehandling facility using a front-end loader and placed onto a conveyor for transport to a pretreatment unit (rotary trommel screen). The primary residue of the pretreatment unit is transported to the thermal desorption treatment unit by another conveyor. The oversized residues of the pretreatment unit and the solids residues of the treatment unit are transported to the disposal facility by conveyor. The liquid (organic) residue of the treatment process is placed into a tank trailer for transport to a commercial incinerator. Water from the rehandling, pretreatment, treatment, and disposal units is routed to a wastewater treatment system through pipelines.

For a remedial alternative such as the one shown in Figure 5-2, it is likely that some modes of transport would be subcontracted as parts of other components (e.g., the pipeline would be supplied by the hydraulic dredging contractor), while others (e.g., conveyors) might be subcontracted separately. For most sediment remediation projects, all transport equipment would be leased or contracted. The transport costs would therefore be entirely capital costs, with no operation and maintenance costs.

Churchward et al. (1981) indicate that the main considerations for selection of the transport modes include cost, flexibility, capacity, and speed. A comparative analysis of these characteristics for pump, barge, railcar, and truck trailer transport, as developed by Churchward et al. (1981), is shown in Table 5-5.

In comparison with the other components, especially treatment, transport unit costs are relatively low. Therefore, the transport process should be scheduled for continuous operation to ensure that the other, more expensive processes can operate without interruption.

Souder et al. (1978) indicate that cost estimates should be regarded as generalized evaluations of the related costs of selected transportation modes under representative operating conditions. When specific applications are considered, the unique aspects of each application (e.g., terrain, weather conditions, labor rates) should be evaluated individually and more precise costs related to each specific application should be derived. The Corps' *Construction Equipment Ownership and Operating Expense Schedule* (USACE 1988) contains a method for computing dredging plant operating rates, which includes methods for estimating pipeline and barge transport costs.

Dredged material transport involves three major operations: loading, transport, and unloading. The loading and unloading activities are situation-dependent and are the major cost items for short-distance transport.

Souder et al. (1978) evaluated the costs of transporting large volumes (300,000 to >2.3 million m[3]) of clean dredged material over long distances (up to 500 km) as part of a study conducted by the Dredged Material Research Program. They indicate that, irrespective of the volume of material to be transported, the truck trailer and conveyor transport modes were considerably more expensive than the pipeline, barge, or railcar transport modes. They further concluded that truck trailer transport is labor- and fuel-intensive in comparison to other transport systems. Conveyors have a high investment cost but can move material efficiently. At lower volumes, conveyor costs are much higher than for other systems. However, at high volumes and shorter haul distances (<30 km) conveyor costs are competitive with all other transport modes except the pipeline system (not including conveyor chute systems for unloading facilities).

Based on technical considerations and cost derivation assumptions, Souder et al. (1978) concluded that pipeline transport is the most economical choice in most instances for transport volumes up to 760,000 m[3] and distances up to 160 km. Depending on the transport volume, barge or railcar transport will be the most economical systems for long-distance hauls. Railcar transport becomes more economical at higher volumes. Because of routing limitations, not all haul distances will be the same for each transport system.

Souder et al. (1978) indicated that for haul volumes <380,000 m[3] it is very difficult to realize the economies of scale required to achieve the relatively low transport rates derived in their analysis. If the transport costs developed by Souder et al. (1978) were modified for application to sediment remediation projects, it is likely that the loading/unloading costs for barge, truck trailer, and rail transport would increase because of the controls required to limit spills, and the relative costs of conveyors might be more favorable for the short hauling distances, such as those between remediation components (i.e., <1.5 km).

## Pipeline Transport

For projects involving hydraulic dredging and pipeline transport over short distances (<3 km), the costs for pipeline equipment, mobilization, and labor are included in the dredging costs, as described in Chapter 4. Separate transport costs should be developed for pipeline transport over longer distances, or for pipeline transport of sediment or residues independent of the dredging contract.

Souder et al. (1978) developed unit cost information for pipeline transport of various dredged material haul volumes from a rehandling basin to a disposal site at various haul distances. This hypothetical operation involved using a portable dredge to remove the dredged material from the rehandling basin and transporting the material by a permanently installed pipeline, operated by a contractor. However, the unit cost information provided here was adjusted to include only the discharge pipeline, centrifugal booster pump, and related labor costs. No real estate or right-of-way costs were considered.

Unit cost estimates for this hypothetical operation are shown in Figure 5-3. These unit costs include the discharge pipeline and booster pump costs, including installation, maintenance and repair, lay-up time, insurance, and miscellaneous costs. Discharge pipeline costs include annual costs for the purchase of the pipeline. Centrifugal booster pump costs include annual costs for the pump and motor, reduction gears, controls, foundation, and housing, and costs for power and a sealing water supply (Souder et al. 1978).

## Barge Transport

Barge carriers include major-line, branch-line, and local operations. Barge transport on the Great Lakes is provided under contract rates or long-term charters, with 26 percent of services provided by independent carriers (Churchward et al. 1981). Many dredging firms own barges and will subcontract additional barges as needed for a large job. For a project involving mechanical dredging and barge transport over short distances (i.e., <5 km), the costs for barge transport are included in the dredging costs presented in Chapter 4. If longer haul distances are required, or for barge transport of sediments or residues independent of the dredging contract, additional transport costs need to be estimated.

Souder et al. (1978) developed unit cost information for contracted tank barge transport of various dredged material haul volumes from a rehandling basin to a disposal site at various haul distances. This hypothetical operation involved using a bulldozer and backhoe to excavate the rehandling basin material, placing the material in a dump truck, moving the material from the truck into the tank barge, towing the barge to the disposal site, removing the material from the barge using a rehandling bucket, placing the material into a dump truck, and dumping the material into the disposal site.

Unit cost estimates for this hypothetical operation are shown in Figure 5-4. The cost information assumes that the rehandling basin and disposal site are both 2.4 km, by way of an existing road, from an existing barge mooring dock. As with the pipeline transport operation, this operation assumes that dredged material is transported under ideal conditions. Project-specific conditions may greatly affect these costs. The operation costs include annual costs for barge loading and unloading and the towboat and barge. Loading costs include backhoe, bulldozer, dump truck, and road maintenance costs. Unloading costs include crane and dump truck costs. Transport costs include towboat and barge costs, crew quarters and subsistence pay, and miscellaneous costs.

The cost engineering office of the Detroit District typically uses unit costs in the range of \$0.70 to \$1.50/yd[3]-mile (\$0.57 to \$1.23/m[3]-km) for preliminary estimates of barge transport of dredged material in the Great Lakes (Wong 1993).

## Railcar Transport

Railcar rates are quoted by either a class rate or commodity rate. Class rates generally apply to small-volume shipments like single-car transport and occur on an irregular basis. These rates are influenced by route terrain and distance, the number of railcar switches required, and the haul volume. Class rates are readily obtained, but are usually prohibitively expensive for hauling dredged material. Commodity rates generally apply to regularly scheduled shipments of large volumes, like unit train transport, and are obtained from local rail carriers on a case-by-case basis. Commodity rates are lower than class rates (USEPA 1979; Souder et al. 1978).

Souder et al. (1978) developed unit cost information for contracted hopper railcar transport of various dredged material haul volumes from a rehandling basin to a disposal site at various haul distances. This hypothetical operation involved excavating the rehandling basin material using a backhoe and placing it on a conveyor system that emptied into a hopper railcar. The railcars were towed by a locomotive to the elevated loop track at the disposal site where the material was emptied.

Unit cost estimates for this hypothetical operation are shown in Figure 5-5. The operation costs include annual costs for hopper railcar loading and unloading and the locomotive and railcars. Loading costs include a backhoe, portable and fixed conveyor systems (including feed and feedout bins), and elevated loop track construction costs. Unloading costs include elevated loop track construction costs. Transport costs include locomotive and railcar carrier costs.

Tank railcars are usually leased by the month from a private tank car rental company, with a 5-year minimum lease. In 1978, a large tank car rented for \$450/month (USEPA 1979). Hopper railcars are usually leased from the carrier.

## Truck Trailer Transport

Souder et al. (1978) developed unit cost information for contracted dump trailer transport of various dredged material haul volumes from a rehandling basin to a disposal site at various haul distances. This hypothetical operation involved using a backhoe to excavate the rehandling basin material and placing the material on a conveyor system that emptied into the dump trailer. The filled trailer was towed on an existing roadway to a newly constructed road leading into the disposal site and emptied.

Unit cost estimates for this hypothetical operation are provided in Figure 5-6. The operation costs include annual costs for loading the dump trailer and transporting it to the disposal site. Similar to railcar loading, trailer loading costs include backhoe and portable and fixed conveyor system (including feed and feedout bin) costs. Transport costs include truck trailer, driver, and fuel costs. Unloading costs are limited to the cost of constructing a temporary road into the disposal site.

The Detroit District uses unit costs between \$1.30 and \$2.50/yd[3]-mile (\$1.07 to \$2.05/m[3]-km) for preliminary estimates of truck trailer transport of dredged material (Wong 1994). The Chicago District estimated dump truck trailer unit costs (including truck trailer rental and labor) for 1-, 19-, and 32-mile (1.6- , 30- , and 51-km) haul distances to be \$2.21/yd[3] (\$2.91/m[3]), \$11.25/yd[3] (\$14.80/m[3]), and \$17.80/yd[3] (\$23.42/m[3]), respectively. They also estimated a unit cost of \$2.72/yd[3] (\$3.58/m[3]) to remove dredged material from a barge and place it into a truck trailer (Engel 1994).

### Conveyor Transport

Souder et al. (1978) developed unit cost information for contracted belt conveyor transport of various dredged material haul volumes from a rehandling basin to a disposal site at various haul distances. This hypothetical operation involved using a bulldozer and backhoe to excavate the rehandling basin material and placing the material on a conveyor system that moved the material to the disposal site where it was dumped. The operation assumed that the conveyor was routed over flat terrain and that there were no costs associated with obtaining right-of-ways and other real estate.

Unit cost estimates for this hypothetical operation are provided in Figure 5-7. The operation costs include annual costs for loading and operating (energy and labor costs) a portable and fixed conveyor system. Conveyor loading costs include backhoe and bulldozer costs. Conveyors do not require additional equipment for unloading.

## ESTIMATING CONTAMINANT LOSSES

There are a limited number of mechanisms for contaminant loss during the transport of contaminated sediments, and only one mechanism of contaminant loss can be predicted using *a priori* techniques (Myers et al., in prep.). Contaminant losses during loading and unloading operations are primarily the result of spills and volatilization. The amount of spillage during loading and unloading reflects the level of care taken by the operators and the efficiencies of any controls (e.g., drip aprons). Loading and unloading areas should be designed with systems to collect spillage and water used to wash transport vessels. This water should be routed to wastewater treatment systems. Contaminant losses from such treatment systems are discussed in Chapter 9, *Residue Management*.

Losses during transport are the result of leaks, volatilization, and accidental spills. The amount of leakage during transport reflects the containment efficiencies of the carrier vehicles. Accidental spills may occur as a result of equipment failure, operator error, or external influences (e.g., meteorological conditions). Although it is not feasible to entirely eliminate spills and leakage from transport systems for contaminated sediments, it is easier to design controls for these mechanisms of contaminant loss than to quantify them.

There is no *a priori* method for predicting the amounts of contaminants lost by spillage, leaks, and accidents from a transport mode. The only mechanism of contaminant loss that can be predicted is volatilization from transport systems without covers (i.e., barges, trains, trucks, and conveyors). Methods for predicting the loss of volatile and semivolatile organic contaminants from exposed sediments and ponded water have been developed, and are summarized in Myers et al. (in prep.). These predictive methods are almost entirely theoretical and have not yet been field verified.

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 6. PRETREATMENT TECHNOLOGIES

Pretreatment is a component of a remedial alternative in which sediments are modified or conditioned prior to final treatment or disposal. This definition is somewhat artificial, because some of the pretreatment technologies do "treat" the sediments, and if conducted alone, could logically be called a treatment component.

There are two primary reasons for pretreating contaminated sediments. The first reason is to condition the material such that it meets the requirements of the treatment and/or disposal components of the remedial alternative. Most treatment technologies require that the feed material (e.g., sediment) be relatively homogeneous and that its physical characteristics (e.g., solids content, particle size) be within a narrow range for efficient processing. Pretreatment technologies may be employed to modify the physical characteristics of the feed material to meet subsequent processing needs. Examples of the feed requirements for selected treatment technologies are shown in Table 6-1. Sediment treatment technologies that use a continuous feed system generally have more stringent requirements for pretreatment than those using a batch feed system. For example, oversized material can cause blockage or ruptures in conveyance systems. In addition, excessive fluctuations in the solids content can alter the process conditions, thereby reducing treatment efficiencies. Pretreatment requirements for sediment disposal are generally less stringent than those for treatment.

The second reason for pretreating contaminated sediments is to reduce the volume and/or weight of sediments that require transport, treatment, or restricted disposal. Some physical separation technologies can separate fractions of sediments that may be suitable for unrestricted disposal or beneficial use, and concentrate the contaminants in a smaller fraction of the sediments.

Most of the design and operating experience with the pretreatment technologies discussed in this chapter was developed from applications involving municipal and industrial sludges and mining and mineral processing. These applications are generally of a larger scale than that expected for most sediment remediation projects and are usually part of a permanent process operation, whereas most sediment remediation projects will be of shorter duration. These differences should be considered when applying guidance developed for processing municipal and industrial sludges and mining materials to contaminated sediment sites.

The applicability of pretreatment technologies to dredged material was examined by the Corps as part of a pilot program to investigate alternative disposal methods for dredged material from the Great Lakes (USACE Buffalo District 1969) and as part of the Dredged Material Research Program (Mallory and Nawrocki 1974). A detailed literature review of pretreatment technologies is provided by Averett et al. (in prep.).

This chapter provides descriptions of two types of pretreatment technologies--dewatering and physical separation. Discussions of the factors for selecting the appropriate technology and techniques for estimating costs and contaminant losses are also provided.

## DESCRIPTIONS OF TECHNOLOGIES

### Dewatering Technologies

Dewatering technologies are used in sediment remedial alternatives to reduce the amount of water in sediments or residues and to prepare the sediments for further treatment or disposal. The need for dewatering is determined by the water requirements or limitations of the treatment or disposal technologies and the solids content of the sediments following removal and transport.

Mechanically dredged sediments typically have a solids content comparable to that of *in situ* sediments (about 50 percent by weight for most fine-grained sediments). Hydraulically dredged sediments are in a slurry with a solids content typically in the range of 10-20 percent. Some hydraulic dredge pumps are able to move slurries with higher solids content, but the average solids content in an extended dredging operation is rarely greater than 20 percent. To prepare dredged sediments for most treatment or disposal technologies, water must be removed and/or the solids content of the sediments must be made more uniform. Dewatering will be required for most sediment remedial alternatives that involve hydraulic dredging or transport. If the sediments are mechanically dredged and transported, the dewatering requirements may be greatly reduced or eliminated.

Another function performed by dewatering is the reduction of the volume and weight of the sediments, which decreases the subsequent costs of handling, transport, and treatment and/or disposal of the solids. Dewatering will reduce the weight of a sediment load, but the effects of dewatering on the volume of a sediment load are more complex. When a sediment slurry is dewatered, the removal of free water will directly reduce the volume of material remaining in a nearly one-to-one relationship. Sediments that have been partially dewatered or mechanically dredged will lose additional water, but the volume will not always be reduced because the water driven from the voids between sediment particles is replaced by air. Some dewatering processes may even increase the volume of the sediments. The water removed during dewatering may be contaminated and require further treatment, as discussed in Chapter 9, *Residue Management*.

Three general types of dewatering technologies are discussed below:

- ✍ Passive dewatering technologies
- ✍ Mechanical dewatering technologies
- ✍ Active evaporative technologies

***Passive Dewatering Technologies***

In this document, the term "passive dewatering" refers to those dewatering techniques that rely on natural evaporation and drainage to remove moisture. Drainage may occur by gravity or may be assisted (e.g., using vacuum pumps). Some mechanical movement of the sediments, such as the construction of trenches, may also take place.

Dewatering of dredged material has traditionally been accomplished in CDFs, which rely on primary settling, surface drainage, consolidation, and evaporation. Subsurface drainage and wick (vertical strip) drains have also been demonstrated or used at CDFs to promote dewatering and consolidation. These technologies require significant amounts of land and are most effective if the sediments can be spread out in thin layers or "lifts."

Sediments can also be dewatered in temporary holding/rehandling facilities, tanks, and lagoons using the same design principles developed for CDFs. CDFs are discussed in more detail in Chapter 8, *Disposal Technologies*. Specific aspects of dewatering within a CDF or CDF-like structure are described below.

> ***Surface Drainage***--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 that remain permeable as they become filled. Water drains through the permeable sections, and suspended sediments become entrapped by the dike material (Miller 1990). At upland facilities, and at in-water CDFs that have filled above the water table, surface water is drained to the discharge point(s), which may include overflow weirs, filter cells, or pump control structures. Drainage water from a CDF includes both the water in the sediment slurry and rainfall runoff. Progressive trenching is a method employed to aid the drainage of water in CDFs and hasten evaporative drying.
>
> ***Evaporative Drying***--The desiccation of dredged material by evaporative drying results in the formation of a crust at the sediment surface. This method of drying is a two-stage process. The first stage of drying occurs until all free-standing water has been decanted from the dredged material surface. The corresponding void ratio at this point is termed the initial void ratio (eoo) and has been determined to occur at a water content of approximately 2.5 times the Atterberg liquid limit of the material. The second stage of drying occurs until the material reaches a void ratio called the desiccation limit (edl). At this point, evaporation of any additional water from the dredged material will effectively cease. The edl corresponds to a water content of 1.2 times the Atterberg plastic limit (USACE 1987b). The thickness of the crust and rate of evaporative drying and consolidation are dependent on local conditions and sediment properties, and can be estimated using the Primary Consolidation and Desiccation of Dredged Fill (PCDDF) module of the Automated Dredging and Disposal Alternatives Management System (ADDAMS) model (Schroeder and Palermo 1990).

***Subsurface Drainage***--A subsurface drainage system can be used at a CDF for dewatering of dredged material and/or leachate collection. One approach is the placement of perforated pipes under or around the perimeter of a CDF that drain into a series of sumps from which water is withdrawn. The pipes can be placed in a thin layer or trenches of drainage material, typically sand or gravel. The feasibility of subsurface drainage as a sediment dewatering technology may be limited where several layers of fine-grained sediments are to be disposed because they may clog the drainage materials.

Several variations of subsurface drainage systems can be used, including the gravity underdrain, vacuum-assisted underdrain, vacuum-assisted drying beds, and electro-osmosis. The gravity underdrain system provides free drainage at the base of the dredged material by the gravity-induced downward flow of water. The vacuum-assisted underdrain is the same as the gravity-fed system, but uses an induced partial vacuum in the underdrainage layer. The latter system improves dewatering by 50 percent (Haliburton 1978), but requires considerable maintenance and supervision.

***Wick Drains***--Wick drains or "wicks" are polymeric vertical strips that provide a conduit for upward transport of pore water, which is under pressure from the overlying weight of the material. By placing the vertical strips on 5-ft (1.5-m) centers to depths of 40 ft (12 m), both radial and vertical drainage are promoted. Wick drains can reduce consolidation time by a factor of 10 compared to natural consolidation (Koerner et al. 1986).

### *Mechanical Dewatering Technologies*

Mechanical dewatering systems have been extensively used for conditioning municipal and industrial sludges and slurries, as well as mineral processing applications. These systems require the input of energy to squeeze, press, or draw water from the feed material. Generally, mechanical dewatering technologies can increase the solids content up to 70 percent by weight. The features and requirements of six mechanical dewatering processes are summarized in Table 6-2 [part i] [part ii] [part iii].

The performance of a mechanical dewatering system is measured by a number of parameters, including:

- Chemical conditioning dosage, measured as the mass of conditioner per mass of dry solids
- Solids capture, defined as the dry mass of dewatered solids per dry mass of solids fed into the process
- Solids content of the dewatered material

With sewage sludges, the dosage of organic (polymer) conditioners in mechanical dewatering systems is generally <0.1 percent by weight, while the dosage of inorganic conditioners is substantially higher. For example, lime and ferric chloride may be used in dosages as high as 20 percent (Dick 1972).

A high solids capture is desirable, because solids lost from the process (i.e., in the filtrate or centrate) represent a route for contaminant loss. Some particulate loss during mechanical dewatering is inevitable; therefore, the effluent stream must be treated using treatment technologies described in Chapter 9.

Most mechanical dewatering processes increase the solids content of the feed material to a level comparable to that of the *in situ* sediment deposits (about 50-percent solids). These dewatering processes work best with homogeneous waste streams at a constant flow rate. Because hydraulic dredging produces highly variable flow rates and solids concentrations, direct dewatering of hydraulically dredged slurries would be inappropriate. Temporary storage in a tank, lagoon, or CDF would be necessary to equalize flows and concentrations prior to further dewatering by one of the mechanical processes.

Mechanical dewatering has been tested with dredged sediments on a limited scale (Averett et al., in prep.). A vacuum filtration unit was tested on sediments from Toledo Harbor, Ohio (Long and Grana 1978). The solids content prior to conditioning with lime ranged from 15 to 23 percent. The post-treatment solids content was consistently above 43 percent. An 2.5-m belt filter press was demonstrated on sediment from the Ashtabula River in Ohio at a rate of 23 tonnes/hour. Solids were increased to 50-60 percent by weight, with solids losses of 2-5 percent (Rexnord, Inc. 1986).

A substantial amount of design and operating guidance on mechanical dewatering systems has been developed for municipal and industrial wastewater applications (USEPA 1987b) and mineral processing applications (Weiss 1986). There are some fundamental differences between sediments and sludges that need to be considered when using this guidance, including:

- Sediments are usually less compressible, less gelatinous, and lower in organic content than wastewater sludges, and thus are generally easier to dewater
- The solids content of feed material, typically 3-6 percent in a wastewater treatment plant, will be considerably higher for sediments (15-25 percent)

- Sediments can contain rocks and large particles that can interfere with or damage dewatering equipment, necessitating pretreatment by screening
- Municipal sludges are generated on a continuous basis, whereas dredging produces sediments over a relatively short time scale
- The disposal of wastewater and filtrate is a relatively minor concern for municipal sludges because this water can be easily returned to the treatment process; however, wastewater from the dewatering of contaminated sediments is a significant concern, and separate treatment for this water may need to be employed

There are numerous manufacturers of mechanical dewatering equipment. Vendor contacts are listed in USEPA (1987b) and may be obtained through wastewater treatment and mining/mineral processing trade journals.

### *Active Evaporative Technologies*

Active evaporative technologies are different from the evaporative drying techniques used at CDFs in that artificial energy sources are used to heat the sediments, as opposed to solar radiation. Evaporation is the most expensive dewatering technology, but has been effectively used to prepare municipal sludges for incineration or for sale as fertilizer (Dick 1972). Nearly all of the water is removed, resulting in a solids content of about 90 percent. Technologies applied to sludges that may be applicable to fine-grained sediments include:

- Flash dryers
- Rotary dryers
- Modified multiple hearth furnaces
- Heated auger dryers

The most common conventional evaporation process used for waste recycling is agitated thin-film evaporation (Averett et al., in prep.). This process is capable of handling high-solids content slurries and viscous liquids. It may also be possible to use conventional evaporation equipment commonly found in the chemical-and food-processing industries. These technologies remove water in the form of steam and may also remove volatile contaminants.

Evaporative dewatering technologies have not been demonstrated with sediments on any scale. Most of the design and operating experience and guidance on these technologies are from municipal and industrial wastewater applications (USEPA 1987b).

## Physical Separation Technologies

Physical separation technologies are used in sediment remedial alternatives to remove oversized material and debris in order to produce an acceptable feed material for subsequent handling and treatment. These technologies are also used to separate the sediments into two or more fractions based on physical properties or characteristics to reduce the quantity of material requiring treatment or confined disposal.

The following types of physical separation technologies may be applicable to contaminated sediments:

- Debris removal
- Screens and classifiers
- Hydrocyclones
- Gravity separation
- Froth flotation
- Magnetic separation

The general features of these technology types are summarized in Table 6-3 [part i] [part ii] [part iii] and discussed in the following paragraphs. Many of the physical separation technologies discussed below are mineral processing technologies, which have been widely used in the mining industry to recover valuable minerals or metals from ores. Methods such as size classification, magnetic separation, gravity separation, or froth flotation, collectively known as mineral processing, can be applied in some cases to separate contaminated sediment fractions from the bulk sediments.

### *Debris Removal Technologies*

Dredged material often has significant quantities of debris and oversized materials. Examples of debris commonly encountered during dredging include: cobbles, bricks, large rocks, tires, cables, bicycles, shopping carts, steel drums, timbers, pilings, and automobiles.

Pockets of bulk materials, such as coal or gravel, may be encountered near docks and loading areas. The amount of debris is generally greatest in sediments along riverbanks and at bridge crossings, especially where there is unrestricted public access to the waterway.

Debris can be a significant problem for a dredging operation because it can clog hydraulic cutterheads and cause bucket dredges to be raised without full closure, resulting in increased sediment resuspension. Debris can also complicate the transport of dredged sediments, possibly requiring separate handling. Large debris must be separated and removed prior to any other pretreatment or treatment process. The size requirements of feed materials for various treatment technologies are shown in Table 6-1.

Debris may be separated during removal (dredging) or as part of material handling activities in between other components. For example, debris might be separated while sediments are being removed from a barge and transferred into truck trailers for transport, or while sediments are being removed from a disposal/storage area and fed into a pretreatment process. The technologies available for debris removal are relatively simple, such as a drag-line, grapple bucket, mechanical removal, and screens (discussed in later sections of this chapter).

A drag-line is a grappling hook or rake that is dragged along the river bottom with a steel cable from a boat or from a land-based winch. A grapple bucket is a specialized crane-operated bucket, commonly used for placement of large stones, that can be used to remove debris from a waterway. Large debris can be cleared from the sediments prior to dredging. This method may also be used to clear debris from a CDF prior to excavating sediments for treatment.

Mechanical removal is the separation of large debris using mechanical dredging or construction equipment. During a dredging operation employing a clamshell dredge or backhoe, large debris can be separated from the bulk of the dredged material. This requires a skilled operator and a place to store the debris. For a land-based operation, the debris might be separated and placed in a bin or dumpster for storage and transport. During marine operations, a clamshell dredge is often placed on a large floating platform, which may provide sufficient space for storing debris. Conventional earthmoving equipment that may be used for handling and rehandling of sediments between other components could also be used for separating large debris. Large plants may require grinding to ease rehandling and disposal.

Debris that has been separated is generally covered with contaminated sediments and may need to be decontaminated. Possible reasons for decontaminating debris include:

- The cost of disposal of the decontaminated debris is lower than the cost of disposal along with contaminated sediments
- The disposal facility for sediments will not accept the contaminated debris
- Transport of the contaminated debris is not allowable
- The decontaminated debris has a salvage value

Contaminated debris should be stored in a secure place or container until disposed or decontaminated. Decontamination may involve washing with water or steam. Wash water must be collected and treated as necessary.

### *Screens and Classifiers*

While hydrocyclones are the most popular separation devices, grizzlies, trommels, vibrating screens, and mechanical classifiers are all widely used in mineral processing applications. Screens and classifiers may be the first units in a complex separation process or the only units in a simple process. A trommel and vibrating screen were used in the ARCS Program demonstration at Saginaw, Michigan (USACE Detroit District 1994). A grizzly, vibrating screen, and screw classifier were used at a sediment remediation demonstration conducted at Welland, Ontario (Acres International Ltd. 1993).

### *Hydrocyclones*

A hydrocyclone is a high-throughput, particle-size classifier that can accurately separate sediments into coarse- and fine-grained portions. The typical hydrocyclone (Wills 1988) is a cone-shaped vessel with a cylindrical section containing a tangential feed entry port and axial overflow port on top and an open apex at the bottom (the underflow). A slurry of the particles to be separated enters at high velocity and pressure through the feed port and swirls downward toward the apex. Near the apex the flow reverses into an upward direction and leaves the hydrocyclone through the overflow. Coarse particles settle rapidly toward the walls and exit at the apex through a nozzle. Fine particles are carried with the fluid flow to the axial overflow port.

The particle size at which separation occurs is primarily determined by the diameter of the hydrocyclone. Hydrocyclones from 0.4-50 in. (0-125 cm) in diameter make separations from 1 to 500 um. The common practice is to employ several identical cyclones from a central manifold to achieve the desired capacity. Most manufacturers provide detailed manuals for selecting and sizing hydrocyclones (Arterburn 1976; Mular and Jull 1980).

The feasibility of using hydrocyclones for processing dredged material was investigated by the USACE Buffalo District (1969) and Mallory and Nawrocki (1974). A 12-in. (30-cm) hydrocyclone was tested using sediments from the Rouge River in Michigan. The physical separation was considered good, but the coarse fraction contained a large amount of volatile solids, determined to be detritus and light organic matter (USACE Buffalo District 1969).

Hydrocyclones were the major process unit used in a pilot-scale demonstration of particle size separation technologies conducted at Saginaw, Michigan, by the ARCS Program (USACE Detroit District 1994) and at a similar demonstration in Toronto, Ontario (Toronto Harbour Commission 1993). At the Saginaw demonstration about 75 percent of the sediments were successfully separated into a sand fraction, reducing the concentrations of PCBs from 1.2 ppm in the feed material to 0.2 ppm in the sand fraction.

#### *Gravity Separation*

Gravity separators separate particles based on differences in their density. Organic contamination in sediments is often associated with solid organic material or detritus, which have much lower densities than the natural mineral particles of the sediment. Particles with high concentrations of heavy metals would be significantly more dense than the natural mineral particles. A dense media separator was used at the ARCS Program demonstration at Saginaw, Michigan (USACE Detroit District 1994), and at the demonstration conducted in Toronto, Ontario (Toronto Harbour Commission 1993).

#### *Froth Flotation*

Froth flotation is used in the mining industry to process millions of tonnes of ore per day. Copper, iron, phosphates, coal, and potash are a few of the materials that can be economically concentrated using this process. The process is based on manipulating the surface properties of minerals with reagents so that the mineral of interest has a hydrophobic surface (i.e., lacks affinity for water) such as wax. The minerals to be rejected have, or are made to have, a hydrophilic surface (i.e., a strong affinity for water). When air bubbles are introduced, the hydrophobic minerals attach themselves to the bubbles and are carried to the surface and skimmed away.

When using flotation to remove oily contaminants from sediments, a surfactant is used in a manner that resembles a detergent. Most organic contaminants are naturally hydrophobic, and the objective in using a surfactant is to reduce the hydrophobicity of the oil phase to the point where it will be wetted by the water phase and detach itself from solid surfaces. Surfactants are able to accomplish this because such molecules have a lipophilic (fat-soluble) head, which is absorbed into the oil phase, and a hydrophilic tail, which extends into the water phase. The result of this is that the overall hydrophobicity of the oil phase is decreased. The strength of a surfactant's attachment to an oil phase is approximated by the hydrophile-lipophile balance of the surfactant. Once freed of the solid surface, an oil droplet is assisted to the surface by air bubbles and skimmed away.

#### *Magnetic Separation*

Magnetic separations are classified as two types depending on the intensity of the magnetic field employed (or the magnetic susceptibility of the minerals to be separated). Low-intensity separations usually employ permanent magnets, and are most often used for material coarser than about 75 um with high magnetic susceptibility, such as iron ore. High-intensity separations that employ electromagnets are much more versatile and capable of recovering iron-stained or rusted silicate minerals from other purer, nonmagnetic phases.

Wet, high-intensity magnetic separation (WHIMS) appears to be most applicable to sediment remediation, with separations possible down to 5 um, although at very low capacity. The WHIMS unit is essentially a large solenoid. Magnetic material is trapped on magnetized media in the chamber of the device, then flushed free in a rinse cycle when the feeding of sediment and magnetic current are stopped. Thus, the WHIMS is not technically a continuous throughput device, but operates in separate loading and rinsing cycles (Bronkala 1980).

Magnetic separation was used during part of the dredging and treatment demonstration conducted with sediments from the Welland River, Ontario (Acres International Ltd. 1993).

## SELECTION FACTORS

Not all remedial alternatives will require a pretreatment component, while others may require several process options for pretreatment. The need for pretreatment is generally driven by the treatment and/or disposal components selected for a remedial alternative and the physical characteristics of the sediments. A treatment technology with restrictive feed requirements may necessitate a multiunit pretreatment system, as illustrated in Figure 6-1.

The design of a pretreatment system must be compatible with other remedial components. Sufficient lands must be available at the treatment or disposal sites to operate pretreatment units and accommodate residues. Water extracted from dewatering technologies and process water from separation technologies may require a separate treatment system from that used for disposal site effluent or leachate. Some of the pretreatment water may be reusable within the process system.

## Dewatering Technologies

The selection of a dewatering technology usually involves choosing between a passive and a mechanical approach. Active evaporative technologies would only be employed where subsequent processes (e.g., thermal desorption or incineration) require extremely dry materials. The advantages and disadvantages of passive and mechanical dewatering are listed in Table 6-4.

If a permanent or temporary confined (diked) facility is a part of the remedial alternative, passive dewatering can be conducted within this facility. Facility design might accommodate a number of functions, including settling, dewatering, storage, rehandling, and disposal. Other pretreatment and treatment equipment might be stationed within or adjacent to the facility to minimize transport distances. Separate cells might be constructed in the facility to accommodate different functions. The design of CDFs is discussed in Chapter 8, *Disposal Technologies* .

Haliburton (1978) and the Corps' engineering and design manual, *Confined Disposal of Dredged Material* (USACE 1987b), provide detailed guidance on the use of CDFs for dewatering and consolidating sediments. The Corps developed computer software for evaluating the primary consolidation and desiccation of dredged material as part of ADDAMS (Stark 1991).

Mechanical dewatering is most suitable where land is not available for a temporary or permanent diked facility. Selection of a specific type of mechanical dewatering equipment depends on the requirements of the treatment or disposal components to follow. Maximum solids content is generally achieved using a recessed plate or diaphragm plate filter. However, if lower solids content is acceptable (e.g., for transport to a landfill), less costly processes such as centrifugation or belt filter presses may be more appropriate. A summary of selection factors is provided in Table 6-5.

Laboratory methods are available for predicting the performance of some mechanical dewatering systems. Prediction of vacuum and pressure filtration performance and capacity can be done with a filter-leaf test, which involves filtration on a filter medium disc of known area (Dahlstrom and Silverblatt 1980). Laboratory methods are also available to predict the performance of gravity thickening. The method of Coe and Clevenger (1916) is standard for simple gravity thickening, while the method of Kynch (1952) is more useful for coagulated or flocculated solids. For some mechanical dewatering systems, bench-scale or pilot-scale applications may be needed to fully assess equipment performance and operating conditions, and to select conditioning agents.

Evaporative (drying) technologies, which are by far the most expensive form of dewatering, would usually not be employed for sediments. In certain cases, such as when sediments are to be processed in a thermal treatment system, the removal of water is a primary consideration in reducing the cost of treatment. In these cases, thermal treatment systems may provide a source of waste heat that could be used for evaporation. The primary concern regarding use of this technology is volatile emissions. Because sediments are heated, volatile and semivolatile contaminants are released. Contaminants of concern for this process include low molecular weight PAHs, PCBs, and mercury. Subsequent treatment of off-gases would probably be required and could add significant costs to the process.

## Physical Separation Technologies

The factors for selecting a physical separation technology will depend on the objective of pretreatment. If the objective is to remove materials from the sediments that may interfere with subsequent handling, treatment, or disposal, selection factors would be related to the feed requirements of these subsequent components and the physical character of the sediments delivered by front-end components. If the objective is to separate the sediments into two or more fractions with differing treatment and disposal requirements, the selection factors would be related to the distribution of contaminants within the sediment matrix and their separability based on physical characteristics.

The selection of equipment for removing oversized material from a process stream is fairly straightforward. Each process unit will have a maximum feed size (above which the unit might be damaged) and a target particle size separation, as summarized in Table 6-6. Most of the equipment is available in different screen sizes or diameters to accommodate a range of particle size separations. Equipment selection must consider the characteristics of the incoming sediments and the feed requirements of subsequent components with the operation and performance specifications of the pretreatment unit.

Aside from removing oversized materials that might disrupt subsequent pretreatment or treatment processes, physical separation processes may reduce the quantity of materials requiring expensive treatment or disposal. Virtually any sediment can be separated into two or more fractions based on one or more physical properties (i.e., particle size, mineralogy, density, magnetic, and particle surface properties). With some sediments, contaminants can be separated into specific fractions by mineral processing technologies that use these same physical properties.

Best results will be obtained when the pretreatment system is chosen based on a detailed knowledge of the physical and chemical characteristics of the sediment. Mineral processing unit operations appropriate to the physical characteristics of the sediment can then be arranged into an integrated system. Detailed characterization of the physical properties of the sediment, including the analyses shown in Table 6-7, and chemical analysis of separable fractions are needed to determine the selection of a mineral processing method or methods.

Other testing that is helpful is sediment mineralogy, or identification of chemical phases, using scanning electron microscopy with energy-dispersive techniques and possibly x-ray diffraction. Equally important is knowledge of the history of the contaminated site, which could provide information about the nature of the contaminant-bearing phases.

If discrete sediment phases containing contamination have been identified, then an appropriate mineral processing method can be selected. Mineral processing methods are selected to separate sediments based on the known physical properties of the phases found to be present. For example, if most of the contamination is found to be associated with fine silt or clay particles, size classification techniques may be appropriate. The distribution of PCBs in relation to particle size in sediments from the Saginaw River is shown in Figure 6-2. As illustrated, most of the PCBs were associated with a relatively small particle size fraction of the sediments. Particle size separation of the Saginaw River sediments during a pilot-scale demonstration yielded a small fraction (20 percent of original material) of silt and clay containing most of the PCBs, and a large fraction (80 percent of original material) of sand with reduced concentrations of PCBs (USACE Detroit District 1994). Toxicity testing of the sand fraction showed a slight decrease in comparison to the untreated sediments, indicating that these materials may be suitable for unrestricted disposal, pending further analyses.

A few important points about mineral processing technologies should be noted. Mineral processing makes particle-particle separations. No chemical bonds are broken, and no contaminants are destroyed. This is in contrast to many other remediation technologies, where a process such as incineration actually destroys the contaminants. In addition, mineral processing separations are based on differences in the physical properties of particles, so that no separation can be achieved if all particles are physically similar. Finally, the capacity and efficiency of most mineral processing operations decreases with particle size. Each individual mineral processing operation has a range of particle sizes for which the technology is effective. Further information on mineral processing methods is available from several sources, including Collins and Read (1979) and Somasundran (1979).

Selection and feasibility testing of mineral processing methods are described in an extensive handbook published by the Society of Mining Engineers (Weiss 1986). Bench-scale testing to verify mineral processing performance is inexpensive, and scale-up reliability is well documented. Most plants with capacities up to 2,700 tonnes/day are designed from laboratory studies without pilot-scale plant testing.

### *Debris Removal Technologies*

Large debris is most likely encountered during mechanical dredging, especially in urban areas with unrestricted public access to the waterfront. Debris may be separated by the dredge operator as it is removed and placed into a barge, or it may be separated at the first transfer point where the sediments are placed into a disposal facility or loaded for transport. The advantages of removing debris at the first transfer point include: 1) mechanical equipment (i.e., cranes and backhoes) used for rehandling are typically smaller than the dredge, 2) more space is available to store debris, 3) it is easier to contain drippage, and 4) a properly designed site can also be used for decontamination.

### *Screens and Classifiers*

Grizzlies and trommels are frequently used to remove small debris and are useful in sediment processing to capture driftwood, junk, or large rocks that would foul or damage other processing equipment. Vibrating or other moving screens are often chosen for separations of particles larger than about 100 um in diameter (Colman 1980; Reithmann and Burnell 1980).

Grizzlies are the simplest and coarsest devices for removing small debris. Their most likely application in sediment remediation would be to remove rocks and debris 5 cm or larger in diameter to prevent damage to subsequent equipment. A grizzly should always be used if there is a possibility of equipment damage from large rocks or foreign objects.

Trommels are used to remove gravel, rocks, or trash 1-10 cm in diameter from sediment prior to further processing. Difficulty has been reported with the formation of clay balls on trommel screens, effectively trapping fine particles that should pass through the device. If a significant clay fraction is present in the sediment, a water spray may be helpful to prevent the formation of clay balls. A log washer or similar disaggregating device might be used in conjunction with a trommel.

Vibrating screens are used to make particle size separations in sediments with particle diameters from 4,000 to 100 um. Hydrocyclones could also be used for separations in this range, usually with a lower unit cost. Selection of a vibrating screen over a hydrocyclone might be justified if variations in feed rate are anticipated, lower volumetric capacity is required, there is a wide variation in particle densities, or the feed solids content exceeds 25-30 percent.

Mechanical classifiers such as spiral or rake classifiers can also be used for separations in the same size range as hydrocyclones. A spiral or rake classifier might be selected for a sand-silt separation when a high solids content is required in the sand product (e.g., when sand is to be transported by belt conveyor). Mechanical classifiers are very sensitive to variations in the solids content of the feed material, and require a constant volumetric feed rate for reliable performance.

***Hydrocyclones***

The selection of hydrocycloning pretreatment to reduce the volume of contaminated material to be treated is dependent on three factors. First, the contamination must be strongly distributed toward either the coarse- or fine-grained particles (usually the fines), so that the remaining fraction of the sediment is clean enough to be suitable for disposal without treatment or for unrestricted disposal (van Veen and Annokkée 1991). Second, the mass of the sediment must be sufficiently distributed toward the cleaner fraction so that an appreciable amount of clean material is recovered. As a general guideline, this would require that the contaminated material make up no more than about 40 percent of the total sediment weight. Third, the subsequent treatment to be used on the contaminated material must be as efficient and economical with a smaller volume of more heavily contaminated material as it would with the unseparated bulk sediment.

In the usual hydrocyclone application, it is the fine particles that carry the most contamination. Therefore, it is important in making a separation that the coarse product or underflow be as free of misplaced fine particles as possible. Some fine particles are always carried along with the water that exits the cyclone with the underflow, so the amount of this water should be kept to a minimum. Proper selection of the size and design of the apex nozzle will accomplish this. Another way of ensuring a clean underflow product is double -desliming, where the underflow product is subjected to a second hydrocyclone treatment, resulting in fewer misplaced fine particles. A final option recommended by at least one hydrocyclone manufacturer is to add clear water to the hydrocyclone just above the apex nozzle. The additional water forces some of the water containing misplaced fine particles back to the overflow, resulting in a cleaner underflow product.

***Gravity Separation***

The traditional methods for evaluating the feasibility of gravity separation in the laboratory are "sink-float" tests using a variety of dense liquids, such as bromochloromethane and tetrabromoethane (Mills 1985). A sediment sample can be separated into fractions of differing specific gravity using these liquids and specially constructed separatory funnels. These heavy liquids are suitable for density separations of sediment for metal contaminants. Density separations of organic contaminants can be predicted using water elutriation, in which closely sized material is allowed to settle against a rising current of water.

A density-based separation may be successful if contamination is found to reside disproportionately in a phase of different specific gravity than the bulk of the sediment matrix. For example, organic contaminants are frequently found attached to detrital material such as wood and leaf fragments. This material is much less dense than mineral matter and can be easily separated in a gravity separator. Most metallic phases are considerably denser than most sediment matrices, and can also be recovered. A specific gravity difference (between the phases to be separated) of about 0.4 is usually enough to effect a separation with most equipment.

The applicability of gravity separation to a contaminated sediment is dependent on the size of the sediment, sediment density, and the concentration criterion (C), defined as:

C = P − P [illegible]

[illegible]

The feasibility of gravity separation for sediments of varying particle sizes is related to the concentration criteria in Table 6-8 (from Aplan 1980).

***Froth Flotation***
The use of froth flotation is warranted when most of the contamination is found in a phase (or phases) distinct from the bulk of the sediments. The most promising application would be with sediments containing an oily phase, where surfactants could be used to aid in detaching the organic-phase contaminants from sediment particles, followed by collection of the contaminants in an organic-laden froth. Another possible application might be in connection with a minerals industry-related site, where metal contamination is associated with a specific mineral phase. In this case, a flotation system could be designed to recover that phase.

Determining the feasibility of froth flotation for a given assemblage of particles involves two components. First, the phases present must be identified. In minerals processing, phases are usually identified using a combination of microscopic analysis and x-ray diffraction. Infrared spectroscopy might be used to identify principal organic phases. Second, bench-scale testing is used to identify surfactants and operating conditions for an effective separation. This is an expensive and time-consuming process relative to the characterization required for a particle size separation, for example. Accurate and complete knowledge of the identity of phases in the system will hasten and economize this process.

***Magnetic Separation***
Only the low-intensity, rotating, drum-type separators and the WHIMS system appear to have significant applicability to sediment remediation, because they operate on wet material. The choice between these two devices is based on the particle size and magnetic susceptibility of the phase(s) to be recovered. Fine or paramagnetic material requires the WHIMS system. The low-intensity systems are generally applicable only when the material to be recovered is ferromagnetic.

The most practical method of evaluating the feasibility of magnetic separation is to conduct separability tests using laboratory-scale equipment.

## ESTIMATING COSTS

There is considerable cost estimating guidance available on applications of mechanical and evaporative dewatering technologies to municipal and industrial sludges, and considerable cost data exist on applications of physical separation technologies in the mining and mineral processing industries. Most of these applications involve permanent installations that process large quantities of materials at controlled rates under near-ideal conditions. Sediment remediation will typically have none of these features. Cost information from wastewater and mineral processing operations will be provided in this document because it is the best or only information available, but applications to sediment remediation should be expected to be significantly more expensive.

### Dewatering Technologies

***Passive Dewatering Technologies***
The capital costs for construction of CDFs are discussed in Chapter 8, *Disposal Technologies*. Capital costs for temporary diked facilities for dewatering can be estimated in a manner similar to that for CDFs. Although the design requirements may be less stringent for temporary facilities, one additional cost that would be incurred after the remediation is completed is the removal of the facility and decontamination of the site. Costs for sand drying beds may be adapted from guidance published for municipal sludge (USEPA 1985a). No cost data are available on the installation of wick drains at CDFs.

Activities associated with operating a CDF for dewatering may include water-level management, operation and maintenance of pumps and overflow weirs, and progressive trenching. At Corps CDFs around the Great Lakes, water level management is typically conducted by the dredging contractor (or subcontractor) and represents a relatively small effort. The cost of progressive trenching is highly site-specific. Haliburton (1978) estimates that the cost of implementing three trenching cycles over 2 years at a 100-acre (41-hectare) CDF would be approximately $128,000 (updated to January 1993 dollars). This cost assumes 70-percent operational efficiency, with administrative costs assumed to be 20 percent.

***Mechanical Dewatering Technologies***
Mechanical dewatering equipment may be purchased outright or leased. In addition, dewatering services are available on a contractual basis. If sediment dewatering is to be performed intermittently, or just once, contracted services may prove to be more cost effective. Contractors generally offer belt filter presses and recessed plate filters, although centrifuges are also sometimes available. Several vendors contacted during preparation of this document indicated "typical" pricing in the range of $3-$10 per hundred gallons ($0.79-$2.64 per hundred liters) of feed material. This can be expressed on a dry-ton basis if the feed solids concentration is known, as shown in Table 6-9:

Contractual costs are controlled by the quantity of the material to be processed, the dewaterability of the material, and the required cake solids concentration. The volume of slurry generated during a sediment remediation project might be considered moderately "large" when considering mobile dewatering. For example, 10,000 yd[3] (7,600 m[3]) of *in situ* sediments in a 10-percent slurry would result in a total volume of approximately 10 million gal (38 million L). Contaminant concentrations may influence cost as well.

Capital costs for construction of mechanical dewatering systems, based on municipal wastewater applications, are presented in Table 6-10. These costs include equipment purchase, installation, and housing costs. All equipment (except gravity thickener) is assumed to be housed in a building.

Operation and maintenance costs for mechanical dewatering include the following components:

- Maintenance of equipment and facilities
- Power requirements
- Chemical costs
- Labor

The operating costs for specific mechanical dewatering systems are discussed in the following paragraphs. The costs of treating and disposing of wastewater streams resulting from dewatering are discussed in Chapter 9, *Residue Management*.

***Belt Filter Press***--Belt filter presses are probably the most energy conservative and, therefore, the most economical mechanical dewatering units to operate. The average power requirements range from 0.8 kW (1 hp) to 5.7 kW (8 hp) per meter of belt width. Replacement of the filter belts is one of the most common maintenance items. The main reasons for failure of the belts are tearing at the clipper seam, inferior quality belt material, ineffective tracking systems, and poor operation and maintenance. Average belt life is about 2,700 running hours with a range of 400-12,000 running hours (USEPA 1987b).

Process control is extremely important to ensure optimum performance of the dewatering system. By keeping accurate records (i.e., a log) the operator can determine how well the press is performing. In addition, preventive maintenance and waste minimization can be integrated to deter unnecessary shutdown and reduce chemical costs, respectively (USEPA 1987b).

***Solid Bowl Centrifuge***--Operating costs for centrifuge technologies depend on the solids capacity of the centrifuge and polymer dosage. Additional factors such as bowl speed and temperature can affect the final sludge cake. Particular attention should be focused on polymer dosage. Continual laboratory testing will minimize polymer dosage and maximize the dryness of the cake solids, thus minimizing costs (USEPA 1987b). In addition, replacement costs for centrifuge scrolls and bearings can be significant. Examples of operation and maintenance costs for centrifuges from two wastewater treatment works operated by the Metropolitan Water Reclamation District of Greater Chicago are shown in Table 6-11.

An evaluation of the costs of dewatering dredged material using mechanical dewatering methods was conducted by the USACE Buffalo District (1969) for various dredging volumes. The system consisted of slurried dredged material fed into solid bowl centrifuges by pipeline. The centrifuges were sized at 12,500 pounds (27,500 kg) per unit per hour, producing a cake of approximately 50-percent solids. A summary of the system costs is provided in Table 6-12. Total costs are based on a term of 10 years with a 4.625 percent annual interest rate. Operating costs are based on labor, utility, and maintenance.

***Filter Press***--Proper sludge conditioning is a key component of an efficient and effective filter press operation. Routine evaluations and recordkeeping are recommended, because operating conditions may vary, leading to conditioner changes (USEPA 1987b). Operation and maintenance costs include the labor needed to operate the press, power to pressurize the feed material, and maintenance of the equipment. Most of the maintenance costs are for replacement of the filter cloths (USEPA 1985a). Requirements for power and materials costs, based on municipal wastewater experience, are shown in Table 6-13. Manpower and polymer requirements are a function of processing rate and dewatering characteristics, respectively.

### ***Evaporative Technologies***

No cost data are available on evaporation of sediments. In general, there is very limited information on evaporation of waste solids. Probably the best indication of evaporative costs are those for the Carver-Greenfield process discussed in Chapter 7, *Treatment Technologies*. Based on a hypothetical site with 21,000 tonnes of drilling mud wastes, with a solids content of 52 percent and an oil and grease content of 7-17 percent, processing costs have been estimated to range from $180-$200 per tonne of feed material (Schindler 1992).

## Physical Separation Technologies

Because physical separation technologies are economically applied on a large scale to ores of low value-to-mass ratio, they are among the least expensive processes in modern industry. For example, in processing copper, five or six separate mineral processing operations are performed, plus smelting and refining, at a rate of more than 91,000 tonnes/day, all on an ore that contains less that $10 worth of copper per tonne. It is important to note that large economies of scale are seen in mineral processing operating costs. The cost of treating a tonne of ore in a small operation may be 2-3 times the cost of treating the same amount in one of the larger facilities.

Mining industry costs for all major mineral-processing unit operations are well documented; however, considerable difficulty is encountered in applying these costs to an environmental remediation project. The U.S. Bureau of Mines has published and uses a cost estimating system to calculate capital and operating costs based on plant throughput by summing incremental costs of the unit operations and other contributions to cost. In sediment remediation, this system would appear to be most useful for larger projects, in excess of about 500 tonnes/day of sediment (U.S. Bureau of Mines 1987).

### *Debris Removal Technologies*

Debris removal is an anticipated inconvenience during most maintenance dredging projects at Great Lakes harbors. Contractors are typically advised in dredging contracts to expect some debris and be prepared to remove it. Removal generally requires additional time by dredge operators to handle large debris and causes decreased production. The costs of debris removal are generally factored into the dredging cost estimates.

During sediment remediation, additional provisions may be necessary because of the highly contaminated nature of the sediments. Most of these costs can also be factored into the costs of other components. If the debris is removed by the dredge operator or during mechanical rehandling or transport, the costs will be reflected as decreased productivity. The costs of additional equipment and labor needed to store the debris and costs for decontamination are project specific.

### *Screens and Classifiers*

Few data are available in the mining industry for these (coarse) size separations. Their cost is typically calculated as part of a larger grinding or mineral processing system. As an example, the operating cost for a washing and screening circuit consisting of a trommel, log washer, and vibrating screens, with ancillary equipment, is estimated to be $8.25/tonne. Such a circuit might be encountered in the gravel or crushed stone industries. With screens and classifiers, equipment costs are generally incidental to the costs of moving material to and through the system.

### *Hydrocyclones*

A typical hydrocyclone designed for soil or sediment remediation, which makes a separation at 75-150 um with a throughput of 18-55 dry tonnes per hour, would cost from $3,750-7,500 (1993 dollars), depending on the exact size and configuration (costs are adjusted from 1990 prices using ENR's CCI factor of 1.07). Because capacity is determined by hydrocyclone size, the cost increment for higher throughput would be linear (i.e., capacity would be increased by increasing the number of hydrocyclones). Pumping and support equipment must also be provided.

Operating costs for hydrocyclones are essentially the cost of pumping the slurry through the unit and costs for occasional replacement of the hydrocyclone liners. These costs are estimated at about $0.12-0.35 per dry tonne (1993 dollars; costs are adjusted from 1990 prices using ENR's CCI factor of 1.07). The highest costs associated with hydrocyclone applications are the manpower costs associated with operating the plant.

An evaluation of the costs of particle size separation of dredged material was conducted by the USACE Buffalo District (1969) for various dredging volumes. The system consisted of a dredged material slurry pumped from a wet well (equalization basin) into hydrocyclones. The underflow (fine fraction) was discharged to a CDF and the overflow (coarse fraction) passed through a spiral classifier before being disposed. A summary of the system costs is shown in Table 6-14. Total costs are based on a term of 10 years with a 4.625 percent annual interest rate. Operating costs are based on labor, utility, and maintenance.

### *Gravity Separation*

A typical gravity separation circuit, employing Humphreys spirals, in a mineral processing plant is estimated to have an operating cost of $6.05/tonne. The capital cost for a 91-tonne/day Humphreys spiral circuit is estimated to be $270,000.

### *Froth Flotation*

Based on mineral processing industry experience, the capital cost of a froth flotation plant designed to process 91 tonnes/day is estimated to be $750,000 (Allen, in prep.). Operating costs for froth flotation are about twice those for gravity separation, because of the cost of reagents. Many of the surfactants proposed for sediment treatment are rather expensive and would drive the operating costs even higher.

**_Magnetic Separation_**
Magnetic separation plants are used in the iron-ore industry and are quite large. No data are available for magnetic separation plants that operate at capacities lower than about 1,900 tonnes/day. Generally, magnetic separation plants will be more costly to build than gravity separation facilities, but will be about equal in cost to operate.

## ESTIMATING CONTAMINANT LOSSES

While methods for predicting contaminant losses from passive dewatering technologies (primarily CDFs) are fairly well developed, *a priori* methods for predicting contaminant losses from mechanical dewatering and physical separation technologies do not exist. For these technologies, mechanisms for contaminant loss can be identified, and controls can be installed to minimize loss.

### Dewatering Technologies

**_Passive Dewatering Technologies_**
Contaminant losses from passive dewatering systems are expected to be comparable to those experienced at CDFs. Chapter 8, *Disposal Technologies*, and Myers et al. (in prep.) provide further discussion of these losses.

**_Mechanical Dewatering Technologies_**
The mechanisms for contaminant loss from mechanical dewatering systems will include volatilization and leakage/spillage of solids or water. Systems that are housed can be equipped with controls to collect and route all leakage/spillage for treatment as necessary. Leakage/spillage would most likely be washed into a wet well and pumped to the water residue treatment system.

If the sediments have significant concentrations of volatile or semivolatile contaminants, controls can be implemented to capture and treat any contaminant losses. Contaminant losses will ultimately be limited to the quantity of emission permitted by the regulatory agencies and the residuals generated during the treatment of the off-gas (e.g., spent carbon). Volatilization losses from systems that cannot be housed (i.e., gravity thickeners) may be estimated using the same methods used for CDFs (Chapter 8, *Disposal Technologies*).

**_Active Evaporative Technologies_**
Contaminant loss mechanisms for active evaporative technologies would be similar to those for mechanical dewatering technologies. Because the sediments are heated, volatilization is more likely to be significant, and more elaborate controls would be required.

### Physical Separation Technologies

**_Debris Removal Technologies_**
The mechanisms for contaminant loss during debris removal include sediment drippage during handling, volatilization, and wash water. If debris is separated during dredging, there are few controls that can be implemented other than having an adequate storage container for debris. If debris is separated during rehandling (between components), drippage can be controlled using drip aprons or by constructing a low-permeability, drained rehandling area. Drippage from a rehandling area and wash water from debris decontamination should be collected and routed for treatment.

**_Screens and Classifiers_**
Contaminant losses from screens and classifiers are the result of volatilization, splashing, or spillage. Mechanical classifiers can readily be fitted with covers to recover volatile contaminants; because these devices require a quiescent flow regime, it is not expected that volatile losses would be much greater than those from sediment in place. Significant losses are not expected from grizzlies. The mixing in trommels and the high-frequency vibration of some moving screens may impart sufficient energy to effect contaminant volatilization; however, substitution of reciprocating or gyratory screens would reduce this possibility.

**_Hydrocyclones_**
Contaminant losses from hydrocyclone treatment are expected to be minimal, because the hydrocyclone is an enclosed unit, and material is transferred to and from the hydrocyclone by pumping through rigid pipes. It is possible that some contaminants could be volatilized in the turbulence of the hydrocyclone, but provisions can be made for capture of the escaping gases.

**_Gravity Separation_**
Contaminant losses from gravity separation devices are expected to be relatively low. An exception to this may be volatile

losses from shaking tables or other flowing-film concentrators. These losses could be controlled if the equipment was enclosed or housed in a building with air capture and treatment capability.

### *Froth Flotation*

The most likely loss pathway for froth flotation is volatilization of organic contaminants, which results from forcing quantities of air through the sediment pulp. Ventilation hoods can be fitted on flotation cells to capture volatile emissions.

### *Magnetic Separation*

Contaminant losses from magnetic separations will be no greater than from any other simple materials-handling operation, because no heating or significant increase in air-slurry interface is involved.

U.S. Environmental Protection Agency

Great Lakes Contaminated Sediments

Recent Additions | Contact Us | Print Version Search: GO

EPA Home > Great Lakes > Monitoring > Sediments > ARCS > EPA-905-B94-003 (Remediation Guidance Document) Chapter 7

*R/V Lake Guardian*
Indicators
Limnology
Sediments
Air
Data Projects
Fish
Beach closings
Plankton
Biology
Benthic invertebrates

# Assessment and Remediation of Contaminated Sediments (ARCS) Program
# REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 7. TREATMENT TECHNOLOGIES

There are numerous treatment technologies for sediments contaminated with hazardous substances. Many of these technologies have been developed for treating contaminated soils at hazardous waste sites, especially those designated under the Superfund Program. This chapter provides an introduction to some of the better-established technologies, particularly those that have been demonstrated on contaminated sediments. However, other sources of information should be consulted for more up-to-date and detailed information on specific applications.

The list of potential remediation technologies is continually changing as new technologies are developed and become available, and other technologies are withdrawn from use. The need for an up-to-date database of treatment technologies has been recognized by governmental agencies in both the United States and Canada. Three of the more useful databases developed to date are described below:

<table>
<tr><th colspan="2">Sediment Treatment Technologies Database (SEDTEC)</th></tr>
<tr><td><b><i>Available from:</i></b><br>Wastewater Technology Centre<br>867 Lakeshore Road<br>Burlington, Ontario L7R 4L7</td><td><b><i>Sponsored by:</i></b><br>Environment Canada<br>Great Lakes Cleanup Fund</td></tr>
<tr><td colspan="2"><b><i>Description:</i></b><br>Currently in its second edition, SEDTEC provides fact sheets on 168 different technologies submitted to the Wastewater Technology Centre from vendors and technology developers around the world.</td></tr>
<tr><td colspan="2"><b>Vendor Information System for Innovative Treatment Technologies (VISITT)</b></td></tr>
<tr><td><b><i>Available from:</i></b><br>PRC Environmental Management, Inc.<br>1505 PRC Drive<br>McLean, Virginia 22102</td><td><b><i>Sponsored by:</i></b><br>U.S. Environmental Protection Agency<br>Office of Solid Waste and Emergency Response<br>Technology Innovation Office<br>Washington, DC 20460</td></tr>
<tr><td colspan="2"><b><i>Description:</i></b><br>Similar to SEDTEC, except that only innovative technologies are included, and technologies are not specific to sediments. The current Version 1.0 contains 94 technologies for treating sediments. Specific performance data may be included.</td></tr>
<tr><td colspan="2"><b>Risk Reduction Engineering Laboratory (RREL) Treatability Database</b></td></tr>
<tr><td colspan="2"><b><i>Available from:</i></b><br>U.S. Environmental Protection Agency<br>Risk Reduction Engineering Laboratory<br>Cincinnati, Ohio 45268</td></tr>
<tr><td colspan="2"><b><i>Description:</i></b><br>Provides results of published treatability studies that have passed the USEPA's quality assurance review. Although the most current data are for wastewater treatment, recently available treatment data for soils and sediments will likely be added in future updates.</td></tr>
</table>

New technologies must be subjected to a lengthy process of testing and evaluation before they can be applied in a full-scale remediation project. Many innovative technologies have only been demonstrated in bench-scale (i.e., laboratory) tests, while others have undergone pilot-scale testing. In general, both bench- and pilot-scale testing of any treatment technology must be conducted prior to the application of that technology for full-scale remediation.

Sediment that is contaminated to the extent that it requires decontamination or detoxification in order to meet environmental cleanup goals may be treated by using one or more of a number of physical, chemical, or biological treatment technologies. Treatment technologies reduce contaminant concentrations, contaminant mobility, and/or toxicity of the sediments by one or more of four means:

- Destroying the contaminants or converting the contaminants to less toxic forms
- Separating or extracting the contaminants from the sediment solids
- Reducing the volume of contaminated material by separation of cleaner sediment particles from particles with greater affinity for the contaminants
- Physically and/or chemically stabilizing the contaminants in the dredged material so that the contaminants are fixed to the solids and are resistant to losses by leaching, erosion, volatilization, or other environmental pathways

Destruction technologies described in this chapter include thermal destruction, chemical treatment, and bioremediation; separation technologies include extraction and thermal desorption. Volume reduction using particle separation techniques was discussed in Chapter 6, *Pretreatment Technologies*. Immobilization or stabilization techniques are also described in this chapter. Discussions of the factors for selecting from the available technology types, methods for evaluating their feasibility, and techniques for estimating costs and contaminant losses are also provided.

## DESCRIPTIONS OF TECHNOLOGIES

### Thermal Destruction Technologies

The processes considered in this section are those that heat the sediment several hundreds or thousands of degrees above ambient temperature. These processes are generally the most effective options for destroying organic contaminants, but are also the most expensive. Included in this category are:

- Incineration
- Pyrolysis
- High-pressure oxidation
- Vitrification

Most of the thermal technologies are highly effective in destroying a wide variety of organic compounds, including PCBs, PAHs, chlorinated dioxins and furans, petroleum hydrocarbons, and pesticides. They do not destroy metals, although some technologies (e.g., vitrification) immobilize metals in a glassy matrix. Volatile metals, particularly mercury, will tend to be released into the flue gas. Additional equipment for emission control may be needed to remove these contaminants.

These technologies will be briefly summarized here; for a more complete discussion see Averett et al. (in prep.) and USEPA (1985b, 1991e, 1992g).

***Incineration***

Incineration is by far the most commonly used process for destroying organic compounds in industrial wastes. Incineration basically involves heating the sediments in the presence of oxygen to burn or oxidize organic materials, including organic compounds. A critical component of the overall treatment process is the emission control system for the gases produced by the process. A diagram of an incineration process is shown in Figure 7-1. Application of incineration to wet solids such as sediments is relatively uncommon; all traces of moisture must be driven off before the solids will burn. This requires the expenditure of large quantities of energy, which makes the process very expensive. Moreover, incineration tends to be a very controversial issue for communities where such facilities are to be sited.

As with most processes that destroy organic compounds, incineration does not remove heavy metal contamination. Most incineration processes increase the leachability of metals through the process of oxidation (exceptions include the slagging or vitrifying technologies, which produce a nonleachable, basalt-like residue). This increased leachability of metals would be advantageous only if the resulting ash were to be treated using a metals extraction process; otherwise, it is a distinct disadvantage. The leachability of metals is generally measured using the toxicity characteristic leaching procedure (TCLP) test. Incinerator ash that "fails" this test must be disposed of as a hazardous waste in accordance with RCRA.

Incineration technologies can be subdivided into two categories: conventional and innovative. Because gaseous emissions from incinerators present a potentially large contaminant loss pathway, the emission control system is a critical component for both categories. Conventional technologies include rotary kiln, fluidized bed, multiple hearth, and infrared incineration. These technologies, summarized in Table 7-1, typically heat the feed materials to between 650 and 980deg.C. An afterburner, or secondary combustion chamber, is generally required to achieve complete destruction of the volatilized organic compounds. All of these processes produce a dry ash residue.

In contrast, there are a number of innovative processes that are designed specifically for hazardous and toxic wastes. These proprietary technologies, listed in Table 7-2, operate at higher temperatures and generally achieve greater destruction and removal efficiencies compared with conventional incineration. Most of these technologies produce a dense slag or vitrified (glass-like) solid instead of a free-flowing ash. These technologies tend to be very expensive, but offer the advantage of producing a nonleachable end product.

### *Pyrolysis*

In contrast to incineration, pyrolysis involves the heating of solids in the absence of oxygen. A pyrolysis system consists of a primary combustion chamber, a secondary combustion chamber, and pollution control devices. High temperatures, ranging from 540 to 760deg.C, cause large, complex molecules to decompose into simpler ones. The resulting gaseous products can then be collected (e.g., on a carbon bed) or destroyed in an afterburner at 1,200deg.C. A summary of proprietary technologies is provided in Table 7-3.

The Thermal Gas Phase Reduction Process is a specialized process in which a reducing agent (hydrogen gas) is introduced to remove chlorine atoms from PCBs or dioxins. In Hamilton, Ontario, a pilot-scale reactor was used to process PAH- and PCB-contaminated harbor sediments in July 1991. This process produced high destruction efficiencies for PAHs (99.92-99.99999 percent) and PCBs (99.999-99.99999 percent) in dilute sediment slurries (5-10 percent solids) (ELI Eco Logic International 1992). In late 1992, this technology was tested under the Superfund Innovative Technology Evaluation (SITE) Program with PCB-contaminated soil from a landfill in Bay City, Michigan (USEPA 1994b).

Pyrometallurgy, or smelting/calcination, is a nonproprietary form of pyrolysis. This commercial technology is commonly used to treat metal-bearing ores. High levels of metals or metal oxides can be recovered from waste materials of similar metal content because the effectiveness of recovery is directly proportional to the metal content of the waste. However, this process has the potential for forming toxic sludges and has high process costs (Averett et al., in prep.).

### *High-Pressure Oxidation*

This category includes two related technologies: wet air oxidation and supercritical water oxidation. Both processes use the combination of high temperature and pressure to break down organic compounds. Typical operating conditions for both processes are shown in Table 7-4. As indicated in the table, wet air oxidation can operate at pressures of one-tenth those used during supercritical water oxidation.

Wet air oxidation is a commercially proven technology, although its use has generally been limited to conditioning of municipal wastewater sludges. This technology can degrade hydrocarbons (including PAHs), some pesticides, phenolic compounds, cyanides, and other organic compounds (USEPA 1987a). A bench-scale test using sediments from Indiana Harbor showed greater than 99 percent destruction of PAHs (USEPA, in prep.a). However, destruction of halogenated organic compounds (e.g., PCBs) with this process is poor. In bench-scale testing of the process conducted under the ARCS Program, using sediments from Indiana Harbor, it was found that only 35 percent of influent PCBs were destroyed (USEPA, in prep.a). It may be possible to improve oxidation through the use of catalysts (Averett et al., in prep.). One vendor of this technology is Zimpro Passavant (Rothschild, Wisconsin).

The supercritical water oxidation process is a relatively new technology that has received limited bench- and pilot-scale testing. Available data have shown essentially complete destruction of PCBs and other stable compounds. Vendors of this process include Modar, Inc. (Natick, Massachusetts) and VerTech Treatment Systems (Air Products and Chemicals, Allentown, Pennsylvania). Modar uses high-pressure pumps and an above-ground reactor. In contrast, VerTech uses a well between 2,500 and 3,000 m deep to achieve the necessary pressures.

### *Vitrification*

Vitrification is an emerging technology that uses electricity to heat and destroy organic compounds and immobilize inert contaminants. A typical unit consists of a reaction chamber divided into two sections: the upper section introduces the feed material containing gases and pyrolysis products, while the lower section contains a two-layer molten zone for the metal and siliceous components of the waste. Wastes are vitrified by passing high electrical currents through the material. Electrodes are inserted into the waste solids, and graphite is applied to the surface to enhance its electrical conductivity. A large current is applied, resulting in rapid heating of the solids and causing the siliceous components of the material to melt. The end product is a solid, glass-like material that is very resistant to leaching. Temperatures of about 1,600deg.C are typically achieved.

Vitrification units demonstrated in pilot- scale and full-scale tests have solidified 300,000 kg/melt. Vitrifix N.A. (Alexandria, Virginia) is developing a full-scale unit for asbestos waste. Geotech Development Corp. and Penberthy Electromelt also offer vitrification systems.

*In situ* vitrification is a patented thermal destruction technology developed by the Battelle Memorial Institute's Pacific Northwest Laboratory. Although it was designed to treat contaminated soils in place, it could presumably be adapted to treat dredged sediments. This technology is available commercially from Geosafe Corp., (Kirkland, Washington).

### *Summary of Thermal Destruction Technologies*

The advantages and disadvantages of the five thermal destruction processes reviewed in this section are summarized in Table 7-5 for comparative purposes.

## Thermal Desorption Technologies

Thermal desorption physically separates volatile and semivolatile compounds from sediments by heating the sediment to temperatures ranging from 90 to 540deg.C. Water, organic compounds, and some volatile metals are vaporized by the heating process and are subsequently condensed and collected as liquid, captured on activated carbon, and/or destroyed in an afterburner. An inert atmosphere is usually maintained in the heating step to minimize oxidation of organic compounds and to avoid the formation of compounds such as dioxins and furans. Figure 7-2 shows a typical process for thermal desorption. The temperature of the soil in the desorption unit and retention time are the primary variables affecting performance of the process. Heating may be accomplished by indirectly fired rotary kilns, heated screw conveyors, a series of externally heated distillation chambers, or fluidized beds (USEPA 1991c).

### *High-Temperature Thermal Processor*

The high-temperature thermal processor (Remediation Technologies, Inc. [ReTec]) uses a Holoflite (TM) dryer, which is a heated screw conveyor, to heat the sediment and drive off water vapors, organic compounds, and other volatile compounds. The screws for the dryer are heated by a hot molten salt that circulates through the stems and blades of the augers, as well as through the trough that houses the augers. The molten salt is a mixture of salts, primarily potassium nitrate. Maximum soil temperatures of 450deg.C are attainable (USEPA 1992g). The motion of the screws mixes the sediment to improve heat transfer and conveys the sediment through the dryer. Off-gases are controlled by cyclones, condensers, and activated carbon. This technology was evaluated in ARCS Program bench- and pilot-scale demonstrations. Removal efficiencies from 42 to 96 percent were achieved for PAHs in Buffalo River sediments (USACE Buffalo District 1993). Greater than 89 percent of the PCBs in Ashtabula River sediments were removed by the ReTec pilot unit (USACE Buffalo District, in prep.).

### *Low-Temperature Thermal Treatment System*

The low-temperature thermal treatment system (Roy F. Weston, Inc. [Weston]) also uses a Holoflite (TM) dryer, similar to the ReTec process. However, Weston's heating fluid is a thermal oil heated by a separate, gas-fired unit. Maximum temperature for the heating fluid is a limiting factor for this process. The typical oil medium has a maximum operating temperature of 350deg.C, which allows soils to be heated to approximately 290deg.C (Parker and Sisk 1991); however, higher temperatures would likely be required to effectively remove PCBs from sediments. Vapors from the contaminated material are passed through a particulate filter, scrubbers or condensers, and carbon adsorption columns, and may require additional post-treatment. In past demonstrations, Weston has attached an afterburner to the gas stream at temperatures as high as 1,200deg.C to destroy the organic compounds. Removal efficiencies >99 percent have been reported for volatile organic compounds; removal efficiencies of about 90 percent have been reported for PAHs (USEPA 1991c). Bench-, pilot-, and full-scale units are available. The capacity of the full-scale system is 6.8 tonnes/hour (Parker and Sisk 1991).

#### *X*TRAX System*

The X*TRAX thermal desorption system (Chemical Waste Management) uses an externally fired rotary kiln to heat soil to temperatures ranging from 90 to 480deg.C. Water and organic compounds volatilized by the process are transported by a nitrogen carrier gas to the gas treatment system. First, a high-energy scrubber removes dust particles and 10-30 percent of the organic compounds. The gases are then cooled to condense most of the remaining vapors. About 90-95 percent of the cleaned gas is reheated and recycled to the kiln. The remaining 5-10 percent is passed through a particulate filter and activated carbon and is then released to the atmosphere (USEPA 1992g). Pretreatment requirements include screening or grinding to reduce the particle size to less than 5 cm. Post-treatment includes treatment or disposal of the condensates and spent carbon. Removal efficiencies greater than 99 percent have been demonstrated for volatile organic compounds, pesticides, and PCBs. USEPA (1992g) reported that mercury, one of the more volatile metals, had been reduced from a soil concentration of 5,100 ppm to 1.3 ppm using this process. The X*TRAX system is available in bench- , pilot-, and full-scale units, although this particular thermal desorption process has not been demonstrated with contaminated sediments.

#### *Desorption and Vaporization Extraction System*

The Desorption and Vaporization Extraction System (DAVES[reg.]) process (Recycling Sciences International, Inc.) uses a fluidized bed maintained at a temperature of about 160deg.C and a concurrent flow of 540-760deg.C air from a gas-fired heater. As the contaminated material is fed to the dryer, water and contaminants are removed from the solids by contact with the hot air. Gases from the dryer are treated using cyclone separators and bag houses for removal of particulates and using a venturi scrubber, counter-current washer, and carbon adsorption system for removal of water and organic compounds. Onsite treatment of liquid residues is available as a part of the process. The mobile DAVES[reg.] unit has a capacity of 10-66 tonnes/hour. It is applicable to most volatile and semivolatile organic compounds and PCBs (USEPA 1992g). The process was tested with sediments from Waukegan Harbor, Illinois, with reported reductions in PCB concentrations from 250 ppm to <2 ppm (USEPA 1991c).

#### *Low-Temperature Thermal Aeration System*

The low-temperature thermal aeration system (Canonie Environmental Services Corp.) uses a direct-fired rotary dryer that can heat soil to temperatures of 430deg.C. The gas stream from the dryer is treated for particulate removal in cyclones and/or baghouses. Organic compounds may be destroyed in an afterburner or scrubbed and adsorbed onto activated carbon. The full-scale unit can process 11-15 $m^{3}$/hour. Effective separation of volatile organic compounds and PAHs from contaminated soils has been demonstrated (USEPA 1992g).

#### *Anaerobic Thermal Processor Systems*

The Anaerobic Thermal Processor[reg.] (ATP[reg.]) system (SoilTech ATP Systems, Inc.) also known as the AOSTRA-Taciuk process, consists of four processing zones. Contaminated material is fed into a preheat zone maintained at temperatures of 200-340deg.C where steam and light organic compounds are separated from the solids. The solids then move into a 480-620deg.C retort zone, which vaporizes the heavier organic compounds and thermally cracks hydrocarbons, forming coke and low molecular weight gases. Coked solids pass to a combustion zone (650-790deg.C) where they are combusted. The final zone is a cooling zone for the flue gases. The organic vapors are collected for particulate removal and for recovery or adsorption on activated carbon (USEPA 1992g). This system was used for the cleanup of PCB-contaminated sediments and soil from the Outboard Marine Corp. Superfund site in Waukegan Harbor, Illinois. A full-scale unit, rated at 23 tonnes/hour was used and produced PCB removals of 99.98 percent (Hutton and Shanks 1992). Pretreatment is necessary to reduce the feed materials to less than 5 cm. in diameter.

***Summary of Thermal Desorption Technologies***

Thermal desorption processes offer several advantages over thermal destructive processes, including reduced energy requirements, less potential for formation of toxic emissions, and smaller volumes of gaseous emissions. Disadvantages include the need for a follow-on destruction process for the volatilized organic compounds and reduced effectiveness for less volatile organic compounds. Table 7-6 [part i] [part ii] [part iii] provides a summary of various thermal desorption technologies, and Table 7-7 identifies factors that affect the efficiency of the thermal desorption process.

## Immobilization Technologies

Immobilization alters the physical and/or chemical characteristics of the sediment to reduce the potential for contaminants to be released from the sediment when placed in a disposal site. The principal contaminant loss pathway reduced by immobilization is contaminant leaching from the disposal site to groundwater and/or surface water; however, contaminant losses at the sediment surface may also be reduced by immobilization processes. Solidification/stabilization is a commonly used term that covers the immobilization technologies discussed in this chapter. Table 7-8 lists some of the sediment characteristics that can affect the immobilization process.

Physical stabilization processes improve the engineering properties of the sediments, such as compressive strength, bearing capacity, resistance to wear and erosion, and permeability. Alteration of the physical character of the sediments to form a solid material (e.g., a cement matrix) reduces the accessibility of the contaminants to water and entraps or microencapsulates the contaminated solids within a stable matrix. Because most of the contaminants in dredged material are tightly bound to the particulate fraction, physical stabilization is an important immobilization mechanism (Myers and Zappi 1989). Solidification processes may also reduce contaminant losses by binding the free water in dredged material (a large contributor to the initial leachate volume from dredged material in a disposal site) into a hydrated solid.

Chemical stabilization is the alteration of the chemical form of the contaminants to make them resistant to aqueous leaching. Solidification/stabilization processes are formulated to minimize the solubility of metals by controlling pH and alkalinity. Anions, which are more difficult to bind in insoluble compounds, may be immobilized by entrapment or microencapsulation. Chemical stabilization of organic compounds may be possible, but the mechanisms involved are not well understood (Myers and Zappi 1989).

Binders used to immobilize contaminants in sediment or soils include cements, pozzolans, and thermoplastics (Cullinane et al. 1986b; Portland Cement Association 1991). In many commercially available processes, proprietary reagents are added during the basic solidification process to improve the effectiveness of the overall process or to target specific contaminants. The effectiveness of an immobilization process for a particular sediment is difficult to predict, and can only be evaluated using laboratory leaching tests. A diagram of an immobilization process is shown in Figure 7-3.

Immobilization technologies have been evaluated for treatment of contaminated sediments from both freshwater and saltwater environments. These investigations have shown that physical stabilization of sediments is easily achieved using a variety of binders, including proprietary processes. Results of leaching tests on the solidified products have been mixed; the mobility of some contaminants has been reduced while the mobility of other contaminants has been increased (Myers and Zappi 1992). The ARCS Program evaluated solidification/stabilization of Buffalo River sediments using three generic binders: Portland cement, lime-fly ash, and kiln dust. Leaching of lead, nickel, and zinc was reduced by the cement process, but leachate concentrations of copper were significantly higher for the solidified sediments compared to leachates from the untreated sediments (Fleming et al. 1991). Immobilization of organic compounds in sediments is generally thought to be less effective than for heavy metals; however, Myers and Zappi (1989) demonstrated reductions in PCB leachability in New Bedford Harbor sediments using a solidification process. The results of these studies demonstrate the importance of laboratory evaluations of appropriate protocols for specific sediments, binders, and contaminants prior to selecting an immobilization process for remediation.

## Extraction Technologies

Solvent extraction processes are used to separate contaminated sediments into three fractions: particulate solids, water, and concentrated organic compounds. Contaminants are dissolved or physically separated from the particulate solids using a solvent that is mixed thoroughly with the contaminated sediment. Most extraction processes do not destroy or detoxify contaminants, but they reduce the volume of contaminated material that must be subsequently treated or disposed. Volume reductions of 20-fold or more are possible, depending on the initial concentration of extractable contaminants in the feed material and the efficiency of separation of the concentrated organic (oil) stream and the water evaporated by the process. Another advantage of the volume reduction is that most of the contaminants are transferred from the solid phase to a liquid phase, which is more easily managed in subsequent treatment or disposal processes. The primary application of solvent extraction is to remove organic contaminants such as PCBs, volatile organic compounds, halogenated solvents, and petroleum hydrocarbons. Extraction processes may also be used to extract metals and inorganic compounds, but these applications, which usually involve acid extraction, are potentially more costly than those used for removing organic contaminants. Solvents used for extraction processes can represent a significant cost; therefore, a key component of an extraction process is to separate the solvents from the organic compounds and reuse them in subsequent extraction steps. Usually several extraction cycles are required to reduce contaminant concentrations in the sediments to target levels.

The principal pretreatment operation required for solvent extraction is screening or particle-size reduction to remove or reduce oversized debris (see Chapter 6). The maximum particle size depends on the scale and configuration of the extraction process, but the recommended maximum size is 0.5 cm (USEPA 1988b). A wide range of solids contents are acceptable for sediment treated by extraction processes. Some processes require that the feed material be pumped, which would require that water be added to the sediment to decrease the solids content.

Extraction processes can operate in a batch mode or continuous mode. Sediments and solvents are mixed together in an extractor (Figure 7-4). Extracted organic compounds are removed from the extractor using the solvent and are transferred to a separator where the solvent and organic compounds are separated from the water and the contaminants are separated from the solvent by changes in temperature or pressure, or differences in density. Concentrated organic contaminants are usually associated with an oil phase, which is removed from the separator for post-treatment. The solvent is recycled to the extractor to remove additional contaminants. This cycle is repeated several times before the treated solids are finally removed from the extractor.

When treated solids are removed from the extractor, traces of solvent will be present. The solvents selected for these processes generally vaporize or are biodegradable. Some processes include an additional separation step designed to further remove, by distillation or other means, most of the solvent from the product solids.

A number of process options for extraction are commercially available; however, most of them are proprietary. Most of the processes discussed in this chapter have been used in the USEPA SITE Program, and two of them have been demonstrated with contaminated sediments.

#### *Basic Extractive Sludge Treatment Process*

The B.E.S.T.[reg.] process (Resources Conservation Co.) uses a combination of tertiary amines, usually triethylamine (TEA), as the solvent. The first extraction is conducted at temperatures below 4deg.C where TEA is soluble with water and at a pH greater than 10. Hydrocarbons and water in the sediment simultaneously solubilize with the TEA, creating a homogenous mixture (USEPA 1992g). In the next step of the process, solids are separated from the liquid mixture by settling. The remaining solvent is removed from the solids fraction by indirect steam heating. Water is separated from the water-organic compound-TEA mixture by heating the solution to temperatures above the miscibility point (about 54deg.C). Organic compounds and TEA are separated by distillation, and the TEA is recycled to the extraction step. This process was demonstrated at the Grand Calumet River as a combination ARCS and SITE program demonstration in 1992 (USACE Chicago District 1994), and bench-scale tests were performed for Buffalo River, Saginaw River, and Grand Calumet River sediments (USEPA, in prep.a). A summary of the bench- and pilot-scale results for PCBs and PAHs is provided in Table 7-9.

#### *CF Systems Solvent Extraction*

The solvent extraction process offered by CF Systems uses compressed propane at supercritical conditions as the solvent. Sediment is screened to remove oversized material and debris and can then be pumped through the system as a slurry in a continuous mode. The solvent is mixed with the sediment under normal temperatures and high pressures. Organic compounds are extracted from the sediment and water into the solvent. The solvent-organic compound stream is removed from the extractor, and the propane is separated from the organic compounds by reducing the pressure and allowing the propane gas to vaporize. After recompression, the gas is recycled to the extraction step. Three or more extraction stages are usually required to achieve contaminant removal efficiencies of 90-98 percent (USEPA 1992g). This process was demonstrated using contaminated sediments from the New Bedford Harbor Superfund site during a SITE Program demonstration (USEPA 1990c,h).

#### *Carver-Greenfield Process*

The Carver-Greenfield process (Dehydro-Tech Corp.) is a physical process that can be used to separate oil-soluble organic compounds from contaminated sediments by dissolving the contaminants in a food-grade oil with a boiling point of approximately 204deg.C. Five to ten kilograms of carrier oil per kilogram of solids is combined in a mixing tank where the extraction takes place. Three or more extraction stages may be necessary. From the mixing tanks, the slurry is transferred to a high-efficiency evaporator where the water is removed. The oil is separated from the dewatered solids initially by centrifugation and then by a hydroextraction process that uses hot nitrogen gas to strip the remaining oil from the solids. After separating the contaminants from the oil by distillation, the oil is recycled to the extraction step and the concentrated contaminants are further treated or disposed. Low solids content is not a problem for this process, but particle size must be reduced to less than 0.5 cm in diameter. Demonstration projects have been conducted on drilling mud wastes, a relatively fine-grain material. The requirements of this process for fine particle sizes and wet feed material favor applications to contaminated sediments.

#### *Soil Washing*

The term soil washing is generally used to describe extraction processes that use a water-based fluid as the solvent (USEPA 1990b). Many soil washing processes rely on particle-size separation to reduce the volume of contaminated material. These processes were discussed in Chapter 6, *Pretreatment Technologies*, and will not be addressed in this section. Other water-based techniques involve dissolving or suspending the contaminants in the water-based fluid. Because most sediment contaminants are tightly bound to particulate matter, water alone is not a suitable extraction fluid. Surfactants, acids, or chelating agents may be used with water to effect separation of some contaminants. The particle size and type of contaminant are important factors in the effectiveness of soil washing as an extraction process. Soil washing for clays and silts is only marginally applicable. The U.S. Bureau of Mines evaluated acid extraction for heavy metals in Great Lakes sediments from three AOCs under the ARCS Program and found minor reductions in sediment metal concentrations (Allen, in prep.). The use of surfactants may be successful for removing organic compounds from sandy sediments.

#### *Other Extraction Processes*

Other extraction processes are emerging that have the potential for removing organic, and perhaps inorganic, compounds from contaminated sediments. Table 7-10 [part i] [part ii] lists a number of extraction processes that are commercially available and are advertised as being applicable to contaminated sediments. This list was developed from those technologies in the SEDTEC database (Wastewater Technology Centre 1993). The table lists the name of the process, the classes of contaminants affected, and the extraction fluid or other medium used to separate the contaminants. Most of the vendors of these technologies do not specify a particular solvent, stating that it depends on the contaminant and material characteristics.

#### *Factors Affecting Solvent Extraction Processes*

Sediment characteristics and their effect on performance of extraction processes are shown in Table 7-11.

## Chemical Treatment Technologies

For the purposes of this document, the definition of chemical treatment is restricted to processes in which chemical reagents are added to a sediment matrix for the purpose of contaminant destruction. Certain immobilization, extraction, and thermal procedures also involve chemical inputs, but they are typically added to alter the phase of the contaminant, thus facilitating removal or binding the contaminant in the sediment. A clear distinction between categories cannot always be made, and some overlap may occur between this and other chapters of this document.

Chemical treatment technologies used during the removal component involve mixing chemical additives with sediments or with a sediment slurry. This mixing is typically done in batch operations in some type of process vessel. Chemical treatments may destroy contaminants completely, may alter the form of the contaminants so that they are amenable to other treatments, or may be used to optimize process conditions for other treatment processes. Treated sediments may then be permanently disposed of or put to some beneficial use, depending on the nature and extent of residuals, including reagents and contaminants.

For the ARCS Program, Averett et al. (1990 and in prep.) reviewed eight general categories of chemical treatment for suitability to dredged material. Chelation, dechlorination, and oxidation of organic compounds were considered most promising. The specific processes under these three categories that have been demonstrated to be useful or that are sufficiently developed for consideration are further described in this section. Other promising, emerging technologies are also discussed.

### *Chelation Processes*

Chelation is the process of stable complex formation (a chelate) between a metal cation and a ligand (chelating agent). This process could also be considered an immobilization process, and some extraction processes also use chelating agents. Binding of the metal cation in a stable complex renders it unavailable for further reaction with other reagents in chemical or biological systems. The stability of a complex generally increases as the number of bonds increases between the ligand and the metal cation (Snoeyink and Jenkins 1980). A ligand forming a single bond is known as monodentate, a ligand forming two bonds is known as bidentate, while a ligand forming more than two bonds is known as polydentate. Ethylenediaminetetraacetic acid (EDTA) is a well-known example of a polydentate ligand (Brady and Humiston 1986). pH is one of the most important parameters that affects the treatment process. Efficiency varies with the chelating agent and dosage used (Averett et al., in prep.).

The ENSOL and LANDTREAT process uses a polysilicate as an adsorptive agent (LANDTREAT) to solidify metal hydroxide silicate complexes produced by the ENSOL, which contains sodium silicate and a proprietary chelating agent. The process is carried out in an enclosed, continuous-reaction chamber (Wastewater Technology Centre 1993). The process is available at the full-scale commercial level.

### *Dechlorination Processes*

Dechlorination processes remove chlorine molecules from contaminants such as PCBs, dioxins, and pentachlorophenol through the addition of a chemical reagent under alkaline conditions at increased temperatures (USEPA 1990a,j). The resulting products are much less toxic than the original contaminants. Typically, chemical reagents are mixed with the contaminated sediments and heated to temperatures of 110-340deg.C for several hours, producing the chemical reaction and releasing steam and volatile organic vapors. The vapors are removed from the processor, condensed, and further treated using activated carbon. The treated residue is rinsed to remove reactor by-products and reagent and is then dewatered prior to disposal. Adjustment of the pH of the residue may also be required. The wastewater produced may require further treatment. Processing feed streams with lower solids contents, such as sediments, require greater amounts of reagent, increase energy requirements, and produce larger volumes of wastewater for disposal, all distinct disadvantages of this process for contaminated sediments. Four representative dechlorination processes are discussed in the following paragraphs, other vendors may offer similar processes.

> ***APEG Chemical Dehalogenation Treatment***--This process typically uses an APEG to treat aromatic halogenated compounds (USEPA 1990j). Potassium hydroxide (KOH) is most commonly used with polyethylene glycol (PEG), to form the polymeric alkoxide (potassium polyethyleneglycol [KPEG]), although sodium hydroxide is less expensive and has been used for this purpose. Another reagent is KOH or sodium hydroxide/tetraethylene glycol, which is more effective on halogenated aliphatic compounds. Dimethyl sulfoxide (DMSO) may be added to "enhance reaction rate kinetics" (USEPA 1990j). Products of the reaction are a glycol ether and/or a hydroxylated compound and an alkali metal salt-water-soluble by-products.
>
> ***DeChlor/KGME Process***--KGME is a proprietary reagent of Chemical Waste Management, Inc., and is the active species in a nucleophilic substitution (dechlorination) reaction. Principally used for liquid-phase halogenated compounds (particularly PCBs), KGME has been successfully used to treat contaminated soils in the laboratory. PCBs

have been treated in both liquid and solid matrices (USEPA 1992g).

***Base-Catalyzed Dechlorination Process***--The base-catalyzed dechlorination process combines chemical addition with thermal inputs to dechlorinate organic compounds without the use of PEG (USEPA 1992g). The mechanism appears to be a hydrogenation reaction (Rogers 1993). The hydrogen source is a high-boiling-point oil plus a catalyst. The process has been used for both liquids and solids in *in situ* and *ex situ* applications. The SITE program demonstrated the process at a North Carolina site in 1993, and the Navy with support from the SITE program is also evaluating the process for PCB-contaminated soil.

***Ultrasonically Assisted Detoxification of Hazardous Materials***--This process affects the chemical destruction of PCBs in soil using an aprotic solvent, other reagents, and ultrasonic irradiation (USEPA 1992g). The dechlorination of PCBs in the process is believed to result from a nucleophilic substitution reaction, although this is presently unverified. The purpose of the ultrasonic irradiation is to add heat to the reaction. The technology is currently being tested using a moderate-temperature, heated reactor and reflux column (Kaszalka 1993). The process is suitable for *ex situ* application only; to be economically feasible the reagents must be recovered. This technology currently exists at the pilot-scale development level.

### *Oxidation Processes*

Chemical oxidation involves the use of chemical additives to transform, degrade, or immobilize organic wastes. Oxidizing agents most commonly used (singly or in combination with ultraviolet [UV] light) are ozone, hydrogen peroxide, peroxone (combination of ozone and hydrogen peroxide), potassium permanganate, calcium nitrate, and oxygen. The use of ozone, peroxide, and peroxone has come to be known as advanced oxidation processes. Strictly defined, oxidation is the addition of oxygen to a compound (creation of carbon to oxygen bonds) or the loss of electrons from a compound (increase in the positive valence). Oxidation is used to transform or break down compounds into less toxic, mobile, or biologically available forms. Theoretically, compounds can be decomposed completely to carbon dioxide and water. Adequate process control of pH, temperature, and contact time is important to prevent the formation of hazardous intermediate compounds, such as trihalomethanes, epoxides, and nitrosamines, from incomplete oxidation.

Oxidation is commonly used to treat amines, phenols, chlorophenols, cyanides, halogenated aliphatic compounds, mercaptans, and certain pesticides in liquid waste streams (USEPA 1991b). It can also be used on soil slurries and sludge. The effectiveness of oxidation depends on the organic compound as shown in Table 7-12.

Oxidation is nonselective, and all chemically oxidizable material (including detritus and other naturally occurring organic material) will compete for the oxidizing agent. It is not applicable to highly halogenated organic compounds (Averett et al., in prep.). Certain contaminants, such as PCBs and dioxins, that will not react with ozone alone require the use of UV light with the oxidizing agent. This limits the effectiveness of the process with slurries because the UV light cannot penetrate the mixture.

The LANDTREAT and PETROXY process uses a synthetic polysilicate (LANDTREAT) for adsorption of organic compounds to facilitate the oxidation by the PETROXY reagent, which includes a combination of hydrogen peroxide and other additives. A secondary reaction is the conversion of heavy metal cations to metal silicates on active sites of the LANDTREAT (Wastewater Technology Centre 1993).

### *Other Chemical Treatment Processes*

***Chemical and Biological Treatment Process***--This process combines chemical oxidation and biological treatment for the purpose of enhancing biodegradation processes (USEPA 1992g). The mechanism provides oxygen for biological use, oxidation of organopollutants, and alteration of the soil matrix. The process produces chemical intermediates that are both more biodegradable and, due to the apparent alteration of the soil matrix, more bioavailable. This can be beneficial with high waste concentrations that would typically be toxic to microorganisms.

***D-Plus (Sinre/DRAT)***--This process (Wastewater Technology Centre 1993) involves the use of chemical inputs to stimulate enzymes and to provide a favorable chemical environment (alkaline, reducing, anaerobic) for hydrogenation, dehalogenation, and hydrolysis chemical reactions. A biochemical process, the technology uses heat to break carbon-halogen bonds and to volatilize light organic compounds. Although not yet available on a commercial scale, it may be feasible at the current stage of development to treat up to 900 tonnes of contaminated sediments. There is potential for future development of *in situ* application as well.

***Summary of Chemical Treatment Technologies***

Table 7-13 [part i] [part ii] [part iii] lists the processes discussed above and presents specific applications, limitations, specifications, and efficiencies of these processes.

## Bioremediation Technologies

Bioremediation, sometimes called biorestoration, is a managed or spontaneous process in which microbiological processes are used to degrade or transform contaminants to less toxic or nontoxic forms, thereby remedying or eliminating environmental contamination. Microorganisms depend on nutrients and carbon to provide the energy needed for their growth and survival. Degradation of natural substances in soils and sediments provides the necessary food for the development of microbial populations in these media. Bioremediation technologies harness these natural processes by promoting the enzymatic production and microbial growth necessary to convert the target contaminants to nontoxic end products.

Biological treatment has been used for decades to treat domestic and industrial wastewaters, and in recent years has been demonstrated as a technology for destroying some organic compounds in soils, sediment, and sludges. Bench-scale testing of bioremediation was conducted for the ARCS Program with sediments from Great Lakes sites (Jones et al., in prep.a). The chemical and physical structure of organic compounds affects the ability of microorganisms to use them as a food source. The degradation potential for different classes of organic compounds is illustrated in Figure 7-5. Bioremediation of organic compounds in sediment is a complex process, and its application to specific compounds is based on an understanding of the microbiology, biochemistry, genetics, metabolic processes, structure, and function of natural microbial communities. Microbiology must be combined with engineering to develop effective bioremediation processes. The ARCS Program conducted a workshop on bioremediation of contaminated sediments to document laboratory research and field applications of this technology. The proceedings of this workshop (Jafvert and Rogers 1991) provide an excellent discussion of the state of the art with an emphasis on the microbial and chemical processes involved.

Many of the more persistent contaminants in the environment, such as PCBs and PAHs, are resistant to microbial degradation because of 1) the compound's toxicity to the organisms, 2) preferential feeding of microorganisms on other substrates, 3) the microorganism's lack of genetic capability to use the compound as a source of carbon and energy, or 4) unfavorable environmental conditions in the sediment for propagating the appropriate strain of microorganisms. Alteration of the environmental conditions can often stimulate development of appropriate microbial populations that can degrade the organic compounds. Such changes may include adjusting the concentration of the compound, pH, oxygen concentration, or temperature, or adding nutrients or microbes that have been acclimated to the compound. A summary of sediment characteristics and environmental conditions that limit bioremediation processes, and actions to minimize the effects of these limitations, is presented in Table 7-14.

Biodegradation of refractory organic compounds is not uncommon in nature, but can take many years. The key to improving the usefulness of bioremediation for cleaning up contaminated sediment sites is to determine how to accelerate the rate of biodegradation to detoxify the target compounds in a finite time period (i.e., weeks or months rather than years).

Ideally, biodegradation of organic compounds in sediments would be accelerated *in situ*. However, because of the complexity of the sediment-water ecosystem; the difficulties in controlling physical and chemical, as well as biological, processes in the sediment, and the need to adjust environmental conditions for various stages of the biodegradation process; limited effectiveness has been demonstrated for *in situ* bioremediation. Much research is underway in the area of *in situ* treatment, and future efforts will likely overcome some of these difficulties for certain sites and specific contaminants. However, the best current prospects for successful bioremediation of xenobiotic compounds are engineered treatment systems in which environmental conditions can be carefully controlled and adjusted as the biotransformation processes progress with time.

Biodegradation is accomplished either aerobically or anaerobically. Aerobic respiration is energy-yielding microbial metabolism in which the terminal electron acceptor for substrate oxidation is molecular oxygen, and carbon dioxide and water are the end products. Free oxygen must be present for aerobic reactions to occur. Anaerobic respiration is energy-yielding metabolism in which the terminal electron acceptor is a compound other than molecular oxygen, such as sulfate, nitrate, or carbon dioxide, and methane, sulfides, and organic acids are the typical end products. Aerobic processes generally proceed more quickly and provide a more complete degradation of the organic compounds than anaerobic processes. However, some compounds can only be changed by anaerobic organisms. For example, dechlorination of the more highly chlorinated PCBs by anaerobic processes has been demonstrated in laboratory and field studies. On the other hand, the less chlorinated PCBs are susceptible to degradation by aerobic organisms. Sequential anaerobic treatment followed by aerobic processes appears to offer an effective destruction technology for PCBs (Quensen et al. 1991).

This section addresses surface bioremediation techniques in which sediments are removed from the waterway and treated in bioslurry reactors, contained land treatment systems, compost piles, or CTFs. Pretreatment requirements for these processes include removal of oversized particles for bioslurry reactors and possible adjustment of solids content for all of the processes. One of the advantages of bioremediation technologies is that the physical and basic chemical characteristics of the treated sediments are very similar to the feed material, allowing a wide range of choices for beneficial use of the treated sediment.

### *Bioslurry Processes*

Bioslurry reactors are a relatively new technology that has been applied to contaminated solids mostly in the last 5-10 years. There have been a number of pilot-scale applications, but few full-scale installations. Bioslurry reactors are best suited to treating fine-grained materials that are easily maintained in suspension. In a bioslurry system, a sediment-water slurry is continuously mixed with appropriate nutrients under controlled conditions in an open or closed impoundment or tank. Aerobic treatment, which involves adding air or another oxygen source, is the most common mode of operation. However, conditions suitable for anaerobic microorganisms can also be maintained in the reactor where this oxic state is an essential step in the biodegradation process. Sequential anaerobic/aerobic treatments are also possible in these systems. Contaminants with potential for volatilization during the mixing and/or aeration process can be controlled using emission control equipment. A schematic diagram of an aerobic bioslurry process is shown in Figure 7-6. Systems for treating soils or sediments are often operated in batch mode, because typical retention times are on the order of 2-12 weeks. Once the treatment period is completed, the solids may be separated from the water and disposed of separately. The slurry solids concentrations range from 15-40 percent; therefore, adjustments in solids contents for slurry treatment of sediments may be minor.

The degradation of PCBs using the bioslurry reactor technology was investigated by General Electric Co. (Abramowicz et al. 1992). Researchers concluded that between 35 and 55 percent of the initial PCBs were degraded over a 10-week test period in reactors amended with biphenyl. Remediation of contaminated sediments from Toronto Harbor, Ontario, was tested in pilot-scale reactors in 1992 (Toronto Harbour Commission 1993). Although complicated by analytical interferences, the results showed that oil and grease was completely degraded in several week's time, with a partial degradation of PAHs.

### *Contained Land Treatment Systems*

Contained land treatment systems, which have been demonstrated in Europe, require mixing of appropriate amendments with the sediments, followed by placement of the material in an enclosure such as a building or tank and on a pad or prepared surface (USEPA 1991d). The enclosure protects the material from precipitation, moderates temperature changes, allows moisture control, and provides the capability to control volatile organic compound emissions. A schematic diagram of a contained land treatment system is shown in Figure 7-7.

Leachate from the sediment is collected by underdrains for further treatment as necessary. The layer of sediment treated for each lift is generally no deeper than 6-8 in. (15-20 cm). Regular cultivation of the sediments and the addition of nutrients, and in some cases bacterial inocula, are typically required to optimize environmental conditions for rapid bioremediation. The excess water associated with the sediment as it is placed in the treatment bed may create operational problems for startup and will likely require that the system be designed for lateral confinement of the material.

***Composting***

Composting is a biological treatment process used primarily for contaminated solid materials. Bulking agents (e.g., wood chips, bark, sawdust, straw) are added to the solid material to absorb moisture, increase porosity, and provide a source of degradable carbon. Water, oxygen, and nutrients are needed to facilitate bacterial growth. Sediment solids contents will likely be sufficient for composting operations, and in some cases dewatering of the sediment may be necessary as a pretreatment step. Available composting techniques include aerated static pile, windrowing, and closed reactor designs (USEPA 1991d). Volatilization of contaminants may be a concern during composting and may require controls such as enclosures or pulling air through the compost pile rather than pushing air into and out of the pile. Use of composting to treat sediments should increase permeability of the sediment, allowing for more effective transfer of oxygen or nutrients to the microorganisms. A pilot-scale demonstration of composting is being conducted for Environment Canada's Cleanup Fund at a site in Burlington, Ontario. Approximately 150 tonnes of PAH-contaminated sediments from Hamilton Harbor were placed in a temporary shelter and tilled periodically with additions of a proprietary organic amendment (Seech et al. 1993). The treatment was executed over an 11-month period. Sediments that were tilled with the amendment showed reductions of PAHs of over 90 percent, while controls with tillage and no amendment showed reductions of 51 percent. Controls with no tillage or amendment showed reductions of 73 percent (Grace Dearborn Inc., in prep.).

***Contained Treatment Facility***

CDFs routinely used for dredged material may be used as contained treatment facilities for bioremediation of sediments. These facilities often provide long-term to permanent storage. The size of the CDF and the depth (1.5-5 m) of sediments may limit the capability to control conditions compared to other bioremediation systems. These limitations are similar to those for *in situ* bioremediation processes for contaminated soil sites, except that engineering the biotreatment system for upland CDFs is not as difficult compared to *in situ* systems. A pilot evaluation of a contained treatment facility for PCB-contaminated sediments is underway at the Sheboygan River AOC. Rather than a diked disposal facility, the contained treatment facility is constructed with sheet pile walls and includes an underdrain system that could be used for leachate control and to add nutrients, oxygen, and other additives. The ARCS Program has contributed to the scientific assessment of the operation; a report documenting these investigations will be published at a later date; however, these experiments were inconclusive as of early 1994. Bioremediation in a CDF would offer an economical process for reducing sediment organic contamination, but more research is needed to develop techniques for implementation.

***Summary of Bioremediation Technologies***

The advantages and disadvantages of the bioremediation technologies reviewed in this section are summarized in Table 7-15 [part i] [part ii].

## SELECTION FACTORS

Selection factors for treatment technologies will be discussed in terms of three general categories: target contaminants, sediment characteristics, and implementation factors. The discussion is based on selection of a type of technology (e.g., thermal destruction, extraction, immobilization) for a particular project. Selection of a process option within a technology type will require further evaluation using treatability studies and consideration of the factors affecting the technologies discussed earlier in this chapter. In addition, the evaluation of the overall remedial alternative must consider the effects of each step of the process on preceding and succeeding steps.

### Target Contaminants

Selection of a treatment technology for a particular contaminated sediment site should first consider the contaminants of concern and the effectiveness of each technology in destroying, removing, or immobilizing those contaminants. Table 7-16 rates the effectiveness of each of the major technology types on organic and inorganic compounds typically found in contaminated sediments. For many contaminant/technology combinations, effectiveness of removal or destruction has been demonstrated; however, as the table notes, in some cases the effects are not known or the process is only partially effective in treating the contaminant. A note is also made where a technology may increase contaminant loss for a nontarget contaminant present in the sediment. When both organic and inorganic contaminants are targeted, more than one technology may be required to accomplish project objectives.

### Sediment Characteristics

Table 7-17 shows how three major sediment characteristics can affect the performance of various treatment technologies. These characteristics are predominant particle size, solids content, and high contaminant concentration. Particle size may be the most important limiting characteristic for application of treatment technologies to sediments. Most treatment technologies are very effective on sandy soils and sediments. The presence of fine-grained material adversely affects treatment system emission controls because it increases particulate generation during thermal drying, it is more difficult to dewater, and it has greater attraction to the contaminants (particularly clays). Clayey sediments that are cohesive also present materials handling problems in most processing systems.

Another sediment characteristic that affects process performance is solids content. Two classes of solids contents are shown in Table 7-17: high, representing material at near the *in situ* solids content (30-60 percent solids by weight); and low, representing a hydraulically dredged sediment (10-30 percent solids by weight). Technologies that require the sediments to be in a slurry for treatment are favored for the lower solids contents; however, high solids contents are easily changed to lower solids contents by water addition at the time of processing. Changing from a lower to a higher solids content requires more processing. Thermal processes are adversely affected by lower solids contents primarily because of increased energy consumption. Dechlorination processes are adversely affected because of increased chemical costs and increased wastewater treatment requirements.

The last set of characteristics shown in Table 7-17 is the presence of organic compounds or heavy metals in high concentrations. Incineration and oxidation processes are generally favored for higher organic carbon concentrations (not necessarily the target contaminant). Higher metal concentrations may make a technology less favorable because of the increased mobility of certain metal species following application of the technology.

### Implementation Factors

A number of other factors may affect selection of a treatment technology other than its effectiveness for treatment. Seven of these factors are listed in Table 7-18. Each of these factors must be weighed for each technology. The table indicates with a check mark the technology-factor combination for which the factor may be critical to evaluation of the technology. For example, vitrification and supercritical water oxidation have only been used for relatively small projects and would be very difficult to implement for full-scale sediment projects. Regulatory compliance and community acceptance become prominent issues for any type of incineration system. Land requirements are more of a concern for solidification and solid-phase bioremediation projects. Residuals disposal must be addressed for those processes (i.e., thermal desorption, extraction, soil washing) that generate a contaminated, potentially hazardous, waste stream. Wastewater treatment and air emission control are more of a concern when the technology generates these releases.

## FEASIBILITY EVALUATIONS

It is evident from the previous discussion that there may be several different types of technologies that have potential for successfully remediating a specific contaminated sediment site. A screening process, considering such factors as contaminant type and sediment physical characteristics, will typically narrow the range of applicable technology candidates, but will not reduce them to a single process option.

To proceed from a site screening analysis or remedial investigation to the selection of an optimum technology for full-scale application in the remediation of a contaminated sediment site, there are several types of tests that can be used to further reduce the range of options. The following sections discuss the various testing options, the implications surrounding them, and some general cost ranges for such tests.

## Identifying Testing Needs

The need for technology testing, either in the laboratory (bench-scale) or on a larger scale in a field setting (pilot- or full-scale), is a function of both the particular sediment contamination problem and the state of development of the technology. As Averett et al. (in prep.) have noted, the application of hazardous waste or mineral processing technologies to full-scale sediment remediation projects is in its infancy at this time. The recent completion of the cleanup of the Outboard Marine Corp./Waukegan Harbor Superfund site, which employed a thermal desorption unit to treat more than 11,000 tonnes of contaminated sediments, is the only full-scale, sediment treatment project completed in North America to date.

Until the implementation of the ARCS Program in the United States and the Contaminated Sediment Treatment Technology Program (COSTTEP) in Canada, very few treatment technologies had been evaluated for contaminated sediments in the laboratory or in the field. Through these programs, however, as of summer 1993, about 30 technologies have been tested on sediments in the laboratory. Pilot-scale demonstrations in the field have now been conducted with 12 processes. The experience gained through these programs, in addition to other studies conducted by the Corps and through the SITE Program, has helped advance the state of knowledge on the general effectiveness of treatment technologies for contaminated sediments and will serve as a useful guide for others attempting to select a technology for their site.

Because of the unique characteristics of each contaminated sediment site, some amount of laboratory testing will be necessary to determine if the technology being considered is capable of obtaining the desired treatment efficiencies. Spatial variabilities within a given site may require testing of several sediment samples with different physical and/or chemical characteristics. Only in very rare cases will there be no testing required prior to full-scale remediation efforts. At a minimum, the technology vendor will need to set operating parameters for its full-size treatment unit, requiring at least the performance of glassware simulations of the main components of the treatment technology using samples representative of the specific sediments to be remediated.

The need for pilot-scale tests, using process equipment that closely mimics the unit operations of a full-scale technology, will have to be determined on a case-by-case basis. The decision to conduct pilot-scale tests is a joint one between the parties responsible for the cleanup, the Federal and State agencies regulating the cleanup, and the technology vendor. It is sometimes beneficial, for contracting purposes, to allow the technology vendor flexibility in reaching established treatment goals, as opposed to conducting extensive testing prior to the full-scale operations. Minor changes in field operations can adversely affect processes for which very narrow operating parameters were specified.

## Purpose and Design of Bench-Scale Tests

The purpose of conducting bench-scale, or laboratory, tests on small quantities of sediments (typically less than 1 kg) can range from simply determining gross process efficiencies to setting specific operating parameters for a full-scale technology application. Each sediment sample is unique, combining different contaminant types and concentrations with certain physical characteristics, and all of these variables can affect the ability of a technology to "treat" the sediments.

In an ideal situation, specific cleanup goals will have been set for a site, either expressed as a maximum residual concentration of a specific contaminant (e.g., 2 mg/kg PCBs) or as a minimum percent of the contaminant that must be removed from the raw material. In addition, the contaminant concentrations that are expected in the final, treated products would ideally be measurable using current analytical techniques. By working with the technology vendor, an experimental design can be established to determine the optimum configuration of a process (e.g., operating temperature, residence time, extraction cycles) to meet the cleanup goals. A factorial design, varying two or more parameters in a systematic pattern, is useful to examine the sensitivity of a process when treating the sediment of concern. The USEPA document, *Guide for Conducting Treatability Studies Under CERCLA* (USEPA 1989b), is an excellent reference on this subject.

Under the ARCS Program, bench-scale tests were conducted with no specific treatability goals established. Instead, vendors were directed to optimize the application of their process to one or more sediment samples, keeping in mind that economics would be a prime consideration in the full-scale application of the technology by the users of the information generated by the ARCS Program. A twophased approach was used. During Phase I, the vendors were allowed to adjust operating parameters to determine optimum conditions. During Phase II, the process was run under these optimum conditions, with extensive analyses conducted on all the feed and residual materials produced by the technology to determine process efficiency. A matrix of the parameters analyzed in these tests is provided in Table 7-19.

The selection criteria listed in Table 7-16 should serve as a starting point for other technology evaluations. Contaminants should be added or deleted from the list as appropriate for the specific sediment sample and technology being evaluated. Chemicals used in the process that may be problematic if encountered in treatment residuals should also be monitored. In addition, if concerns exist over the status of the untreated sediments being regulated as a hazardous waste (e.g., the sediments fail the TCLP test for one or more parameters), or if the technology may alter the sediments such that the solid residue produced by the process may fail the TCLP, then appropriate analyses of the raw and treated materials should be conducted.

Quality assurance and quality control issues should receive utmost priority in conducting any evaluation of treatment technologies. Quality assurance project plans (QAPjP) were prepared and followed for all of the bench-scale tests performed under the ARCS Program, in accordance with the Quality Assurance Management Plan (QAMP) for the overall ARCS Program (USEPA 1992c). The ARCS QAMP serves as a useful guide for conducting sediment sampling and analysis activities, and is recommended for further information on this subject.

In addition to analyzing for contaminant concentrations in raw and treated materials, an attempt should be made to perform a mass balance analysis for each bench-scale test. However, the degree of certainty that can be obtained with a mass balance analysis is highly dependent on the representativeness of that sample for the sediments as a whole. Any error in this analysis is magnified when the total mass of the contaminant is calculated by multiplying the contaminant concentration by the total weight of the sample. Weights for all materials entering or exiting a process should be accurately and precisely determined. The masses measured directly for materials such as solids, water, and oil may produce more reliable mass balance results.

## Purpose and Design of Pilot-Scale Tests

The need for pilot-scale demonstrations and testing of a technology will be influenced by the state of development of the technology (whether pilot- or full-scale treatment units exist), the success of previous testing on similar sediment types, and the vendor's confidence in scaling up from bench-scale test results. An additional factor may be the need to demonstrate to the local community that a technology is safe, effective, and aesthetically acceptable. This can be best accomplished through an onsite, pilot-scale demonstration.

Certain critical elements of a sediment remediation process can also be analyzed more realistically during a pilot-scale demonstration than in a bench-scale test. Because a pilot-scale unit uses pieces of equipment and process flow patterns that more closely simulate the full-scale technology, the ability for the unit to deal with the physical characteristics of the contaminated sediments is better evaluated. In addition, the effects of particle size, solids content, and high contaminant concentrations can be evaluated more easily than in the laboratory. The pilot-scale demonstrations conducted under the ARCS Program were most successful in expanding the body of knowledge for engineering issues concerning the application of treatment technologies to contaminated sediments.

The experimental design for a pilot-scale testing program should follow the same logic as that described for the bench-scale test. If bench-scale tests precede the pilot-scale test, the optimum settings for the operating parameters should already be established. The pilot-scale test can then be used to evaluate the effects of other variables (e.g., solids content in the feed material, processor throughput rates, operating temperatures) on the effectiveness of the process.

The larger-scale, high-volume processes in the pilot-scale demonstration may require the sampling and analysis of additional process streams including: air emissions (including carbon canisters used as emission control devices), wastewater discharges, chemical reagent or solvent stocks, and multiple solid product streams (e.g., cyclone residuals). Monitoring of some of these process streams may be necessary to ensure compliance with permits obtained for the demonstration.

### Data Collection and Interpretation from Treatability Tests

The success of a treatability test is usually judged by comparing the concentrations of the contaminants of concern in the untreated sediments with those in the treated solids produced by the process. The evaluation can be made as to whether the residual contaminant concentrations are below the established cleanup goals or the percentage removal from the untreated sediments meets or exceeds an established guideline. These cleanup goals or removal guidelines may be established by regulation or on a project-specific basis.

Consideration must also be given to the potential transformation and fate of contaminants. This is a concern with any process that uses heat to treat chlorinated hydrocarbons, particularly PCBs, because dioxins and furans can be formed at temperatures less than those required for complete destruction by incineration. Any process that causes a chemical transformation to occur should also be evaluated to determine the possibility of the formation of intermediary products that may be of concern. If any such products are expected, they should also be analyzed for in the appropriate process stream. In addition, those technologies that extract or separate contaminants from the sediment matrix require that all residuals be analyzed for the extracted contaminants, to ensure that unexpected and uncontrolled losses are not occurring. It may be necessary to develop specialized analytical protocols for unusual matrices (e.g., activated carbon or condensed oils).

## ESTIMATING COSTS

General cost estimating guidance was provided in Chapter 2. This section provides guidance for estimating the costs associated with the treatment step of the overall remedial action process. Treatment costs will in most cases be the step requiring the largest expenditure of funds. Unfortunately, costs for the treatment step are the most difficult to estimate accurately. Treatment technologies have not been widely applied to full-scale remediation projects for soils or sediments. Historical project construction data and data for relatively standard construction practices are available for other components, such as removal and disposal, but such data are not available for treatment technologies. Most treatment cost estimates are based on information provided by the vendor. Though vendors may act in good faith in providing cost information, comparability of the data from various vendors is often poor because of variability in the items included in the estimates, the effects of variable sediment characteristics on process operations, and other uncertainties in the process.

### Treatment Cost Components

#### *Cost Elements*

The costs directly attributable to the treatment component are discussed below in terms of the cost elements generally used by the SITE Program for evaluating treatment costs based on field (usually pilot-scale) tests for the treatment technologies. The relative importance of each element in selecting various treatment technologies depends on the unit operations involved in the process, the importance of chemical additives for the process, the energy requirements and costs, and project-specific factors.

> ***Site Preparation Costs***--These costs are for the site used to construct and operate the treatment facility. This element includes site design and layout, surveys and site logistics, legal searches, access rights and roads, preparation of support facilities, decontamination facilities, utility connections, and auxiliary buildings. Where the site is used for more than just the treatment technology (e.g., pretreatment or disposal of residues), site preparation costs may be partially included in the costs for other components.
>
> ***Permitting and Regulatory Requirements***--This element includes permits, system monitoring requirements, and development of monitoring and analytical protocols and procedures.
>
> ***Capital Equipment***--Major equipment items, process equipment, and residual materials handling equipment are included in this element. The annualized equipment cost is based on the life of the equipment, the salvage value, and the annual interest rate.
>
> ***Startup and Fixed Costs***--This element includes mobilization, shakedown, testing,

insurance, taxes, and initiation of environmental monitoring programs. Mobilization costs represent a larger share of the total treatment costs for smaller-scale projects.

***Labor Costs***--Labor charges for operational, supervisory, administrative, professional, technical, maintenance, and clerical personnel supporting the treatment processes must be estimated for this element.

***Supplies, Consumables, and Utilities Costs***--Fuel, electricity, raw materials, and supplies required to process the material are included in this element.

***Residue Treatment and Disposal Costs***--Treatment systems may generate one or more residues (e.g., water, oil, solids, sludges, air/gas) that require further treatment before discharge or disposal. Technologies for treatment and disposal of these residues are discussed in Chapter 9.

***Monitoring and Analytical Costs***--Field and laboratory costs for monitoring the conditions of the treatment process and the quality of residues are included in this element.

***Facility Modification, Repair, and Replacement Costs***--This element includes design adjustments, facility modifications, scheduled maintenance, and equipment replacement.

***Demobilization***--Once the sediment cleanup project is completed, all equipment will have to be dismantled and removed from the treatment site and the land will likely have to be restored to its original condition.

***Real Estate and Contingencies***
Other major cost items that should be included in the overall estimate are land purchase or lease and overall contingency costs.

## Factors Affecting Treatment Costs

Table 7-20 lists a number of factors that affect the cost of treatment technologies included in the VISITT database (USEPA 1993b). In USEPA's query of vendors for the database, the vendor was asked to identify the factors that most affected the cost of each process. The top three factors listed in Table 7-20 were the cost factors identified most frequently by the vendors. These factors are waste quantity, initial contaminant concentration, and target contaminant concentration. A wide range of sediment remediation technologies may be available for a given project, and the costs will vary depending on the volume of sediment to be treated and the contaminant concentrations in the feed and treated material. Table 7-21 [part i] [part ii] lists selected vendors from the VISITT database, the cost range reported by each vendor for a technology type, and the three major cost factors affecting that vendor's costs. Although this table shows cost information for individual process options (vendors), the comparability of these costs (within a given technology type) is limited. In other words, a vendor should not be selected based on the costs shown here. This table should only be used to compare the range of costs and cost factors for the various technology types.

## Representative Treatment Costs

Few remediation projects, including those at Superfund sites, have employed the treatment technologies discussed in this section. However, through demonstrations conducted by the SITE Program, the ARCS Program, the Canadian Cleanup Fund, and others, example costs for a number of technologies applied to specific sites have been documented. Information selected from published SITE and ARCS Program reports is presented in Table 7-22. These data were generated based on operational data from field demonstrations of a few cubic meters. The field data were extrapolated to projects of a specific size based on the particular site. For the four ARCS Program demonstration projects, a range of project sizes and associated costs was reported.

Estimating costs for treatment technologies requires defining the project requirements, acquiring treatability data for the sediments, determining cleanup levels, reviewing available cost reports for treatment technologies, and communicating with vendors of the technologies. A consistent set of rules, site conditions, sediment characteristics, target cleanup levels, and cost elements should be provided to each vendor to obtain information for a comparative analysis of treatment costs.

## ESTIMATING CONTAMINANT LOSSES

### Techniques for Estimating Contaminant Losses

Methods for estimating or modeling contaminant losses from various combinations of treatment technologies are complicated by the wide range of chemical and physical characteristics of contaminated sediments, the strong affinity of most contaminants for fine-grained sediment particles, and the limited application of treatment technologies to contaminated sediments. Basic mathematical models may be available for simple process operations, such as extraction or thermal vaporization applied to single contaminants in relatively pure systems. However, such models have not been validated for the sediment treatment technologies discussed in this chapter because of the limited database on treatment technologies for contaminated sediments or soils.

Standard engineering practice for evaluating the effectiveness of treatment technologies for any type of contaminated media (solids, liquids, or gases) is to perform a treatability study for a sample that is representative of the contaminated material. In a management review of the Superfund Program, USEPA (1989b) concluded that "To evaluate the application of treatment technologies to particular sites, it is essential to conduct laboratory or pilot-scale tests on actual wastes from the site, including, if needed and feasible, tests of actual operating units prior to remedy selection." The performance data generated by the treatability studies will usually provide a reliable estimate of the contaminant concentrations for the residual sediment following treatment. Contaminant concentrations and weights for waste streams generated by a technology can also be determined from treatability studies, but the need for this information must be clearly identified as one of the objectives of the treatability study so that appropriate data will be collected. Treatability studies may be performed at the bench-scale and/or pilot-scale level.

### Collection of Contaminant Loss Data

Most treatment technologies include post-treatment or controls for waste streams produced by the processing. The contaminant losses can be defined as the residual contaminant concentrations in the liquid or gaseous streams released to the environment. For technologies that extract or separate the contaminants from the bulk of the sediment, a concentrated waste stream may be produced that requires treatment offsite at a hazardous waste treatment facility, where permit requirements may require destruction and removal efficiencies greater than 99.9999 percent. The other source of contaminant loss for treatment technologies is the residual contamination in the sediment after treatment. Wherever the treated material is disposed, it is subject to leaching, volatilization, and losses by other pathways. The significance of these pathways depends on the type and level of contamination that is not removed or treated by the treatment process. Various waste streams for each type of technology that should be considered in treatability evaluations are listed in Table 7-23.

---

Last updated on Friday, October 11th, 2002
URL: http://www.epa.gov/grtlakes/arcs/EPA-905-B94-003/B94-003.ch7.html#RTFToC94

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 8. DISPOSAL TECHNOLOGIES

Disposal is the placement of material into a site, structure, or facility on a temporary or permanent basis. The disposal component of a remedial alternative may include the disposal of the dredged sediments or the disposal of residues from pretreatment and/or treatment components. This chapter briefly discusses the temporary storage of sediments and residues, but focuses primarily on permanent disposal.

Disposal is a major component of virtually any sediment remedial alternative, except for nonremoval alternatives. The site or location used for disposal may also be used to implement other components, including pretreatment, treatment, and residue management. The identification of disposal sites is often the most controversial part of remedial planning and design.

This chapter provides descriptions of technologies for the disposal of contaminated sediments. Discussions of the factors for selecting from the available technology types and techniques for estimating costs and contaminant losses are also provided.

## DESCRIPTIONS OF TECHNOLOGIES

Technologies for the disposal of contaminated sediments and residues from pretreatment or treatment components include open-water disposal, beneficial use, and confined (diked) disposal.

A detailed literature review of the disposal technologies is provided in Averett et al. (in prep.). The general features of these technologies are summarized in Table 8-1.

### Open-Water Disposal

Dredged sediments and the residues from pretreatment or treatment technologies may be suitable for the following types of open-water disposal: unrestricted, open-water disposal; level-bottom capping; and contained aquatic disposal.

**Unrestricted**
Open-water disposal is the most common disposal technology used for uncontaminated dredged material worldwide. Approximately 2.3 million $m^3$ of sediments are dredged and discharged into the Great Lakes annually (IJC 1982). Most of these materials are discharged into shallow waters (<18 m) within a few kilometers of the dredging location. Some materials are discharged into nearshore waters to "feed" the littoral drift and nourish eroded beaches. Materials are typically discharged from bottom-dump scows and hoppers, or from dredge pipelines, as shown in Figure 8-1.

**Level-Bottom Capping**
Capping is a disposal technology that has been used for contaminated dredged material in ocean and estuarine waters. Contaminated materials are placed on the bottom and then covered with a cap of clean materials to isolate the contaminants both physically and chemically (Palermo et al., in prep.). Level-bottom capping involves the placement of the contaminated materials on a relatively flat surface, forming a mound, as shown in Figure 8-2. The capping material is placed on top of the mound. The thickness and material characteristics of the cap must be carefully designed to ensure that it isolates the contaminants and can withstand the forces of scour and erosion within acceptable maintenance

(replenishment) requirements.

***Contained Aquatic Disposal***
Contained aquatic disposal is a type of capping in which the contaminated materials are placed into a natural or excavated depression or trench, as shown in Figure 8-2. This depression or trench provides lateral containment of the contaminated material. The design and placement of the cap is essentially the same as for the level-bottom cap. One advantage of contained aquatic disposal is that without a mound the cap may be more resistant to erosion and require less maintenance. The depression for contained aquatic disposal can be excavated using conventional dredging equipment or natural depressions or previously mined pits (sand mining from near-shore areas has occurred in the Great Lakes). Uncontaminated material excavated from the depression can subsequently be used for the cap. Palermo et al. (in prep.) provides detailed guidance on contained aquatic disposal and cap planning and design.

## Beneficial Uses

Dredged sediments and solid residues from pretreatment or treatment technologies may be suitable for a variety of beneficial and productive uses, including beach nourishment, land application, general construction fill, and solid waste management.

The feasibility of these disposal technologies depends on the physical properties of the material, the type and level of contamination, and the local need for materials for these or other beneficial uses. A general discussion of beneficial uses is provided in Averett et al. (in prep.). The Corps' engineering and design manual, *Beneficial Uses of Dredged Material* (USACE 1987a), should be consulted for more detailed information.

***Beach Nourishment***
Shoreline erosion is a chronic problem throughout the Great Lakes and is responsible for damage to public and private properties and the destruction of valuable habitat (IJC 1993). About 10-20 percent of the sediments dredged by the Corps from Great Lakes harbors and tributaries are used to nourish existing beaches or are placed into shallow waters to reform or renourish eroded beaches and shorelines. In most cases, beach nourishment is accomplished using hydraulic (cutterhead) dredging with pipeline transport to a nearby beach or shoreline. Sediments are mounded on the beach and the pipeline discharge is moved periodically to distribute the sediments as desired. Residues of pretreatment or treatment technologies found suitable for beach nourishment would have to be transported from the pretreatment or treatment location, offloaded, and possibly redistributed using earth-moving equipment.

***Land Application***
Sediments and residues from pretreatment or treatment technologies may be used to replace eroded soils or amend marginal soils for agriculture, horticulture, and forestry. Materials such as silt or sandy silt can be readily incorporated into existing silt and clay soils, and may improve drainage and add nutrients (USACE 1987a). Substantial quantities of the sediments dredged from navigation channels on the Mississippi River, Ohio River, and Illinois River are discharged directly onto adjacent fields and incorporated into existing agricultural soils (USACE 1987a). In most cases, the sediments are dredged hydraulically and transported to farm fields by pipeline. Sediments or residues might also be reclaimed from a CDF or treatment operation and transported to the application site.

***General Construction Fill***
Sediments and treatment residues may be used as a fill material for a variety of construction projects. Some dredged material has poor foundation qualities; thus its applicability to a particular construction project would depend on the physical and engineering properties of the material and the specific requirements of the project. Sandy sediments were reclaimed from a CDF in Duluth, Minnesota, and used for road construction fill (Bedore and Bowman 1990). Some sediments/residues may be suitable for use in the production of concrete (see discussion of solidification in Chapter 6).

***Solid Waste Management***
Sediments and treatment residues may be used by municipal or commercial landfills for dike and cap/cover construction and/or as daily cover. Most landfills will only accept materials that have low organic content and are dewatered sufficiently to pass a paint filter test (EPA Method 9095, SW-846; USEPA 1991h). Sediments reclaimed from a CDF and residues from treatment operations might be transported by truck to a nearby landfill for use. At the landfill, the sediments/residues could be stockpiled for later use and spread out using conventional earth-moving equipment. Some landfills will offer a discounted rate for disposal of contaminated sediments if the sediments can be used for daily cover.

## Confined Disposal

Confined disposal is the placement of dredged material into a site or facility designed to contain the material and control contaminant loss. The two types of confined disposal are commercial landfills and CDFs.

Technically, the designs of these facilities may be quite similar. The primary difference between them is the types of materials for which they are constructed. Commercial and municipal landfills may be constructed to receive a variety of wastes, including municipal and commercial refuse, sewage sludge, construction debris, industrial solid wastes, contaminated soils, and other materials. In the Great Lakes, CDFs have been constructed solely for the disposal of contaminated dredged material.

The difference in materials can have major effects on the operation of these facilities. Most solid waste landfills are designed to accept a physically heterogeneous mixture of materials that has very little water. A CDF is designed to receive a physically homogeneous material that may be 10- to 50-percent solids by weight.

A general discussion of confined disposal is provided in Averett et al. (1990 and in prep.). The Corps' engineering and design manual, *Confined Disposal of Dredged Material* (USACE 1987b), should be consulted for more detailed information. In addition to the above disposal technologies, temporary storage facilities for sediments awaiting treatment or residues awaiting transport are discussed below.

### *Commercial Landfills*

Landfills are operated by municipalities and commercial interests for the disposal of various wastes. Landfills are categorized by the types of wastes they accept and the laws regulating them. Some landfills are constructed for specific materials, such as municipal sewage sludge and construction wastes. Most solid waste landfills will accept all types of materials that are not regulated as RCRA-hazardous or TSCA-toxic materials. There are a relatively limited number of landfills that are licensed to receive RCRA-hazardous and TSCA-toxic materials. Only a few licensed chemical waste landfills in the country can accept TSCA-regulated materials. There are 86 commercial RCRA-regulated land disposal facilities in the United States.

A landfill is constructed in an existing or excavated depression or using earthen dikes. The design of a landfill involves one or more of the following types of controls to reduce the loss of contaminants: barrier systems, caps/covers, drainage systems, and leachate collection systems.

The types of controls at a landfill reflect the nature and level of contamination in the materials approved for disposal and the regulatory requirements of the permitting authority. Landfills for RCRA-hazardous and TSCA-toxic materials have more sophisticated and redundant control systems. A comparison of the control systems of solid waste (RCRA Subtitle D), hazardous waste (RCRA Subtitle C), and chemical waste (TSCA) landfills is shown in Figure 8-3.

Contaminated sediments that have been dewatered and residues from pretreatment or treatment technologies may be disposed in commercial or municipal landfills. The current use of commercial landfills for disposal of contaminated sediments is generally limited to small quantities of materials from marine construction projects (e.g., bridge rehabilitation, pipeline and cable crossings). Some landfills have used sediments for daily cover or for the construction of interior dikes and caps/covers.

### *Confined Disposal Facilities*

For many years, dredged material from navigation projects in which open-water disposal was impractical has been disposed in diked structures. The purpose of the diked structures was to promote settling so that the sediments would not return to the waterway and need to be dredged again. It was not until the 1960s that dredged material was confined because of environmental concerns. In 1967, the Corps, in cooperation with the Federal Water Pollution Control Administration (the predecessor of the USEPA), initiated a 2-year pilot investigation of alternative methods for dredged material disposal in the Great Lakes (USACE Buffalo District 1969). The first CDFs on the Great Lakes were constructed as part of this program.

CDFs are the most widely used disposal technology for contaminated sediments from both navigation dredging and remediation projects. Since the 1960s, approximately 50 CDFs have been constructed around the Great Lakes, in the United States and Canada, for dredged material from navigation projects. About two-thirds of these facilities are lakefills, constructed with stone dikes. The remainder are upland facilities, constructed with earthen dikes or placed within existing or excavated depressions. CDFs around the Great Lakes currently contain sediments dredged over periods of 10 or more years, have capacities from less than 38,000 to more than 3 million m[3], and have areas from a few to several hundred hectares (Miller 1990).

The goal of confined disposal is to isolate and contain sediment contaminants. Because of the nature of dredged material, a CDF must have features of both a wastewater treatment facility and a solid waste landfill to effectively meet this goal. A CDF that receives sediments that are hydraulically dredged or transported must provide for the settling of the sediments and primary treatment of the effluent water (see Chapter 9). Through effective solids retention, a CDF can retain most of the sediment contaminants (Saucier et al. 1978). Most CDFs are capable of retaining more than 99.9 percent of suspended solids discharged in hydraulic slurries.

A CDF must also provide for the dewatering of sediments to facilitate consolidation and compaction and to maximize the usable space in the facility (as discussed in Chapter 6). CDFs have been constructed with the same types of controls used in commercial landfills to limit contaminant loss, although some of these controls may be less feasible at in-water CDFs and the efficiency of others may be affected by fine-grained sediments within the CDF.

***Temporary Storage Facilities***

Remedial alternatives that involve treating sediments and disposing of the residues at locations remote from the treatment site will usually require a facility for the temporary storage of sediments and/or residues. Temporary storage may be necessary for a number of reasons and purposes, including:

- Treatment processes cannot keep pace with dredging operations
- It is more economical to store residues and transport them all at one time
- Residues must be separated for different disposal locations or by different methods
- A secure land area is needed for or to support pretreatment or treatment operations

A temporary storage facility is usually part of the property where pretreatment or treatment operations are conducted, and might be divided into two or more compartments or cells to accommodate the different types of sediments and residues. The facility may also be part of a CDF used for the permanent disposal of residues. Locations where materials are transferred from one means of conveyance to another (e.g., a site where sediments are removed from a barge and placed in truck trailers) are not included in this category.

The types of environmental controls (i.e., barrier and leachate collection systems) constructed at the temporary storage facility would depend on the physical properties and contaminant concentrations in the sediments and/or residues to be stored.

## SELECTION FACTORS

Within the evaluation and decision-making process discussed in Chapter 2, disposal technologies must be screened for feasibility and compatibility with other components. Factors that can be used to determine the suitability of a disposal technology for a specific application are discussed in this section; these factors are summarized in Table 8-2.

The most critical factors in determining the feasibility of a disposal alternative are the availability and location of a disposal site. These factors are common to all disposal technologies (and are therefore not shown in Table 8-2). The location of a potential disposal site, its distance from the dredging location, and its accessibility from existing transportation routes are factors that may limit the choice of dredging and transportation equipment and increase transportation costs (see Chapter 5, *Transport Technologies*).

The boundaries of the area for disposal site evaluation should be established with some consideration of reasonable travel distances. In some cases, there may be reasons for limiting the site consideration to certain political boundaries. For example, if the project proponent is a city or county government, they may require that the disposal site be within their jurisdiction. The availability of sites or facilities for the various disposal technologies is highly site specific. The task of identifying potential sites is best conducted with a team of representatives from local governmental and public organizations who are familiar with the region.

### Open-Water Disposal

***Unrestricted***

The discharge of dredged or fill materials into waters of the United States is regulated under section 404 of the Clean Water Act. The unrestricted discharge of contaminated dredged material is prohibited; therefore, sediments that have been removed as part of a remediation project are not likely to be suitable for unrestricted, open-water disposal. However, the solid residues from sediment pretreatment or treatment processes (treated sediments) may be suitable for such disposal.

The acceptability of this disposal technology can be determined through the application of a technical framework developed by the USEPA and the Corps for evaluating the environmental effects of dredged material management alternatives (USACE/USEPA 1992). This framework, introduced in Chapter 2 (Figure 2-1), was developed to address the regulatory requirements under section 404 of the Clean Water Act and NEPA.

The framework begins with an evaluation of the dredging and disposal needs. Disposal alternatives are then identified and screened. The detailed assessment of open-water disposal includes the testing of proposed dredged or fill materials to show that they are not contaminated and are suitable for open-water disposal. The Corps/USEPA framework for testing and evaluation for open-water disposal is shown in Figure 8-4. National guidance (USEPA/USACE 1994) and regional guidance specific to the Great Lakes (USEPA/NCD 1994) are available on testing and evaluation procedures for making this determination. The framework integrates physical, chemical, and biological effects tests to make a decision.

Guidance on the designation of disposal sites in the ocean has been prepared by the USEPA and the Corps (USACE/USEPA 1984; USEPA 1986a; Pequegnat et al. 1990). No comparable guidance for the selection of disposal sites in inland waters has been developed; however, the ocean disposal site designation guidance is generally applicable with a few exceptions. Factors to consider in selecting a disposal site include, but are not limited to:

- Currents and wave regime
- Water depth and bathymetry
- Potential changes in deposition or erosion patterns
- Chemical and biological characteristics of the site
- Other uses of the site that may conflict with disposal

Most of the open-water disposal sites around the Great Lakes are dispersive, meaning that materials discharged are rapidly dispersed and transported away from the disposal site. The most common concern with unrestricted, open-water disposal in the Great Lakes, other than the contamination, is the potential impact on aquatic habitat and water supply intakes.

### ***Level-Bottom Capping***

The placement of contaminated material into waters of the United States can be permitted under section 404 (40 CFR 230.60(d)) if "constraints are available to reduce contamination to acceptable levels within the disposal site and to prevent contamination from being transported beyond the boundaries of the disposal site." The Corps/USEPA framework for open-water disposal testing and evaluation (Figure 8-4) considers capping and other benthic controls.

Capping may be suitable for sediments or residues with moderate levels of contamination. Grossly contaminated materials are not likely to be suitable for capping. The determination of suitability requires the concurrence of the Corps and the USEPA on controls and monitoring requirements.

The Corps has developed guidance on capping contaminated dredged material (Palermo et al., in prep.), and additional guidance on *in situ* capping in the Great Lakes is being developed under the ARCS Program (Palermo and Reible, in prep.). The major elements in the planning and design of a capping disposal project are:

- Characterization of contaminated and capping sediments
- Selection of capping site
- Selection of placement equipment and techniques
- Determining cap thickness
- Determining maintenance and monitoring requirements

Each of these elements is discussed below.

> ***Characterization of Contaminated and Capping Sediments***--Physical properties of the contaminated sediments and potential capping materials that need to be tested include visual classification, natural solids content, plasticity indices, organic content, grain size distribution, specific gravity, and Unified Soil classification (Palermo et al., in prep.). Standard methods for these tests are provided in the Corps' soils testing manual (USACE 1970).
>
> ***Selection of Capping Site***--Potential capping sites must be evaluated with consideration of the same factors as for unrestricted, open-water disposal. In addition to these considerations, the capping site should be in a relatively low-energy environment with little potential for erosion of the cap (Palermo et al., in prep.). This may require that sites be in deeper waters than are commonly used for most unrestricted disposal in the Great Lakes.
>
> ***Selection of Placement Equipment and Techniques***--Conventional dredging and transport equipment have been used for capping. The objective is to reduce water-column dispersion and bottom spread to the greatest extent possible. Cap material must be placed so that it does not displace or mix with the contaminated sediments. Specialized equipment has been developed and demonstrated for precise

placement of contaminated materials on the bottom and the application of a cap (Palermo et al., in prep.).

***Determining Cap Thickness***--The cap must be designed to chemically and biologically isolate the contaminated materials from the aquatic environment. Cap thickness is determined by the physical and chemical properties of the contaminated sediments and capping material, the potential bioturbation by aquatic organisms, and the potential for consolidation and erosion of the cap material (Palermo et al., in prep.). A capping effectiveness test has been developed to determine the thickness required for chemical isolation (Sturgis and Gunnison 1988).

***Determining Maintenance and Monitoring Requirements***--A monitoring program is needed to ensure that the contaminated material and cap are placed as intended and that the cap is effectively isolating the contaminants (Palermo et al., in prep.). Monitoring is also necessary to determine when additional capping material or other maintenance is required.

### *Contained Aquatic Disposal*

The major requirements and design elements for contained aquatic disposal are generally the same as those discussed for level-bottom capping.

## Beneficial Uses

The acceptability of sediments or treated sediments for beneficial use is addressed in the Corps/USEPA technical framework introduced in Chapter 2 (USACE/USEPA 1992). In most cases, the suitability of a sediment will depend on its physical properties as well as its contaminant properties. A beneficial use typically requires specific physical properties (i.e., coarse- or fine-grained, low or high organic content).

Most beneficial use technologies have some land requirements to be provided by the project sponsor or proponent. Lands may be purchased for use, or a temporary easement or right-of-way may be obtained from the existing landowners. In some cases, a fee or other consideration may be paid to the landowner. Beneficial use is most feasible where the conditions of the site are improved and the landowner derives benefits from the sediments.

### *Beach Nourishment*

Disposal by beach nourishment is regulated under section 404 of the Clean Water Act, and contaminated sediments are not likely to be suitable for beach nourishment. However, sediments that have been treated may be suitable for such disposal. The suitability of a material for beach nourishment is generally determined by its physical properties, particularly grain size distribution. Evaluation of the suitability of sediments for beach nourishment is usually made by comparison with existing beach sand. The general rule of thumb is that nourishment material should be as coarse, if not coarser, than native beach material (Johnson 1994). Uncontaminated treatment residues that have a high percentage of sand and gravel, such as those from physical separation technologies (see Chapter 6), are most likely to be suited for this use.

### *Land Application*

The application of sediments and treated sediments to upland sites may be suitable for materials with moderate levels of contamination. This type of land application is regulated by State or local statutes. Materials including any associated water discharges that are returned to a stream, river, or lake would be regulated under section 404 of the Clean Water Act.

The suitability of a material for agricultural or other land applications is determined by its physical and chemical characteristics. The physical requirements are often determined by the needs of the existing soil to be amended. Sandy materials may be needed to enhance drainage in clay soils while silty materials may be needed to supplement sandy soils. Other suitability factors include the need for pH adjustment (with lime) and control of weed infestation (USACE 1987a).

Sediments and treated sediments with some types and concentrations of contaminants may still be suitable for land application. The mobility or availability of contaminants through appropriate pathways must be considered (USACE/USEPA 1992). Laboratory tests to evaluate the potential for contaminant leaching (Myers and Brannon 1991) and bioaccumulation in plants and animals (Folsom and Lee 1985; Simmers et al. 1986) have been developed for dredged material. Materials with acceptable ranges of contaminant mobility and bioavailability may be used for agricultural lands, nonconsumptive uses (i.e., horticulture and silvaculture), or landscaping.

### *General Construction Fill*

The regulations, requirements, and suitability factors for use of sediments and treated sediments as construction fill are generally the same as for land applications. Potential disposal sites may be identified through construction proponents (e.g., city, county, or State departments of highways, or public works) or construction contractors. The physical requirements for construction fill will depend on the application. Construction contractors are likely to require that materials be suitably dewatered and free of debris, and that regulatory agencies have preapproved the material for use. The laboratory tests for measuring the leaching and bioaccumulation potential of contaminants (cited for land application) may be appropriate, depending on the application.

***Solid Waste Management***
The use of sediments or treated sediments in landfill management is regulated by the State and Federal statutes under which the landfill is permitted. Contaminated materials are generally suitable for use as daily cover and for construction of internal dikes, providing they meet certain physical requirements. For example, materials must be sufficiently dewatered to pass the paint-filter test (EPA Method 9095, SW-846; USEPA 1991h) and free of debris. Contaminated materials may also be suitable for use as part of the landfill cap or cover, provided they will not promote bioaccumulation in the vegetation grown on it. However, some states may have restrictions on the use of "waste" materials for landfill caps and covers.

## Confined Disposal

### *Commercial Landfills*

Municipal and commercial landfills are available that can accept most types of contaminated sediments and treatment residues. The suitability of a material for a landfill is determined by the type and concentrations of contaminants and the regulatory requirements (as addressed in Chapter 2). Most contaminated sediments and treatment residues are not RCRA-hazardous or TSCA-toxic and are suitable for disposal in municipal or commercial solid waste or sanitary landfills.

Location and cost are the primary factors in identifying potential landfills for disposal. While there are numerous commercial solid waste and sanitary landfills, there are only 86 commercial RCRA landfills and 4 commercial TSCA landfills in the country (Petrovski 1994). Another factor to be considered is the remaining capacity of the landfill. A remediation project with a large volume of contaminated sediments to dispose could overwhelm a single landfill, and the rapid loss of landfill capacity might have adverse impacts on regional waste management practices.

The only requirements for the material's physical characteristics for landfill disposal are related to solids content. RCRA requires that all materials disposed to a solid waste or RCRA-hazardous landfill pass the paint-filter test (EPA Method 9095, SW-846; USEPA 1991h); however, there are no published data on the paint-filter test using dredged sediments, and it is not known at what solids content sediments are likely to fail.

### *Confined Disposal Facilities*

Most of the contaminated sediments dredged from navigation and remediation projects are placed in CDFs. A CDF may be used solely for the disposal of contaminated sediments, or it may also serve as the staging area where pretreatment, treatment, and residue treatment/disposal are implemented. A CDF can therefore serve as the base upon which preliminary designs for other remedial alternatives are developed, and as a baseline for comparing the costs and impacts of alternatives.

> ***Regulation***--The construction and operation of a CDF may be regulated under a number of environmental laws. The construction of CDFs in water or wetlands is regulated under section 404 of the Clean Water Act. The effluent from a CDF, if discharged to waters of the United States, is also regulated under section 404. If the materials to be disposed (or handled) in the CDF are TSCA- or RCRA-regulated, the facility must be permitted as appropriate. RCRA (40 CFR 268) requires the treatment of hazardous wastes prior to land disposal. Other site-specific State and local statutes may also apply.
>
> Currently, the Corps has no policy concerning the disposal of sediments or treatment residues from remediation projects in existing CDFs. CDFs operated by the Corps were constructed for specific navigation projects, and there is limited capacity in these facilities. Materials dredged by industries, municipalities, or others from the slips and docking areas adjacent to the navigation channel are routinely disposed in these existing CDFs, at cost.
>
> The suitability of materials for disposal in an existing CDF is determined by the level of contamination. Materials with levels of contamination comparable to those of sediments for which the facility was constructed are generally acceptable for disposal. The disposal in a CDF of materials that are more highly contaminated may require that the section 404 evaluation and section 401 water quality certification for the facility be modified. In addition, the EIS for the CDF may have to be revised if sediments other than those evaluated in the original EIS are proposed for disposal.
>
> ***Physical Properties***--There are generally no limitations on the physical characteristics of sediments and residues disposed in a CDF. Most facilities are designed to accept materials that have been dredged

hydraulically or mechanically and contain variable amounts of oversized material and debris, with a few exceptions. For example, some small CDFs and larger facilities that are nearly full do not have the capacity to handle hydraulically dredged material because they cannot provide adequate settling times for efficient solids retention. Mechanical dredging and transportation may be required if the dredged material is to be disposed in such facilities.

***Contaminant Properties***--The suitability of a material for disposal in a CDF and the design of the facility are primarily determined by the nature of contamination in the sediments and the potential for contaminant release. The Corps/USEPA technical framework, discussed in Chapter 2, includes a framework for testing and evaluation for confined disposal, as shown in Figure 8-5. This framework identifies the following contaminant pathways of concern: effluent, surface runoff, groundwater leachate, and plant and animal uptake.

The Corps/USEPA framework uses a series of laboratory tests to evaluate the potential contaminant loss or migration from the sediment disposed in a CDF through these pathways. Specific requirements for these tests, as well as approximate costs for analysis, are summarized in Table 8-3.

The modified elutriate, surface runoff, and plant/animal uptake testing protocols are well established and have been verified in the field. The leachate tests have been developed, but no field confirmation has been conducted. A contaminant pathway (not shown in Figure 8-5) that has only recently been considered for sediments is volatile loss to the atmosphere. A test to evaluate volatilization losses from dredged sediments is still in development (Semmler 1990). Sites where the testing and evaluation framework has been fully applied include Puget Sound (Cullinane et al. 1986a), Indiana Harbor (USACE 1987), the New Bedford Superfund site (Francinques and Averett 1988), and the Navy Homeport at Everett, Washington (Palermo et al. 1989).

***Basic Design***--Detailed guidance on CDF design and operation is provided in the Corps' engineering and design manual (USACE 1987c). The most fundamental features of a CDF design are the surface area and dike height. The design of these features is dependent on the following factors:

- Quantity of material to be disposed
- Dredging and transport methods
- Operating plan
- Material physical properties
- Target raw effluent quality

The first two of these factors are self-explanatory. The operating plan is the way in which the facility is filled (e.g., in a one-time operation or in two or more operations separated by some period of time). The physical properties of the material relevant to the basic design are settling and consolidation characteristics. Recommended laboratory testing procedures for these properties are summarized in USACE (1987c). The target raw effluent quality is the maximum level of suspended solids in the primary (raw) effluent from the CDF during disposal.

The ADDAMS model is a series of computer models developed by the Corps for evaluating disposal alternatives and assisting in CDF design (Schroeder and Palermo 1990). For purposes of illustration, a hypothetical CDF design was developed using the ADDAMS model and the following assumptions:

- Design capacity: 100,000 yd$^{[3]}$ (76,000 m$^{[3]}$)
- CDF shape: rectangular
- Dike construction: earthen dikes
- Dike slope: 3 horizontal, 1 vertical
- Dike crest width: 10 ft (3 m)

If the materials disposed in this hypothetical CDF are mechanically dredged and transported sediments, or residues that are of comparable solids content, the design of the CDF surface area and dike height would be relatively simple. For this hypothetical CDF, the relationship between surface area and dike height required for 100,000 yd$^{[3]}$ (76,000 m$^{[3]}$) of sediments (in place) is shown in Figure 8-6. In this case, the CDF design is driven by the volume of sediments. No additional dike height is needed for ponding or settling with mechanically dredged sediments. The facility could be designed to fit within land or height restrictions, or optimized to cost. Sediment dewatering and consolidation would provide additional capacity, which might be used for more sediments or the placement of a cap/cover. The experience of the Buffalo and Detroit Districts has shown dredged material consolidation in CDFs of about 20 percent.

If the materials disposed in the CDF are hydraulically dredged or transported, the design must accommodate more variables. Because the material is contained in a slurry, the CDF design must provide adequate conditions for settling to occur, not just bulk storage capacity for the solids. The SETTLE model of ADDAMS can be used to determine the basic design of a CDF needed to achieve the target raw effluent quality. For illustration, the above hypothetical CDF was designed for hydraulic disposal using the following additional assumptions:

- Average solids concentration: 740 g/L
- Minimum freeboard: 2 ft (0.6 m)
- Depth of withdrawal: 3 ft (0.9 m)
- Percent of area ponded at end of disposal: 80 percent
- Hydraulic efficiency: 60 percent
- Target raw effluent concentration after primary settling: 1,000 mg/L suspended solids

The physical, settling, and consolidation properties of the sediments were based on laboratory tests with Indiana Harbor sediments (Environmental Laboratory 1987). Comparable data should be obtained for a detailed CDF design. For preliminary designs, Schaefer and Schroeder (1988) have compiled physical, settling, and consolidation data from dredged material from numerous locations for application to ADDAMS.

The relationship between surface area and dike height for the hypothetical upland CDF with production (dredging) rates of 1,000 and 5,000 yd[3] (760 and 3,800 m[3]; in place) per day is shown in Figure 8-7. By limiting the production of the dredge, the surface area requirements of the CDF can be significantly reduced. In a CDF with a fixed surface area and dike height (other factors being equal), greater production rates would result in reduced solids retention and higher levels of suspended solids in the raw effluent. The basic design of a CDF for hydraulically dredged sediments should achieve a balance among the key factors: dredge production, surface area, dike height, and raw effluent quality. The design of a CDF must therefore be interactive with the design of the dredging, transport, and residue management components of the remedial alternative.

***Selection of Contaminant Controls***--The types of controls selected for a CDF are determined using the Corps/USEPA testing and evaluation framework (Figure 8-5). The results from the laboratory testing described previously are used with information about the disposal site and computer models to evaluate the potential for contaminant migration and to determine the need for and efficiency of environmental controls (Francinques et al. 1985).

Computer programs that have been used to evaluate CDF environmental controls include the ADDAMS program for characterizing primary effluent quality (Schroeder and Palermo 1990) and the HELP model, developed to assist the design of landfill caps, liners, and leachate collection systems (Schroeder et al. 1984). A modified version of HELP has been developed specifically for CDFs.

The type and number of controls in a CDF design depend on the characteristics of the sediments and the site. There is no generic or default design. Available control technologies, and their application at existing CDFs, are discussed in the ARCS Program literature review (Averett et al., in prep.) and in the Corps' engineering and design manual (USACE 1987c). Designers are cautioned in applying controls commonly used at solid and hazardous waste landfills without due consideration of the physical properties of sediments and the quantities of water that may need to be drained, routed for collection, and treated.

Fine-grained sediments, when properly consolidated, can have very low permeabilities. Laboratory tests with Indiana Harbor sediments produced permeabilities on the order of $10^{-8}$ cm/sec (Environmental Laboratory 1987). Fine-grained sediments dredged as part of sediment remediation or for other purposes might be an integral part of the contaminant controls for a CDF. For example, a CDF designed for contaminated and TSCA-regulated sediments might place the contaminated sediments in a manner that creates an additional barrier between the TSCA-regulated sediments and the outside of the CDF.

***Operation and Maintenance***--A detailed discussion of the construction, operation, and maintenance of CDFs is provided in Chapter 10.

### *Temporary Storage Facilities*

The construction and operation of a temporary storage facility are regulated in the same manner as CDFs. The fact that the structure is temporary will not affect the applicability of Federal regulations such as the Clean Water Act. The requirements of State and local regulations are site specific. Some environmental regulations have restrictions on the temporary storage of materials. For example, RCRA-hazardous waste can be stored 90 days without a storage permit. Permits are issued under both RCRA and TSCA for the temporary storage of regulated hazardous and toxic wastes for up to 1 year.

Temporary storage facilities are designed to accommodate the physical and chemical characteristics of the project sediments and fulfill the needs of other components of the remedial alternative. If sediments are to be processed using a treatment technology, a facility may be needed to store the dredged sediments while awaiting pretreatment and treatment. The temporary storage facility may be used to perform some types of pretreatment, such as dewatering or physical separation. The size and capacity of the facility may be determined by several factors:

- Quantity of materials to be dredged
- Production rate of the dredging
- Pretreatment requirements of the treatment technology
- Process rate of the treatment technology

The design of a temporary storage facility is determined by the same factors that apply to CDFs. Because the facility is not permanent and will be removed when the remediation is completed, controls for long-term contaminant migration may not be necessary. However, temporary facilities should be designed with consideration of how the site will be cleared and decontaminated when the remediation is completed.

## ESTIMATING COSTS

For some of the disposal technologies described in this chapter, there is no disposal cost. This means that the costs for dredging, transportation, or other components include any equipment or labor costs associated with disposal. For other disposal technologies, information is provided about disposal costs that are separate from other component costs. In this section, the equipment and effort required for each disposal technology are described, and unit costs from the literature or other project cost estimates are provided, when available. The elements of the disposal technologies and available unit costs are summarized in Table 8-4.

### Open-Water Disposal

#### *Unrestricted*

Unrestricted, open-water disposal is generally the least costly disposal technology for uncontaminated sediments and residues. The disposal process does not require any additional equipment, other than the equipment used for dredging and transportation, or any additional effort on the part of the contractor, other than opening the barge doors or positioning the pipeline discharge. Monitoring requirements for unrestricted, open-water disposal are site specific, but are generally limited, if any. There are, therefore, no separate costs for unrestricted, open-water disposal.

#### *Level-Bottom Capping*

Not all of the costs of capping are covered by the dredging and transportation components. Specialized equipment, such as a submerged diffuser and sophisticated positioning equipment, may be required. The contractor will need additional time to place the material with greater levels of precision and control than necessary with unrestricted, open-water disposal.

The material for the cap and its placement can be a major cost item. If the capping is conducted in conjunction with the disposal of suitable uncontaminated sediments from another project, there may be no additional cost for the cap. This presumes that the capping material was planned to be dredged and disposed in the vicinity of the capping site with or without the remediation project. If the cap material must be furnished solely for the capping, the costs for dredging, transportation, and placement will be included in the disposal costs.

Ideally, the cap is situated in a location that is depositional, where natural settling particulate matter will deposit on the cap and further isolate the contaminated sediments. In other locations, the cap may have to be replenished periodically. The maintenance of the cap should be included in the disposal costs, unless the maintenance material is provided without cost from other dredging projects.

The monitoring requirements for capping may include periodic bathymetric surveys and camera profiles. Less frequent monitoring might also include analysis of core sediment samples and toxicity or bioaccumulation measurements (Fredette et al. 1990a,b). The type and frequency of monitoring are site specific, but the costs of monitoring and cap performance evaluation are part of the disposal costs. Experience with dredged material capping in New England indicates that routine monitoring, consisting of a bathymetric survey and a camera profile, is conducted every 2-3 years at a cost of about $30,000 per cycle (Fredette 1993).

### *Contained Aquatic Disposal*

The cost items for contained aquatic disposal are basically the same as those described for level-bottom capping. The only additional disposal costs are related to the construction of the depression or trench for placement of contaminated material. If the contained aquatic disposal site is in deep water, the selection of dredging equipment may be limited to mechanical (bucket) dredges. If the material excavated to form the depression or trench is suitable for the cap, the cost for cap material may be offset, although there may be additional costs associated with temporarily stockpiling and rehandling the excavated material for later use as the cap material.

## Beneficial Uses

### *Beach Nourishment*

The placement of uncontaminated materials onto beaches will generally not require additional equipment, effort, or costs beyond those included in the dredging and transportation components. The only disposal cost would be for the earthmoving equipment and effort needed to spread the material across the beach or to form dunes.

### *Land Application*

The land application of sediments or treatment residues that have been mechanically dredged or have been suitably dewatered will generally not require additional equipment, effort, or costs beyond those included in the dredging and transportation components. The only disposal cost would be for the equipment and effort needed to spread the material, incorporate it into the existing soil, and properly grade the site. It is assumed that the landowner or local government would be responsible for any seeding or planting.

If the sediments or residues to be applied on land are hydraulically dredged or transported, additional effort and equipment will be needed to promote the retention of solids. A diked area or CDF will have to be constructed onsite. The level of sophistication for this structure would be very basic, and the only environmental controls would be related to effluent quality. Costs for dike construction are discussed for CDFs below. Costs for effluent treatment are discussed in Chapter 9.

### *General Construction Fill*

The use of sediments or treatment residues as construction fill will generally not require additional equipment, effort, or costs beyond those included in the other remediation components. It is assumed that suitable sediments or residues would be appropriately dewatered, and the materials would be either picked up by the construction contractor or delivered to the construction site. If fill material is in demand, construction contractors may be willing to pay for the excavation and transport of sediments from a CDF.

### *Solid Waste Management*

The use of sediments or treatment residues as daily cover or for construction in municipal or commercial landfills will generally not require additional equipment, effort, or costs beyond those included in the other remediation components. It is assumed that suitable sediments or residues would be appropriately dewatered, and the materials would be either picked up by the landfill operator or delivered to the landfill.

## Confined Disposal

### *Commercial Landfills*

Costs for the disposal of contaminated materials to municipal or commercial landfills are determined by the market value of landfill space in a particular region. There are no additional equipment or effort requirements beyond those included in other remediation components. The transportation contractor will place the material as directed by the landfill operator, who will be responsible for its spreading and compaction.

Representative costs of disposal to commercial landfills in the metropolitan areas of Buffalo, Chicago, and Detroit were obtained through telephone interviews with landfill owners/operators in April, 1993, and are summarized in Table 8-5. Unit costs are based on weight ($/ton) or volume ($/yd[3]). Although a landfill operator is ultimately basing the quoted price on how much capacity (volume) the disposed material will require, many operators are now using weight-based payment because it can be measured more accurately at delivery (Payne 1993).

The landfill unit costs that are based on weight are consistently higher than unit costs based on volume. This is because the majority of materials disposed in commercial landfills have a density of less than 1 tonne/yd[3]. Residential and commercial solid wastes (uncompacted) typically have densities less than 0.5 tonne/yd[3] (Tchobanoglous et al. 1977).

The weight of a given volume of sediments or treatment residues will depend on its grain size distribution, solids content, and amount of organic material. A typical saturated sediment (50 percent solids) with about 70 percent silt and clay and 10 percent organic material (volatile solids) would probably weigh about 2,400-2,700 lbs/yd[3] (1,400-1,600 kg/m[3]).

Because the density of sediments and treatment residues is much higher than that of most materials disposed in commercial landfills, the weight-based unit costs may not accurately reflect market price. The volume-based unit costs are probably more representative. Therefore, landfill owners/operators should be provided information about the density and other physical properties of the sediments or residues in order to form a competitive unit cost.

As discussed above, landfills may accept sediments for beneficial use as daily cover. Depending on the local availability of cover material, the landfill may accept the material at no cost or offer a price discount. The discount should be approximately equal to the amount the landfill has to pay for daily cover from other sources. Most of the landfill operators contacted indicated a willingness to offer a price discount. A discount of $10/ton was offered by one operator. Some states or municipalities have restrictions on the type of material used for daily cover at landfills.

***Confined Disposal Facilities***
The principal elements of the capital costs for a CDF include:

- Engineering and design costs
- Lands and easements
- Materials for dikes
- Materials for contaminant controls
- Construction equipment and labor costs

Of these elements, the costs for lands and materials for dikes and contaminant controls typically are the highest of the capital costs. As an illustration, the capital costs of hypothetical, upland CDFs with a design capacity of 100,000 yd[3] (76,000 m[3]) were estimated for two sizes and three contaminant control system designs. The CDFs had the same basic design assumptions discussed earlier in this chapter, with the following unit costs provided by Corps district personnel as being representative of the Great Lakes region:

- Cost of land: $10,000/acre ($24,700/hectare)
- Cost of dike material (constructed): $3/yd[3] ($4/m[3])
- Cost of clay (compacted): $3/yd[3] ($4/m[3])
- Cost of plastic liner (70 mil): $1.5/ft[2] ($16/m[2])
- Cost of leachate collection system (4-in. [10-cm] polyvinyl chloride): $5/linear ft ($16/linear m)
- Cost of sand/gravel: $12/yd[3] ($16/m[3])

The capital costs for these hypothetical, upland CDFs are shown in Figure 8-8. The two sizes shown (10 and 30 acres; 4 and 12 hectares) reflect the areas needed to handle hydraulic dredge production rates of 1,000 and 5,000 yd[3]/day (760 and 3,800 m[3]/day), respectively, and produce equal levels of suspended solids removal. As shown, the rate of hydraulic dredging can significantly affect the surface area and cost of the CDF required. Had the sediments been dredged mechanically, an even smaller area could be used for the CDF.

Figure 8-8 also compares the capital costs for these CDFs with earthen dikes and no cap or liner (no control system) to identical facilities with RCRA Subtitle C and RCRA Subtitle D control systems (as depicted in Figure 8-3). The costs of these types of controls increases with CDF surface area. The costs shown in Figure 8-8 do not include the costs for engineering and design, construction oversight, permits, or systems for treating effluent or leachate. The costs shown reflect facilities where dike and contaminant control materials had to be imported. Sites with native soils suitable for dike construction would have lower costs. The availability of clay for contaminant barriers (e.g., liners and caps) can also affect CDF costs.

The most complete actual costs for CDF construction are available for the facilities constructed by the Corps around the Great Lakes under the authority of the Rivers and Harbors Act of 1970 (PL 91-611), section123. These costs, shown in Figure 8-9, represent the construction contract costs for facilities constructed between 1970 and 1988, adjusted to January 1993 costs using ENR's CCI. Figure 8-9 shows unit costs ($/yd[3]) for CDFs vs. total CDF capacity. CDFs are also indicated as being upland or in-water. These costs do not include the costs for engineering and design, construction oversight, or permits, but may include costs for effluent treatment systems (e.g., weirs and filter cells). The CDF costs shown do not include any costs for land acquisition, which was a requirement of local sponsors under this authority.

Although there is a general trend showing the economy of scale (lower unit costs for larger CDFs), the variation attributable to site-specific conditions and designs (as indicated by the amount of scatter) predominates..

***Temporary Storage Facilities***

The costs for a temporary storage or rehandling facility can be estimated using the capital cost information for CDFs provided above. The types of contaminant controls in a temporary facility may be less stringent than those designed for a permanent CDF. Land costs may not be appropriate if a limited easement or right-of-way is obtained. Long-term maintenance costs would also not be incurred.

An additional cost for temporary facilities would result from the demolition of the structures and decontamination of the site. Materials that have contacted contaminated sediments or residues may have to be treated or disposed in the same manner as the sediments.

## ESTIMATING CONTAMINANT LOSSES

Disposal technologies have more mechanisms for contaminant loss than most other remediation components. Procedures to estimate contaminant losses from disposal technologies are also more developed than for other components, primarily as a result of research conducted by the Corps in relation to dredged material disposal and broad-based research on landfills of all types. Myers et al. (in prep.) provides a summary of predictive tools for estimating contaminant losses from sediment disposal technologies.

Contaminant loss pathways of concern for open-water disposal technologies are different from those for beneficial use and confined disposal. One of the primary differences is the movement of dredged material through the water column and subsequent water column impacts associated with open-water disposal. Beneficial use and confined disposal technologies usually do not involve the type of direct water column impacts associated with open-water disposal.

Contaminant migration pathways for beneficial uses and confined disposal alternatives are similar because both types of disposal options involve some type of confinement in most cases. There is always a potential for leachate and volatile loss pathways to be of concern when considering beneficial use and confined disposal. In addition, hydraulic placement will involve an effluent pathway for both beneficial use and confined disposal. The relative significance of plant and animal uptake depends on the ultimate use and engineering design of the disposal site.

### Open-Water Disposal

Within a sediment remedial alternative, unrestricted, open-water disposal is feasible only for sediments or residues that have been decontaminated. Regulatory testing procedures to determine if dredged or fill materials are suitable for unrestricted, open-water disposal are contained in USEPA/USACE (1990) for ocean disposal and in USEPA/USACE (1994) for disposal to inland and near coastal waters.

Capping and contained aquatic disposal may be viable disposal technologies for contaminated sediments or residues from treatment technologies. Procedures for evaluating the acceptability of capping and contained aquatic disposal technologies are identified in USACE/USEPA (1992). The main objectives are to determine water column impacts during dredged material placement and impacts on benthic organisms after placement. The procedures for evaluating water column impacts can be adapted to estimating contaminant losses. Equipment to reduce water column impacts (i.e., tremies and submerged diffusers) is available. Controls on benthic impacts are generally the primary concern in determining cap design.

In addition to water column and benthic impacts associated with capping and contained aquatic disposal, there is a potential for contaminant loss associated with diffusion through caps. Techniques for estimating diffusion losses are described in Myers et al. (in prep.). The information needed for estimating diffusion losses is described in Chapter 3, *Nonremoval Technologies*. Some type of mathematical tool (e.g., spreadsheets, numerical models, commercially available software for performing mathematical calculations) is needed to solve the model equations described in Myers et al. (in prep.).

### Beneficial Use

For beneficial use technologies, the potential for plant and animal uptake of contaminants can be a major concern. Some beneficial uses, such as construction fill, may eliminate plant and animal uptake pathways through engineering design.

Solid waste management uses (daily sanitary landfill cover) also may not involve plant and animal uptake pathways, unless the material is used as final cover. The contributions of contaminated sediments or treatment residues to leachate generation can be a concern for solid waste uses. Because sanitary landfills are now required to be lined, groundwater impacts should be minimal if the landfill is properly designed and constructed.

Volatile emissions will be a major factor for land application alternatives. In a land application scenario, volatilization may potentially account for more loss than any other mechanism, depending on the chemical properties and land application operations. For this reason, worker health and safety and air quality impacts are potential concerns for land application of sediments or treatment residues containing certain organic chemicals.

Leachate and volatile loss pathways are potentially significant for most sediment remedial alternatives, including those involving beneficial use. Construction fill and solid waste management use alternatives are especially likely to require evaluation of these losses. Because the basic mechanisms by which contaminants are lost along these pathways are the same for beneficial uses and CDFs, the estimation techniques developed for CDFs (Myers et al., in prep.) can be applied to beneficial uses. Modification of procedures and interpretation may be appropriate, depending on project-specific conditions.

## Confined Disposal

Contaminant migration pathways for an upland CDF are shown in Figure 2-6. Pathways involving movement of large masses of water, such as CDF effluent during hydraulic filling, have the greatest potential for releasing significant quantities of contaminants from CDFs. Pathways such as volatilization may also result in the release of organic chemicals in highly contaminated dredged material at certain stages in the filling of a CDF. Techniques for estimating effluent, leachate, and volatile losses are described in Myers et al. (in prep.).

If dredged material is placed hydraulically, effluent will be a temporary, but major, contaminant loss pathway. Effluent from a CDF is considered a dredged material discharge under section 404 of the Clean Water Act and is also subject to water quality certification under section 401. Losses along this pathway can be controlled by proper design of the disposal site, management of disposal operations for minimizing losses, and effluent treatment. Techniques for estimating effluent losses are described in Myers et al. (in prep.). Modified elutriate and column settling tests (see Table 8-3) are required for CDF design and effluent loss calculations.

Subsurface seepage from CDFs may reach adjacent aquifers or enter surface waters. Fine-grained sediments tend to form their own disposal-area liner as they settle and consolidate. Evaluation of leachate quality from a CDF must include a prediction of which contaminants may leach and the mass release potential. Laboratory procedures are available for prediction of leachate quality (Myers et al. 1992). These procedures are based on theoretical analysis of laboratory batch and column leach data. Experimental testing procedures only provide data on leachate quality. Estimates of leachate quantity must be made by considering site-specific hydrology. Computerized procedures such as the USEPA HELP model (Schroeder et al. 1984) can be used to estimate water balance for CDFs (Myers et al., in prep.).

The potential for volatile emissions should be evaluated in cases where sediments contain volatile or semivolatile organic compounds. Volatile emissions should be evaluated to protect workers and others who could inhale contaminants released through this pathway. Although no laboratory procedures for measuring volatilization from dredged sediments have been developed, volatile flux equations based on chemical vapor equilibrium concepts and transport phenomena fundamentals are available for estimating volatile losses (Myers et al., in prep.). Volatile emission rates are primarily dependent on the chemical concentration in the dredged material, the surface area through which emission occurs, and climatic factors such as wind speed.

Some contaminants in exposed dredged material can bioaccumulate in plant and animal tissue and become further available to the food web. Prediction of uptake is based on plant or animal bioassays (Folsom and Lee 1985; Simmers et al. 1986). Contaminants in plant or animal tissue are chemically analyzed, and the results are compared with Federal criteria for food or forage. Management strategies can be formulated to minimize plant and animal uptake by directing where to place dredged material (e.g., using cleaner materials to cover more contaminated materials).

Immediately after dredged material placement (beneficial use or confined disposal) and after ponding water is drawn down, rainfall may generate contaminated runoff from the settled dredged material. Presently, there is no simplified procedure for predicting runoff quality. A soil lysimeter testing protocol (Lee and Skogerboe 1983) has been used to predict surface runoff quality with good results. If runoff concentrations exceed standards, appropriate controls may include placement of a cap, maintenance of ponded water conditions (although this may conflict with other management goals), vegetation to stabilize the surface, treatments such as liming to raise the pH, and treatment of the runoff (as for effluent).

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 9. RESIDUE MANAGEMENT

Residues are materials, products, or waste streams generated by components of a sediment remedial alternative. Residues may be water, wastewater, solids, oil fractions, or air and gas emissions. The management of these residues may involve treatment, containment, or discharge to the environment.

The types of residues anticipated from most sediment remedial alternatives and management options for them are provided below. Some sediment treatment technologies may generate unique residues, requiring special management considerations. At a minimum, the inert solid particles that were present in the original, untreated sediment, will still be present following the application of any treatment technology.

### WATER RESIDUES

Water is likely to be the most important residue for consideration at most sediment remediation projects simply because of the volumes generated. The removal and transport technologies selected will have a profound effect on how much water residue is generated through the treatment process. For example, if the sediments are dredged hydraulically and transported by pipeline, a large area will probably be needed for gravity settling. In contrast, if the sediments were removed with a mechanical dredge and transported by truck, there would be much less "free water" to handle.

Some pretreatment and treatment processes may require the addition of even more water. For final disposal of sediments and solids residues, most of this water must be removed. Depending on how the sediments are handled, treated, and disposed, the volume of water that must ultimately be managed can be less than one-half of the volume of sediments (in place) dredged, or greater than five times this volume.

Water residues from a sediment remedial alternative are commonly referred to as effluent or leachate. The term "effluent" may be applied to a wide variety of water residues, including:

- Discharges from an active CDF
- Surface runoff from a landfill or CDF
- Sidestreams from a dewatering process (e.g., filtrate from a filter press or centrate from a centrifuge)
- Wastewater or condensate from a pretreatment or treatment process

The term "leachate" refers specifically to water that has flowed through the sediment, such as pore water, or precipitation that has infiltrated sediments in a CDF or landfill. The volume of leachate is generally much smaller than that of effluent, but the concentration of dissolved contaminants is typically higher.

The flow rate of effluents and leachates is highly dependent on their source. The effluent from a CDF during filling operations from a hydraulic dredge can be quite substantial--hundreds or even thousands of liters per minute. The duration of such discharges, however, is limited to the duration of dredging, which is typically on the order of weeks or months. Sidestreams from pretreatment or treatment operations are technology-dependent, but generally will produce smaller flows over a longer period of time (months to years). Once the remediation project is completed, the need for effluent treatment is limited to storm water (runoff), which could remain a long-term source if water comes into contact with contaminated sediments.

Leachate is generated over very long time periods, and therefore a permanent leachate collection and treatment system is a common requirement at municipal and industrial landfills.

## SOLID RESIDUES

Solid residues include the bulk of sediment solids following treatment as well as smaller fractions of solids separated from the sediments or produced by the treatment processes. For most remedial alternatives involving a properly designed and thorough treatment system, the treated solids will not require additional treatment and can be disposed using the technologies discussed in Chapter 8. Exceptions to this may include solid residues with special physical properties or concentrations of contaminants requiring special handling. Some treatment technologies produce small volumes of sludges. Other solid residues include debris and oversized materials separated during dredging or pretreatment, sludges from water or wastewater treatment systems, spent media from granular filters or carbon adsorption systems, and particulates collected from air pollution control systems.

## ORGANIC LIQUID AND OIL RESIDUES

Thermal desorption and solvent extraction technologies, as discussed in Chapter 7, can produce fractions of concentrated organic liquids and oil materials. These residues are generally small in volume but contain high concentrations of organic contaminants. An organic liquid fraction extracted from sediments with relatively low levels of PCBs may require treatment or disposal in accordance with TSCA requirements, because these processes concentrate the majority of the PCBs in a volume of oil and other organic liquids that is much smaller than the original sediment volume.

## AIR AND GASEOUS RESIDUES

A number of treatment technologies produce emissions of air or gas that may require treatment before discharge to the atmosphere. Thermal destruction and thermal desorption treatment technologies commonly have substantial volumes of air and gas emissions, while (solvent) extraction and chemical treatment technologies are typically in closed reactors with incidental air venting.

"Active" biological treatment technologies, such as bioslurry processes, require an input of oxygen and are likely to have larger quantities of air emissions than passive bioremediation systems. Volatilization of organic contaminants may have to be controlled in some pretreatment and disposal technologies, as well as in treatment technologies. Processes that involve the agitation and mixing of sediments contaminated with volatile and semivolatile compounds should be considered as possible sources of contaminant emissions.

## DESCRIPTIONS OF TECHNOLOGIES

### Water Residue Treatment

Technologies for treating wastewater from municipal and industrial sources are well established and well documented (Weber 1972; Metcalf & Eddy, Inc. 1979; Corbitt 1990). Averett et al. (in prep.) evaluated the applicability of these technologies to effluent and leachate from sediment remedial alternatives on the basis of cost, effectiveness, implementability, and availability.

Effluent/leachate treatment technologies may be categorized according to the type(s) of contaminants that are removed. This chapter discusses technologies that remove the following contaminant categories:

- Suspended solids
- Metals
- Organic compounds

While there is some degree of overlap between the processes, these categories reflect the primary areas of treatment. There are a number of other contaminants that may also need to be addressed during a sediment remediation project, including:

- Ammonia
- Sulfides (especially hydrogen sulfide)
- Oxygen demand (biological oxygen demand [BOD5]; chemical oxygen demand [COD])
- Cyanide

### Suspended Solids Removal Technologies

The removal of suspended matter is generally the most important process in the treatment of effluents and leachates from sediment remedial alternatives because most of the contaminants in water residues are associated with the solid particles. An effective solids removal system can significantly reduce contaminant concentrations, leaving behind only those contaminants that are dissolved or associated with colloidal material. Solids removal is a frequently required pretreatment for processes that remove dissolved contaminants (e.g., ion exchange, carbon adsorption). The primary technology types for suspended solids removal are sedimentation and filtration.

***Sedimentation***--Sedimentation is the basic form of primary treatment employed at most municipal and industrial wastewater treatment facilities. There are a number of process options available to enhance gravity settling of suspended particles, including chemical flocculants, CDFs, sedimentation basins, and clarifiers (Averett et al., in prep.). Of these, gravity settling in CDFs has been used most extensively with contaminated sediments.

CDFs have long served the dual role of a settling basin and storage or disposal facility for dredged sediments (see Chapter 8 for more information on CDFs). Gravity settling in CDFs, with proper design and operation, can take a hydraulically dredged slurry (typically having 10-15 percent solids by weight) and produce an effluent with 1-2 g/L suspended solids (USACE 1987b). Many CDFs on the Great Lakes produce effluents with suspended solids less than 1 g/L (e.g., 100 mg/L) by gravity settling alone.

At most CDFs, a hydraulically dredged slurry is discharged into the CDF at one end and effluent is released over a fixed or adjustable overflow weir at the opposite end, as shown in Figure 9-1. Settling times of several days are commonly achieved at larger CDFs. Improved settling efficiencies can be achieved by dividing the CDF into two or more cells or through operational controls to increase the detention time and prevent short-circuiting. As the CDF becomes filled, and detention times shorten, dredging production rates may have to be reduced or mechanical dredging used instead of hydraulic dredging to provide suitable settling efficiencies. Design guidance for sedimentation in CDFs is contained in *Confined Disposal of Dredged Material* (USACE 1987b).

Sedimentation basins or clarifiers are typically open, concrete or steel tanks with some type of solids collection system that operates on the bottom. Inclined plates may be incorporated into the tanks to improve solids capture for a given flow rate and reduce the size of the clarifier. Rectangular and circular clarifiers are commonly used in municipal and industrial wastewater treatment, but have only been used on a limited basis in applications with contaminated sediments. A cross flow, inclined plate clarifier was used at the ARCS Program's pilot-scale demonstration in Saginaw, Michigan (USACE Detroit District 1994).

Flocculating agents are routinely used in municipal and industrial wastewater treatment in conjunction with clarifiers. There are many proprietary surfactant-type polymers designed for this purpose, although inorganic chemicals such as ferric chloride may also be used. Schroeder (1983) found that low-viscosity, highly cationic liquid polymers were most effective for dredged material effluent treatment and required minimal equipment to implement.

A liquid cationic polymer flocculant was injected into the hydraulic discharge line at dosages of 10 ppm to enhance settling of sediments and fly ash dredged during construction of the Chicago Area CDF (USACE Chicago District 1984). Flocculants were also used during two demonstrations of soil washing technologies on the Great Lakes. Nonionic and anionic polymers were used during the ARCS Program's pilot-scale demonstration at Saginaw, Michigan (USACE Detroit District 1994). A coagulant and a polymer flocculant were used to promote the removal of silty-clay sediments during the pilot-scale dredging and sediment washing demonstration at Welland, Ontario (Acres International Ltd. 1993).

***Filtration***--Filtration is typically used as a polishing step for water that has been pretreated by flocculation and sedimentation in municipal and industrial wastewater applications. This technology is also widely used for treatment of drinking water. Granular media filtration has been used to treat effluents at most in-water and some upland CDFs in the Great Lakes using either filter dikes (Figure 9-2) or filter cells (Figure 9-3). Permeable dikes provide gravity filtration through horizontal flow, and are nonrenewable once clogged. Most in-water CDF dikes have a core of crushed stone. Some have discrete lenses of sand for filtration, as shown in Figure 9-2. Filter cells and sand-filled weirs are vertical-flow gravity filters that can be replaced or regenerated when exhausted. Filter cells may be incorporated into the CDF dike, as shown in Figure 9-3, or can be freestanding structures constructed of concrete, steel, or plastic.

Gravity and pressure filters can be obtained as "package" units, or constructed onsite for larger applications.

Package filtration units are available for purchase or lease. These units are typically mounted on a flatbed trailer for transportation to the site. The flow and filtration capacities of package units can often be designed to fit most small projects. Prefabricated filtration units were used as part of sediment remediation projects in Lorain, Ohio, and Waukegan, Illinois.

Gravity and pressure filters must be taken off line and backwashed periodically to remove accumulated solids. Continuous backwashing systems, which clean a portion of the filter at a time, are also available. The backwash water has high suspended solids content, and must be returned to the sediment disposal/holding area or handled in a sludge treatment system. The operation of one or more filters, including the backwash cycle, can be fully automated.

Filtration media used in Great Lakes CDFs are typically sand and/or graded stone. The filter cell at the Chicago Area CDF uses a combination of sand and anthracite. Alternative media can include limestone, crushed shells, activated carbon, or glauconitic green sands (zeolites). Beds constructed with ion exchange resins may effect ion exchange or precipitation reactions in addition to simple filtration (Averett et al. 1990 and in prep.).

### *Metals Removal Technologies*

Metal contaminants are primarily associated with suspended particulates in most water residues from sediment remedial alternatives. Suspended solids removal technologies should therefore be sufficient to address metals removal needs for the majority of applications. Removal of dissolved metals from water residues can be conducted using ion exchange or precipitation. These technologies have been widely used for industrial wastewater treatment, but have not been applied to water residues from sediment remedial alternatives.

***Ion Exchange***--Ion exchange is a process in which ions held by electrostatic forces of charged functional groups on the surface of a solid are exchanged for ions of similar charge in a solution in which the solids are immersed (Weber 1972). The "solids" are specific resins (usually in the form of beads) that have an affinity for metallic ions. The most common configuration is the fixed bed system, in which the wastewater flows through resin contained in a column (Cullinane et al. 1986a). Ion exchange resins are either highly selective for specific metal contaminants or non-specific for a wide variety of metals.

***Precipitation***--Precipitation is a chemical process in which soluble chemicals are removed from solution by the addition of a reagent with which they react to form a (solid) precipitate. This precipitate can then be removed by standard flocculation, sedimentation, and/or filtration processes. Most heavy metals can be precipitated from water as hydroxides with the addition of a caustic (e.g., sodium hydroxide or lime). Alternatively, sodium sulfide or ferric sulfide may be added to precipitate metals as sulfides. The sulfide process is effective for certain metals, such as mercury, which do not precipitate as hydroxides. Precipitation processes produce a sludge that may have to be managed as hazardous waste due to the presence of concentrated heavy metals. Disposal costs for these sludges may therefore be significant.

### *Organic Contaminant Removal Technologies*

Most organic contaminants, particularly the hydrophobic compounds, are strongly bound to sediment particulates and will be captured through the suspended solids removal technologies discussed above. Removal of dissolved organic contaminants may be necessary where unacceptable concentrations are present in water residues following sedimentation and/or filtration. Most of the organic contaminant removal technologies discussed here require that suspended solids be removed first.

***Carbon Adsorption***--Carbon adsorption is a technology that has been used widely in the drinking water treatment industry, and that is being used with increasing frequency in the wastewater and hazardous waste industry (Corbitt 1990). The process takes advantage of the highly adsorptive properties of specially prepared carbon known as activated carbon. The porous structure of the carbon provides a large internal surface area onto which organic molecules may become attached. Many organic substances, including chlorinated solvents, PCBs, PAHs, pesticides, and others, may be removed from solution using carbon adsorption.

Carbon adsorption is achieved by passing water residues through one or more columns containing granular activated carbon operated in parallel or in series. Carbon columns may be operated in either an upflow (expanded bed) or a downflow (fixed bed) mode. In theory, spent carbon may be regenerated. In practice, however, spent carbon must frequently be discarded, especially if high concentrations of PCBs are present.

Activated carbon was used to remove dissolved PCBs from the water drained from sediment storage lagoons and process water from the thermal desorption process at the Superfund remediation at Waukegan, Illinois (Sorensen 1994). Activated carbon was also used to remove phenols from water drained from a CDF used for the disposal of sediments dredged as part of a remediation project at Lorain, Ohio (Kovach 1994).

***Oil Separation***--Some sediments contain very high concentrations of oil and grease. In most cases, the oil and grease will remain attached to the sediment particulates and be captured by suspended solids removal technologies. In some cases, oil and grease is released from sediment particles, forming a slick, a suspension of discrete particles, or an emulsion in the water residue. In such cases, the oil and grease must be captured or removed prior to treatment processes such as ion exchange, carbon adsorption, and filtration, because oily compounds will foul the surfaces of exchange resins and filters.

Oil booms and skimmers are routinely used in CDFs to capture oil and floating debris. Coalescing plate separators employ a medium that provides a surface for the aggregation of small, emulsified oil droplets, which can then be removed by gravity separation. Emulsified oils are much more difficult to separate from water. Chemical de-emulsifying agents, heat, and/or acids are generally effective for breaking emulsions. Once the emulsion is broken, the oil is amenable to the treatment processes described above.

***Oxidation***--Oxidation is used to partially or completely degrade organic compounds. Complete oxidation of organic compounds can theoretically reduce complex molecules to carbon dioxide and water. Halogenated organic compounds will produce minor amounts of mineral acids (e.g., hydrochloric acid). However, oxidation is often not complete, resulting in the formation of simpler "daughter" compounds that are usually much less toxic or persistent than the original contaminants (Weber 1972).

Two forms of oxidation that might be applicable to water residues from sediment remedial alternatives are chemical oxidation and UV-assisted oxidation. Chemical oxidants suitable for treating wastewater include oxygen, ozone (O3), hydrogen peroxide (H2O2), potassium permanganate, chlorine (or hypochlorites), and chlorine dioxide (Weber 1972). The oxidizing power of hydrogen peroxide and ozone can be significantly enhanced through the use of UV light. This technology is effective for treating a wide variety of organic compounds, including PCBs and PAHs.

## Solid Residues Management

Most of the sediment solids generated by pretreatment or treatment technologies will be disposed using the technologies discussed in Chapter 8. Treated solids may be suitable for beneficial uses, while residues that are still contaminated will likely require confined disposal or subsequent treatment. Sand reclaimed from a CDF in Duluth through a crude soil washing process has been used for road construction fill (Bedore and Bowman 1990). Sediments from Waukegan Harbor treated with a thermal desorption process were confined onsite because of the residual concentrations of PCBs and heavy metal contaminants.

Many of the thermal treatment processes produce solid residues with very little moisture. For example, the solid residues from the thermal desorption process demonstrated at Buffalo, New York, were almost all greater than 99 percent solids by weight (USACE Buffalo District 1993). Fine-grained sediments that have been almost completely dewatered may be difficult to handle and transport without substantial losses as wind-blown dust. Water residues or excess process water may be used to wet the sediments to a manageable consistency.

The easiest place to wet the treated solids is immediately as they exit the treatment process, perhaps by applying a water spray to the residues on a belt or screw conveyer. Other options are to mix the dry residues with wet sediments that are not to be treated or to solidify the residues through the addition of cement, binding agents, and water. These options would require a large mixing tank and agitator.

Other solid residues likely to require special handling include debris and oversized materials removed during dredging or pretreatment, treatment process residues with special properties, spent filter media or carbon from water treatment systems, and particulates collected by air pollution control systems.

Large debris that might be separated during dredging or rehandling may be suitable for salvage or scrap if the contaminated sediments can be washed off. If this is not practical, it may still be necessary to cut or compact the debris into smaller pieces for transport to a landfill. Smaller debris and oversized materials separated during pretreatment will likely require confined disposal.

Filter media and carbon used to treat water residues and particulates collected from air pollution control systems may contain high concentrations of contaminants. These materials may be suitable for co-treatment or co-disposal with the sediments. Granular filter media from the filter cells at the Chicago Area CDF have been routinely disposed in the CDF.

## Organic Residue Treatment

Fractions of concentrated organic materials from thermal desorption and solvent extraction technologies are likely to be relatively small in volume, provided that the treatment process made a good separation of organic and water fractions and there was a good recovery of solvent (if used). For example, 15 kg of oil was collected from 415 kg of sediment during the demonstration of a solvent extraction process at the Grand Calumet River in Indiana (USACE Chicago District 1994). In contrast, a poor separation of oil and water fractions during the pilot demonstrations of a thermal desorption process at the Buffalo and Ashtabula Rivers resulted in a mixed (oil-water) residue with a mass equal to more than one-half that of the feed material (USACE Buffalo District 1993; USACE Buffalo District, in prep.).

Because of their relatively small volume and high concentrations of contaminants (with good separation), subsequent treatment of organic residues is quite feasible and, in many cases, required by regulation. Thermal destructive, chemical treatment, and bioremediation technologies discussed in Chapter 7 may be used to treat organic residues. Some of these technologies were originally developed to treat oil/organic wastes and therefore are more fully developed for organic residues than for sediments. These technologies are also likely to be more efficient with the highly concentrated organic residue than with the sediments.

Oil residues collected from the thermal desorption process used at the Waukegan, Illinois, Superfund cleanup and from the solvent extraction process demonstrated at the Grand Calumet River, Indiana, were incinerated at a licensed TSCA facility. The oil residue from the thermal desorption process demonstrated at Buffalo, New York, and Ashtabula, Ohio, was sent to a commercial oil treatment facility.

Storage onsite, or at a licensed landfill, may be a short-term option for organic residues if a treatment facility is not readily available. The applicability of confined disposal as a permanent option for organic residues will depend largely on regulatory requirements.

## Air and Gaseous Residues

The emission of contaminants to the air is a potential contaminant loss pathway for most sediment remediation components. These air emissions may be a point source, such as the stack or vent from unit operations for a treatment process, or a diffuse source, such as volatilized organic compounds from the surface of a CDF. Although organic compounds are usually the contaminants of concern, inorganic contaminants (heavy metals) may be associated with dust generated by remediation processes that remove water from the sediment. Thermal processes that separate volatile heavy metals such as mercury from the sediment are also a potential source of air contamination.

Point sources are generally easier to control because they are already contained and can be piped through an air pollution control system. Point vapor sources from sediment treatment processes can be treated by adsorption (activated carbon or other media), condensation, spray towers, scrubbers, packed columns, thermal oxidation systems, or catalytic oxidation systems. Particulate control may be accomplished by cyclones, scrubbers, bag filters, and similar systems.

Fugitive emission controls for process equipment such as those used for pretreatment and treatment technologies generally require enclosing the entire process in a structure, either a building or an inflatable bubble. Gases vented from these systems would be pumped through a treatment unit, probably activated carbon.

Volatile emissions from large surface areas, such as CDFs or storage tanks, are more difficult to control. Volatilization from these sites may be reduced by limiting the contact between the contaminated sediment or supernatant and air. Options for covering the CDF include buildings or bubbles, floating covers, foams, and sorbent materials. Mixing and splashing during filling from a pipeline can be reduced by submerging the discharge below the surface. The rate of volatilization can also be reduced by shielding the wind from the pond surface through the construction of fences around the perimeter of the facility.

# SELECTION FACTORS

## Water Residues

The need for treatment of water residues from a sediment remedial alternative is controlled primarily by the regulatory requirements on the discharge. Water residues may be discharged directly into a waterway or into a municipal wastewater treatment plant. The former is termed "direct discharge," while the latter is an "indirect discharge." Both discharges are regulated under the Clean Water Act (PL-92-500), but the treatment requirements may be quite different.

Water that is returned from any dredged material disposal operation back to a river, lake, harbor, wetland, or other "waters of the United States" is considered "dredged material" and regulated under sectionsection 404 and 401 of the Clean Water Act. This would include the effluent from a CDF and water separated from dredged sediments during pretreatment. Water from treatment processes and leachate from disposal facilities may be regulated under section 402 of the Clean Water Act (NPDES). Regardless of which of these permitting authorities applies, the direct discharge must meet State water quality standards for the receiving waterway. In some cases, NPDES effluent limitations are based on technology standards (e.g., Best Available Technology).

For direct discharges, the flow rate will usually not be limited. Mixing zones may or may not be allowed for the initial dilution and dispersion of the discharge. Discharge to a small stream or lake with little dilution may not be feasible for some water residues.

Discharges to a wastewater treatment facility are permitted through the local sewer authority or municipality. A "pretreatment" or "industrial discharger" permit must be obtained in accordance with section307 of the Clean Water Act. Sewer use charges are likely to be levied, although these are usually considerably less than the cost of building a separate treatment system. Effluent limitations for conventional pollutants (e.g., BOD, nitrogen, phosphorus) and heavy metals are generally less stringent than direct discharges, because the water undergoes further treatment at the municipal wastewater treatment plant. However, limitations for toxic organic compounds, such as PCBs, PAHs, and phenolic compounds, may be nearly as strict as those for direct discharge. Representative pretreatment standards for three municipalities are shown in Table 9-1.

Discharges to municipal wastewater treatment facilities are typically through existing sewer systems. The rate of discharge may be limited by the capacity of the wastewater treatment facility or the sewers. Small volumes of water residues can also be trucked from unsewered areas to the wastewater treatment facility.

A sediment remedial alternative may have water residues from several sources. Initially, each water stream should be evaluated separately. Some water residues may be suitable for combining for treatment, while others may have to be treated separately.

Once it has been determined that a water residue from a sediment remedial alternative must be treated, the selection of treatment technologies is determined primarily by the following factors:

- Characteristics of the water residue to be treated
- Required effluent quality
- Flow rate (both magnitude and variability)

The quantity and quality of a water residue reflect the characteristics of the sediments being processed and the remediation component at which the residue is generated. The rate of flow will depend on the processing rate of the component generating the water residue and the water storage capacity available.

Other factors that may influence technology selection include:

- Land availability
- Power requirements
- Operator availability and experience

### *Suspended Solids Removal*

The treatment of water residues requires a sequence of steps to achieve the desired effluent quality. In most sediment remedial alternatives, the first and most important step will be the removal of suspended solids. Gravity settling is capable of removing between 90 and 99 percent of suspended solids. Selection factors for suspended solids removal technologies are summarized in Table 9-2.

If the sediments are to be dredged or transported hydraulically, laboratory settling tests should be conducted to predict settling properties and aid in the design of the settling/containment area (USACE 1987b). Additional information on these tests is provided in Table 8-3. The USACE manual *Confined Disposal of Dredged Material* (1987b) provides guidance on the design and operation of CDFs for removal of suspended solids. The SETTLE routine of the ADDAMS model (as discussed in Chapter 8) can be used to predict gravity settling in a CDF (Schroeder and Palermo 1990).

Flocculants can be used to enhance suspended solids removal, but are generally only recommended for application after primary settling. Schroeder (1983) discusses approaches for applying flocculants to a CDF effluent and compares the effectiveness of several flocculants. With secondary settling, removal efficiencies of 90 percent and greater were readily achieved. Jar tests with a sediment slurry, after allowing for primary settling, are a simple and inexpensive means for selecting flocculating agents and dosage rates.

Filtration systems can provide suspended solids removal efficiencies of up to 90 percent (one pass), but are generally only recommended for water residues with relatively low suspended solids concentrations (less than 300 mg/L). Loadings with higher solids concentrations will cause rapid filter clogging. Guidance on the design of filtration systems for CDFs is provided in Krizek et al. (1976). Laboratory filtration tests are generally not necessary to predict suspended solids removal efficiencies.

Filtration systems typically have a fixed design removal efficiency and flow rate, which may be problematic if the influent water residue has highly variable flow rates or suspended solids concentrations. Flocculant dosages can be adjusted to meet changing flows and suspended solids concentrations, offering greater flexibility in operation. "Package" filtration units can be leased for projects with limited flow rates, and require little space. Filtration may be cost prohibitive for projects with large flow rates. Flocculation and secondary settling can accommodate large flows, but require a secondary settling tank or basin.

### *Metal and Organic Contaminant Removal*

The need for water residue treatment beyond suspended solids removal is determined by laboratory tests to predict the concentrations of dissolved contaminants. The modified elutriate test was developed to predict the quality of an effluent from a CDF during hydraulic dredging/discharge following primary settling (Palermo and Thaxton 1988). The character of surface runoff and leachate from a CDF may be predicted using the methods in Lee and Skogerboe (1983) and Myers and Brannon (1991), respectively. Additional information on these tests is provided in Table 8-3.

Tests for predicting dissolved contaminant concentrations in water residues from treatment technologies will have to be developed on a case-by-case basis. Water residues produced in bench- or pilot-scale demonstrations can be evaluated, but may not adequately reflect the water residues from a full-scale application because of differences in materials handling equipment and the effects of smaller-scale operation.

If water residues require both organic compound and metal treatment technologies, site-specific conditions will dictate which process is to come first. It may be preferable to remove the organic compounds first, because they can interfere with metals removal processes. This is particularly true when metals are chemically or physically bound to organic compounds (e.g., methyl mercury, tetraethyl lead). Conversely, it may be preferable to remove metals in conjunction with suspended solids removal. This would, for example, produce a relatively clean waste stream to be polished with activated carbon.

Reported treatment efficiencies can be used as an initial screening tool in process option selection. However, it is generally necessary to conduct treatability studies with the actual water residue to determine the ultimate feasibility of a specific technology. Treatability studies are particularly important for determining the feasibility of advanced treatment methods (e.g., carbon adsorption, ion exchange) or technologies that are under development (e.g., microfiltration). Selection factors for treatment technologies are presented in Table 9-3 for metals removal and Table 9-4 [part i] [part ii] for organic compound removal.

## Solid Residues

The disposition of solid residues from a sediment remedial alternative will generally be determined by the following factors:

- Material physical and chemical characteristics
- Volume of material
- Regulatory requirements

Treated sediments that have little residual contamination may be suitable for the beneficial use disposal technologies discussed in Chapter 8. Laboratory tests for predicting contaminant mobility and impacts (see Table 8-3) can be used to screen these disposal options. The selection factors for beneficial use discussed in Chapter 8 should apply to solid residues as well as untreated dredged material.

Treated sediments and other solid residues with elevated levels of residual contamination will require subsequent treatment or confined disposal in most cases. Although the physical and chemical properties of treated solids may be quite different from those of the untreated sediments, the selection factors for treatment technologies (Chapter 7) and for confined disposal technologies (Chapter 8) should still apply.

Treated sediments, filter media, and carbon used to treat water residues and particulates collected from air pollution control systems should be tested to determine if their disposal is regulated by TSCA or RCRA.

## Organic Liquid and Oil Residues

The disposition of organic residues is most likely to be controlled by regulation. Thermal desorption or solvent extraction of sediments containing relatively low concentrations (1-5 ppm) of PCBs will probably produce an organic residue with concentrations over 50 ppm PCBs, which must be disposed in accordance with TSCA regulations. In most cases, treatment at an existing, licensed facility will be more cost effective than setting up a second treatment process onsite. As of June 1994, there are four commercial incinerators in the United States licensed to treat TSCA-regulated materials. Other treatment processes (i.e., dechlorination, oxidation, pyrolysis, bioremediation, etc.) may be feasible if an operating, licensed facility is unavailable.

TSCA has specific requirements for the storage, labeling, and transport of PCBs. These, or equally conservative, requirements are likely to be necessary for the storage and handling of organic residues from a sediment remedial alternative. In addition to contaminant control safeguards, the organic residue should also be evaluated for its fire/explosion hazard potential.

## Air and Gaseous Residues

Contaminant losses to the air during sediment handling, storage, or treatment are affected by the following factors (USEPA 1992i):

- **Contaminant Volatility--**The tendency of a contaminant to volatilize from sediments can generally be related to Henry's Constant, which is directly proportional to vapor pressure and the molecular weight of the contaminant and inversely proportional to the solubility of the contaminant in water. Compounds such as PCBs having relatively low vapor pressures, but low aqueous solubilities, may have high Henry's constants and be relatively volatile--hence the need to evaluate potential losses to the atmosphere during sediment remediation (see Myers et al. in prep).

- **Residence Time--**The longer the sediment or contaminated water is exposed to the atmosphere, the larger the fraction of contaminant lost by this pathway. Long storage periods should be avoided where air emissions are an issue.

- **Surface Area--**Air emissions are generally directly proportional to surface area. The exposed surface area should be minimized to reduce the mass of contaminant volatilized.

- **Turbulence--**Agitation or aeration increases the contact time between the contaminated liquid or slurry and increases volatilization.

- **Wind Speed--**Wind blowing across a CDF or pond or across exposed sediment increases the rate of volatilization. Site location or fences to divert the movement of air can reduce the effects of wind (Thibodeaux et al. 1985).

- **Temperature--**Volatilization increases with increased temperatures. Operations in cooler weather would reduce contaminant losses.

- **Extent of Competing Mechanisms--**Contaminant reduction by adsorption, settling, biodegradation, or other treatment techniques could occur at a faster rate than the processes necessary for volatilization, reducing the concentration difference between water and air and consequently the volatilization rate.

The selection of technologies for control of volatile emissions depends on the type of source (point or diffuse), whether vapors or particulates are the concern, and the practicality of capturing or controlling the emission. Selection factors for emission controls for the various components and key technologies of sediment remediation are provided in Table 9-5.

Most vendors of treatment technologies with point souces of air/gaseous emissions should have some operating experience with one or more control systems. The compatability of a specific process unit with a treatment technology will depend on the character and rate of the emission. Control of diffuse emission sources requires changing one of the factors discussed above to reduce the rate and/or mass of volatilization or particulate loss, or requires capturing the emission for treatment by one of the processes used for point sources. The cost for construction and maintenance of structures to capture fugitive emissions is one obvious disadvantage; another disadvantage is the additional health and safety requirements for the personnel who have to operate the equipment and the associated increase in cost and decrease in efficiency. Operation of these structures will require a leak detection and repair program to maintain their effectiveness.

Volatile losses at facilities with large surface areas, such as CDFs, may not be practical to contain and treat. Operational practices may be the only option for minimizing volatile loss. Disposal sites for sediment have their highest emission rates when there is no free water and the sediment is moist, and before a crust forms on the surface. Volatilization losses may be reduced by maintaining ponded water over the sediments or by capping the CDF surface with clean sediment prior to removing the free water.

## COST ESTIMATING

Cost estimates provided by vendors of sediment treatment technologies do not typically include the costs for managing all residues. When evaluating cost data, it is important to identify residue management that is included and that which is not. Costs for the storage, handling, and transportation of residues need to be estimated along with other residue management costs.

The regulatory requirements for residue management may cause increased costs. If the feed material is not RCRA-or TSCA-regulated, but one or more residues are regulated by these statutes, the regulatory requirements can be relatively simple, provided the residues are not stored or treated onsite. If a RCRA-regulated residue is produced, the treatment process must be registered as a hazardous waste generator. If a RCRA-or TSCA-regulated residue is stored or treated onsite, there are substantial cost increases because of the regulatory requirements.

### Water Residues

Considerable cost data are available on technologies to treat wastewater from municipal and industrial applications. Relatively little cost data are available from applications with contaminated sediments, except for CDFs (see Chapter 8). CDFs perform both effluent treatment and disposal functions, and the costs of these are not readily separated. Consequently, if a CDF or similar facility is used for sediment storage, dewatering, rehandling, and/or disposal in a remedial alternative, the costs for effluent treatment (gravity settling) are included in the facility costs.

Features of a CDF that are primarily for effluent treatment include cross dike(s) to enhance settling or provide for secondary settling after flocculant addition, overflow weir(s), oil booms, and special filter dikes. These features may not be included in the basic CDF cost estimate, and should be added as water residue treatment cost items.

Water residue treatment costs are summarized in Table 9-6 [part i] [part ii]. The capital cost of water pollution control structures and equipment is largely dependent on flow rate and contaminant loading. Table 9-6 [part i] [part ii] illustrates example costs based primarily on flow capacities. For metal and organic compound removal technologies, this provides a reasonable basis for comparison. For suspended solids removal technologies, solids loadings are a more critical factor for estimating costs.

Because of the importance of flow rates to the cost of water residue treatment, the ability to store water and treat it over extended periods can be cost effective. This is particularly relevant if hydraulic dredging or transport is used and large volumes of water residues are created in a relatively short period of time. A comparison of the approximate volumes of water residue produced from dredged sediments (volume of water per unit volume of sediment) is as follows:

Hydraulic dredge, 10 percent slurry--1,200 gal/yd[3] (6,000 L/m[3])

Hydraulic dredge, 20 percent slurry--440 gal/yd[3] (2,200 L/m[3])

Mechanical dredge, 20 percent expansion--40 gal/yd[3] (200 L/m[3])

For the above example, it is assumed that the sediment has an *in situ* solids concentration of 50 percent, and that the final solids concentration after settling and consolidation is also 50 percent.

If sufficient land is not available for gravity settling and for storing water for treatment, mechanical dredging should be used to minimize the water residue produced. If the available land allows for water storage, hydraulic dredging may be feasible if the dredging rate is compatible with the storage and treatment system.

For water residues with limited flow rates, leased treatment equipment or contracted treatment services are likely to be most cost effective; however, some specialized treatment equipment is only available for purchase. The second-hand market may also offer opportunities for savings.

The operation and maintenance costs of water treatment systems are highly dependent on flow rate. However, other variables, such as suspended solids loading, contaminant concentrations, and water chemistry also have a significant impact on operating costs. Some technologies require experienced operators. Water treatment systems can also produce solid residues, such as spent filter media, activated carbon, and sludges, that require disposal.

### Solid Residues

Costs for the treatment or disposal of solid residues will generally be the same as those discussed in Chapters 7 and 8. The physical and chemical properties of treated sediment solids are likely to be more homogeneous than those of the untreated sediments. Consequently, solid residues may require little or no pretreatment and may be treated more efficiently and at lower unit costs.

Solid residues will require storage onsite until the material can be treated further, disposed onsite, or transported for offsite treatment or disposal. Duplicate storage areas may be necessary for storing one batch of residue while another is awaiting test results to show that the materials were treated to acceptable levels for subsequent treatment or disposal. Solid residues with high concentrations of contaminants (i.e., spent filter media and carbon, treatment sludges, particulates from air pollution control systems) may require special containers for storage, and may require disposal in RCRA-or TSCA-licensed facilities.

### Organic Residues

Incineration is likely to be the preferred treatment alternative for organic residues from extraction processes. The unit cost for incineration at a TSCA-licensed facility is between $0.55-$1.00/kg (Payne 1993). The availability and unit costs of other treatment processes are difficult to predict because there are so few operating, licensed facilities.

### Air and Gaseous Residues

Most vendors of thermal treatment processes do include the costs for air pollution control equipment in their unit costs. Costs for controls of nonpoint emissions from other treatment technologies and from pretreatment and disposal technologies must be estimated separately. These costs may include shelters or bubbles to contain air emissions, air treatment systems, and operational controls. Secondary costs include increased operating costs and decreased production by treatment or pretreatment units that must operate inside air containment structures.

## CONTAMINANT LOSSES

Residuals are releases or discharges from a sediment remedial alternative to the environment that are managed or controlled. The contaminant concentrations in the residual and the type and level of control exercised determine the contaminant loss.

### Water Residues

Water residues must be treated to a level that meets regulatory requirements. The total contaminant loss can be readily calculated from the estimated effluent contaminant concentration and the volume of water to be discharged. For a more conservative analysis, the effluent contaminant concentration may be assumed to be equal to the discharge standard. Methods for predicting effluent and leachate contaminant losses are discussed in Myers et al. (in prep.). Additional losses can occur in the event of failure of the treatment system, resulting in the discharge of untreated water. Such accidental losses cannot be predicted, but should be preventable with suitable process control.

Another contaminant pathway from water residue treatment is volatile losses from the surface of sedimentation basins or in the off-gasses from process equipment. Volatilization from sedimentation basins can be estimated using the same procedures derived for CDFs (Myers et al., in prep.). Air emissions from water treatment equipment are likely to be minimal due to the relatively small surface areas and residence times involved.

### Solid Residues

Contaminant losses from the treatment or disposal of solid residues can be estimated using the procedures discussed in Chapters 7 and 8.

## Organic Residues

Contaminant losses from the treatment of organic residues can be estimated using the procedures discussed in Chapter 7.

## Air and Gaseous Residues

Air and gaseous emissions from point sources, or fugitive sources that have been contained, will be treated in pollution-control equipment to a level that meets regulatory requirements. The total contaminant loss can be readily calculated from the estimated emission contaminant concentration and the volume of air/gas to be discharged. For a more conservative analysis, the emission contaminant concentration may be assumed to be equal to the discharge standard.

Volatile losses from fugitive and nonpoint sources that cannot be contained may be estimated using the methods discussed in Myers et al. (in prep.) for CDFs.

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 10. OPERATIONAL CONSIDERATIONS

This chapter discusses operational considerations that are relevant to the remediation of contaminated sediments. Topics discussed include contracts and contract administration, water-based operations, and land-based operations.

Most of the experience in the management of contaminated sediments has been in the maintenance dredging of navigation channels. The Corps has a limited fleet of dredges nationwide, but most of the actual dredging is contracted to private dredging companies. In addition, most dredged material transport and rehandling, and all construction of disposal facilities for dredged material, are performed by contractors.

Guidance on contract administration for the design and implementation of Superfund remedial actions is provided in USEPA (1986b). The Corps has developed several pamphlets and manuals that provide guidance on contract administration and construction oversight, including:

- *Resident Engineer's Management Guide* (USACE 1973)
- *Quality Assurance Representative's Guide* (USACE 1992b)
- *Modifications and Claim Guide* (USACE 1987d)
- *Safety and Health Requirements Manual* (USACE 1987e).

### CONTRACTING

As discussed in Chapter 2, contract mechanisms and regulations for sediment remediation projects are specific to the proponent and funding organizations. The number, type, and scope of contracts for implementing a sediment remediation project will also be affected by the complexity of the remedial alternative(s) selected for the site.

#### Contract Administration

Contract administration is a broad term that includes inspection and construction management as well as general administrative activities. Inspection is necessary during all phases of construction activities to ensure adherence to specified quantities and quality standards. Construction management involves coordinating activities beyond the contractor's scope or control, tracking progress, determining and making payments, preparing and negotiating contract modifications, and project acceptance. Other contract administration activities include preparing the project plans and specifications, soliciting bids, and recordkeeping. Contract administration is an important step in the management of a remediation project to control the costs of contractual equipment and labor. The goals of contract administration are to ensure that the work is completed on time and that the contractor receives proper compensation. Contract administration encompasses all dealings with contractors from the time the contract is awarded until the work has been completed and accepted, payment has been made, and disputes have been resolved. Factors influencing the extent of contract administration activities include the nature of the work, the type of contract, and the experience and attitudes of the personnel involved.

The Corps typically estimates the level of effort required for the administration of a construction contract to be approximately 8 percent of the construction costs. Additional funds may be required for administration of environmental remediation projects because of the increase in regulation and safety requirements. Smaller projects (those with total costs less than $500,000) require a higher percentage allowance for contract administration costs.

## Contract Requirements and Clauses

### Dredging

The following general requirements are included in Corps maintenance dredging contracts and may be suitable for environmental remediation contracts:

> ***Contractor Quality Control***--The contractor is required to submit a Contractor Quality Control Plan that identifies personnel, procedures, control, instruction, records, and forms to be used for inspection of construction. Construction is allowed to proceed after acceptance of this plan.
>
> Quality assurance and quality control must be performed to ensure that the contractor dredges to the appropriate depth and at the correct location specified in the contract. For maintenance dredging, this is accomplished by conducting hydrographic surveys before and after dredging. For sediment remediation projects, dredging contracts may be structured around dredging areas, depths, and volumes, or by acceptable contaminant concentrations to be left behind. At the Waukegan Harbor Superfund project, the consent decree specified the elevations to which sediments were to be dredged. Completion of the dredging was also contingent upon sampling and testing of the grain size of sediments at the new surface (USEPA 1984b). Quality assurance also ensures that the dredged material is placed at the location and in the manner specified in the contract.
>
> ***Special Project Features***--Special project features must be identified, such as utility location plan, survey note format, Notice to Mariners, buoy relocation positions, and survey information.
>
> ***Real Estate***--Real estate rights for the use of work and storage areas and access to the disposal site must be obtained and provided in the contract. Any additional real estate rights required by the contractor are obtained at the contractor's expense.
>
> ***Payment***--The Corps typically structures its dredging contracts for payment based on lump sums for mobilization and demobilization and a unit price ($/yd[3]) for the quantity of sediments dredged. An alternative method of payment is time-based, where the dredge and operator are essentially "leased" for a period of time. These methods both have their advantages and disadvantages.
>
> A fixed or unit price contract is more readily used to obtain competitive bids for the entire dredging project. This type of contract gives the contractor an incentive to finish the job as rapidly as possible, which may be a problem if it is desired to slow the dredging process to reduce resuspension or for other reasons. The contract specifications must be tightly written to provide performance criteria for the dredging, penalties for not meeting those criteria, and contingencies for most foreseeable events that could cause delays. A poorly written contract and changes in site conditions are the primary reasons for contract disputes and claims.
>
> A time-based lease contract allows for greater control of the contractor's activities. This type of contract may create a disincentive to the contractor to work quickly, and the total dredging cost is not fixed up front. Specifications may not need to be as tight for a time-based contract, although performance criteria and penalties still need to be defined.
>
> Dredging contracts are typically structured with two unit prices. The first unit price (dollars per time or volume) would apply for a base level of effort for which the contractor is guaranteed payment. The second unit price would apply for additional time or volume necessary beyond the base effort. This method of subdividing the unit price item ensures the contractor a minimum level of effort on which to distribute indirect costs, and typically provides the contracting agency with a reduced unit price for additional effort if needed. Lump sum payments for mobilization and demobilization are appropriate for either type of contract.

### General Clauses

Construction contracts typically include several clauses to assist in contract administration, including the following:

> ***Liquidated Damages***--Liquidated damage provisions establish a rate of assessment that is representative of

the harm expected to be suffered if a contractor fails to perform on schedule. The contractor is required to pay a predetermined amount for each day the project is completed late. This may be especially important in remediation projects where highly contaminated materials are being handled, and poor performance, accidents, and spills can create serious environmental problems. In addition, delays caused by one contractor can have significant cost impacts on other contractors responsible for follow-on processes.

***Bonding Requirements***--Bid guarantees, performance bonds, and payment bonds are a form of security to ensure that the bidder will not withdraw a bid and will execute a written contract and furnish required bonds.

## WATER-BASED ACTIVITIES

### Equipment/Limitations

The various types of dredging equipment are discussed in Chapter 4. Dredging contracts can be advertised in several ways. The contract may specify the dredging equipment in great detail or may offer a limited number of acceptable equipment types. Another approach would be a contract in which all dredges meeting specific performance criteria are considered. Performance criteria could include minimum production rate, average solid content of dredged material, sediment resuspension characteristics, vertical and lateral accuracy of cut, and others.

Qualification or performance-based contracts are more difficult to prepare and administer than contracts for specified equipment. Contractors rarely have the type of quantitative information on performance needed to compare with other equipment, making selection more difficult. However, if performance criteria for the dredging operations are developed, they provide an incentive for contractors to make innovative modifications to their equipment and operations to meet the criteria, and develop the performance data needed for qualification.

Contracts for Federal navigation dredging projects require removal of sediments down to the project-specified depth and typically provide for payment of up to a 1-ft (0.3 m) overdredging to cover inaccuracies and variations in dredging methods. This serves as an equitable means of payment for complete removal of the required sediments. Any material in the allowable overdepth prism and allowable side slopes is not required to be removed. Any dredging below the allowed 1 ft (0.3 m) is considered excessive, and payment is not made for removal of the excess material.

In a sediment remediation project, consideration should be given to the effects of sediments sliding or sloughing into the area dredged and the practicality of overdepth dredging. As sediments are excavated, adjacent sediments will slide or slough into the depression. The side slope of any excavation is determined by the physical properties of the sediments and local hydraulic conditions. A side slope of 1:2 (vertical:horizontal) is commonly used by the USACE Detroit District when estimating the quantity of sediments to be dredged from Great Lakes navigation channels, although the natural angle of repose may be much flatter (Wong 1994).

Extensive sampling and testing may be used to accurately delineate zones of sediment contamination in three dimensions. When converting maps of sediment contamination into dredging plans, however, it should be recognized that dredges are not capable of removing sediments with precise accuracy, even with the most technologically sophisticated equipment. Dredging specifications with complicated variations in depth and width should be avoided. If a small hot spot is identified, it may not be practical for the dredge to excavate the hot spot in isolation from the adjacent material. Under normal operating conditions on Great Lakes tributaries, a vertical dredging accuracy of 0.5 ft (15 cm) can be expected. To obtain a greater degree of accuracy, excavation would have to be slowed significantly and limited to times when conditions (e.g., currents, waves, wind) are ideal.

The scheduling of dredging and other water-based construction activities may be restricted by a number of events, such as recreational boating traffic and the seasonal spawning of migratory fish. On the Great Lakes, the maintenance dredging season generally coincides with the opening (beginning of April) and closing (end of December) of the navigation locks at Sault St. Marie, Michigan. Despite its logistical and operational problems, winter dredging, as conducted at Waukegan Harbor, may be preferable to avoid the traffic and other restrictions during the warmer seasons.

### Access

Most Corps dredging projects are limited to existing navigation channels. Access, therefore, is only limited by the existing shoal or deposit to be removed. For a remediation project, accessibility to the project site may be a problem for the dredging and transportation equipment. This is especially likely in areas outside of navigation channels with naturally shallow depths. In some cases, channels can be dredged to the remediation area to provide waterborne access.

Access and obstructions should be considered in the design phase. If the remediation area is divided by bridges, pipelines, or other obstructions, dredging equipment may have to be remobilized several times. Access points for mobilization should be identified in the project plans, and easements or rights-of-way should be obtained prior to contract advertisement. Another consideration for sediment remediation is the integrity of nearby structures. If the contaminated sediment area is located adjacent to a bulkhead, pier, bridge, or other structure, consideration should be given to the effect sediment removal will have on the integrity of the structure. Dredging at the Superfund project in Waukegan Harbor, Illinois, was prohibited within (6-9 m) because of this concern (USEPA 1984b).

The above discussion applies to dredging and construction from marine plants, which may not be practical for sediment remediation in small rivers and streams. Land-based dredging and construction will require access to the entire length of the waterway to be dredged. Easements and rights-of-way will have to be obtained from landowners, who must be compensated for damages to their property and landscaping. Land-based dredging will require construction equipment to operate in areas that are subject to flooding. The accessibility of the waterway for land-based dredging may therefore vary with the season.

### Authorized Crossings

Authorized utility crossings exist in the bottom sediment of rivers and lakes. The type of utilities with authorized crossings include natural gas pipelines, wellheads/water intakes, electrical utilities, and telephone lines. If the dredge damages a utility, it could result in personal injuries and extended environmental or economic damages to the waterway or users of the utility.

When excavation is considered for a project, a determination of any potential authorized utility crossings in the project area must be made. This can be done by contacting the local utility companies in the area, the Corps district, and the U.S. Coast Guard.

## LAND-BASED ACTIVITIES

The contracting options for land-based operations of a complex sediment remediation alternative are similar to those discussed earlier for water-based (dredging and transport) operations (also see discussion in Chapter 2). Contracts can be structured to a specific technology type or process unit, or can be opened to all technologies that can meet specified performance criteria. These performance criteria may include: minimum destruction or removal efficiencies for target contaminants, physical and/or chemical characteristics of solid residues, constraints on the quantity and quality of water or air emissions, and maximum time to completion.

Because of the interdependance of transport, pretreatment, treatment, and residue management components, the prime contractor should be responsible for providing all equipment and technologies that deliver the material to and between pretreatment and treatment units and manage all residues from them. The only land-based component that might be divided into a separate contract is the initial construction of a CDF.

There is significant documentation on the construction, operation, and maintenance of CDFs, including guidance provided by USACE (1987b). The management of a CDF for contaminated sediments should consider a number of issues, including:

- Water management
- Management of plants and animals
- Health and safety requirements
- Site maintenance and security
- Site monitoring.

For a complex sediment remedial alternative involving removal, it is likely that a facility, similar to a CDF in many respects, would be used for the storage, handling, pretreatment, and treatment of dredged sediments; treatment of water residues; and storage and possibly disposal of solid residues. A hypothetical layout of such a remediation facility is shown in Figure 10-1. At this facility, sediments are pumped into one of two settling basins. After dewatering, the sediments are excavated from the settling basin and transferred to an adjacent pretreatment system. Debris and coarse materials from the pretreatment system are placed into one of three residue storage areas. The bulk of the sediments are transferred to the treatment system. Solid residues from the treatment system are placed in one of the residue storage areas. Two storage areas are needed because the residues must be tested before they can be removed for final disposal offsite. The organic residue is placed in a tank trailer for transport to an offsite incinerator. Water from the treatment and pretreatment processes and the settling basins is routed to the water residue treatment system. Some of the treated sediments are transported to a remote site for beneficial use and others are disposed onsite.

Most of the operation and maintenance issues identified above for CDFs would apply to this hypothetical facility. Some additional issues may have to be addressed including:

- ✍ Materials handling (e.g., supplies, waste streams)
- ✍ Storage of chemicals, reagents, and treatment residues
- ✍ Dust management
- ✍ Energy/power generation and distribution
- ✍ Onsite testing laboratory.

The management of a facility with several process technologies working concurrently would require a significant level of effort.

All of the management issues listed in this section are discussed in the following paragraphs. A discussion of site closure and post-closure maintenance is also provided.

## Water Management

The volume of water to be managed will depend on how the sediments are dredged and transported and on the process requirements of the pretreatment and treatment technologies. Hydraulic dredging will add a significantly greater amount of water to the sediments than will mechanical dredging, which would require that the CDF provide the ponding necessary for sedimentation and retention of suspended solids.

At most Great Lakes CDFs, the depth of the pond is typically maintained by placing boards within the weir structure. Other types of water level control systems include filter cells (passive control) and pumping (active control). Water level management will ensure maximum possible efficiency of the containment area by increasing the retention time. If inefficient settling is occurring in the basin, it may be necessary to operate the dredge intermittently to allow for sufficient retention time and sedimentation, or to install more extensive treatment systems for the CDF effluent. Effective management of the CDF pond can therefore produce significant cost savings to the project.

After a hydraulic dredging operation is completed, the pond within an upland CDF can be drawn down. The rate of drawdown can be slowed to allow settling to remove most of the suspended sediments from the water column and to reduce the loading to effluent treatment systems. Practices for dewatering dredged material are discussed in Chapter 6 and in detailed guidance provided by Haliburton (1978) and USACE (1987b). To facilitate dewatering, rainfall should be routed to one or more collection point(s) and drained as quickly as possible. Trenching and other methods may be used to promote drainage and desiccation.

There are a number of possible wastewater streams produced at a sediment remediation site that will require collection and routing for treatment. Wastewater treatment systems are discussed in Chapter 9. The raw effluent from a CDF during hydraulic dredging/disposal represents the largest potential water flow. Rainfall runoff, leachate, and process water from pretreatment and treatment technologies will have varying flow rates and durations. Depending on their quality and flow rate, some of these wastewater streams may be routed together and mixed before treatment.

## Management of Plants and Animals

### Management of Plants

Contaminated sediments dredged from freshwater sites and placed in an upland area will rapidly develop extensive vegetation without any inducement. In fact, fine-grained sediments from the most contaminated sites seem to support the most extensive vegetation. From freshwater sites, only the most grossly contaminated sediments and sandy sediments without nutrients have shown any limitations on vegetative growth. Sediments deposited in upland areas on Great Lakes CDFs are typically covered with vegetation in the first or second growing season.

Before a remediation project is initiated, the desirability of vegetation within the containment area should be evaluated. Vegetation can be beneficial because it helps to dewater dredged material, control dust, reduce volatilization losses, and improve effluent quality by filtering. Dense vegetation, however, may severely reduce the available storage capacity of the containment area, restrict the flow of dredged slurry within the area, and have to be removed in order to construct a cap/cover. In addition, the management of plant populations may be necessary to minimize uptake and environmental cycling of sediment contaminants.

To assess the potential for contaminant uptake by plants, the laboratory procedure of Folsom and Lee (1985) should be used. The Times Beach CDF in Buffalo, New York, has been used for more than 10 years as a full-scale laboratory for evaluating plant and animal uptake from contaminated sediments. A compilation of these studies was prepared by Stafford et al. (1991). Subsequent studies have identified plant species that have lesser uptake of certain contaminants (Simmers 1994) and may be suitable for some CDF applications.

Options for managing vegetation include periodically cutting or burning the vegetation, tilling, applying herbicides, planting acceptable species, and placing new sediments on top of existing vegetation. Some of these control measures may cause significant contaminant losses. The vegetation management plan for a disposal or holding site with contaminated sediments must weigh the advantages and risks mentioned above.

### Management of Animals

Various animals will use dredged material disposal and holding areas as a habitat, even when facility management controls are in place. Most of the CDFs constructed within the Great Lakes are inhabited by colonies of migratory birds. Vegetated areas are inhabited by small mammals, and ponds (at in-lake CDFs) have limited fish populations. Within highly urbanized areas, disposal facilities for contaminated sediments are some of the most productive wildlife habitats in the area.

Unlike vegetation, animal populations provide no benefits to the operation of a disposal or holding site for contaminated sediments. If migratory bird colonies are present and establish nesting colonies on the facility, there may be conflicts in the scheduling of operations in or around these nesting areas. Fish populations in ponded areas may bioaccumulate contaminants to unacceptable levels and attract birds and humans. Birds and small animals (e.g., rabbits, mice) can attract dogs, and the carrion can attract rats.

Controls that can be used to manage animal populations include the use of noisemakers, predator images, and vegetation management (to discourage birds from using the site). In addition, rotenone, shocking, and elimination of ponds may be used to remove fish populations. Trapping and vegetation management may be used to control populations of small mammals.

### Botulism Prevention

Avian botulism has been recorded in naturally occurring wetlands in nearly all parts of the world. It is due to ingestion of a toxin produced by the bacteria *Clostridium botulinum*. Botulism becomes a concern at CDFs when dredged material forms shallow ponds or is raised slightly above water. These shallow ponded areas provide an attractive food source for waterfowl. When the conditions necessary for bacterial growth occur in the CDFs, the potential for a botulism outbreak is established. Because botulism occurs in mud flats and shallow ponded areas, a preventive strategy for botulism should be part of the water management program. Proper placement of dredged material and drainage of the CDF through an outlet structure will prevent development of extensive mud flats and ponded areas.

A second approach for the prevention of botulism is to schedule the dredging/disposal operations during the cooler seasons. If mud flats or ponded areas develop during these cooler seasons, the potential for a botulism outbreak is minimized because of the inhibition of toxin production by cooler temperatures.

If a botulism outbreak occurs, every possible effort must be made to control its spread. Limitation of the spread of botulism can be implemented by attempting to eliminate the toxin production and by making the site unattractive to waterfowl. This can be accomplished using short-term and long-term methods. Short-term methods include making the site unattractive using noisemakers, power boats in the area, or imitation predators. The removal of bird carcasses from the affected areas is also a necessary short-term action to eliminate toxin production.

Long-term methods involve changing the environmental conditions to eliminate the toxin production. Flooding the site with about 30 cm of water or draining the site to allow the dredged material to dry would eliminate shallow ponded areas. Drainage of shallow pond areas is an effective technique that can be accomplished by using pumps and/or constructing trenches.

**Health and Safety Requirements**

The health and safety requirements for a CDF or a site where sediments are being handled, pretreated, and treated may be determined by the project authority or by regulations covering the materials being handled. The health and safety requirements for all Corps activities and operations are provided in USACE (1987e). A health and safety plan should be developed for all sediment remediation projects, regardless of the funding authority or applicable environmental regulations. Such plans are especially important with treatment processes that use high temperatures, pressure, or reagents that are hazardous, caustic, reactive, or combustible. Guidance on the development of health and safety plans for Superfund remediation projects is provided by USEPA's *Standard Operating Safety Guides* (USEPA 1992h) and *Health and Safety Plan (HASP)* (USEPA 1989f).

PPE, such as gloves, protective clothing, and respirators, is required by OSHA and USEPA for all contractors working on Superfund sites. Some types of PPE are likely to be necessary at sediment remediation sites as well. The purpose of PPE is to shield or isolate individuals from the chemical, physical, and biological hazards that may be encountered at a hazardous waste site when engineering and work practices are not feasible to control exposures. Careful selection and use of adequate PPE should protect the respiratory system, the skin, eyes, ears, face, hands, feet, and head.

The types of PPE that may be required will vary depending on the degree and type of contamination of the material, as well as the methods to remove, transport, and dispose of the material. PPE should be selected and used to meet the requirements of 29 CFR Part 1910, Subpart I.

Safety or contingency plans should be developed to minimize the consequences of accidents or natural disasters (USACE 1987e).

**Equipment Decontamination**

Vehicles leaving the site may have to be decontaminated and safety checks provided to ensure that materials are properly stored for transport, liners and cover tarpaulins are secured, and manifests for materials are properly documented. Routine maintenance of the site may also include periodic inspections and repairs to dikes, fence enclosures, and other site features.

**Site Maintenance and Security**

The purpose of site maintenance is to prevent contamination of the workers, protect the public from site hazards, and prevent vandalism. The degree of site controls necessary depends on site characteristics, site size, and the surrounding community. A site control plan should be developed, including a site map, site preparation, site work zones, site security, and safe work practices.

Site security is necessary to prevent exposure of unauthorized, unprotected people to site hazards; avoid vandalism; and prevent theft. To maintain site security, a physical barrier can be erected around the site, signs can be posted, and access points can be limited. Site security is a common problem at CDFs. Private citizens have vandalized or fished and hunted inside the CDFs. Because of the nature of construction activities, personal injury presents a liability concern at CDFs. Access should be limited during the filling stage of a CDF. This can be accomplished by installing a fence and/or posting signs.

Vehicles leaving the site may have to be decontaminated and safety checks provided to ensure that materials are properly stored for transport, liners and cover tarpaulins are secured, and manifests for materials are properly documented. Routine maintenance of the site may also include periodic inspections and repairs to dikes, fence enclosures, and other site features.

**Site Monitoring**

The scope of a monitoring program for a sediment remediation project will be project-and site-specific. For a complex remedial alternative conducted at an upland facility, items that may be monitored include:

- Pond water levels
- Sediment delivery/flow rates
- Sediment inflow characteristics
- Pretreatment processes (internal and endpoints)

- Treatment processes (internal and endpoints)
- Raw effluent flow and quality
- Treated effluent/leachate flow and quality
- Ambient air quality
- Ambient surface and groundwater quality.

Certain analytical capabilities will be necessary onsite if a treatment technology is used. An onsite laboratory is needed to rapidly measure chemical and physical parameters that are indicators of the performance of the treatment process. These indicators may be surrogates for the major contaminant of concern that can be tested more rapidly and at lower cost. The onsite laboratory may also be needed to support and maintain any continuous or "real-time" monitoring equipment. Offsite laboratories can be used for testing that is less time-critical to the operation of the remedial alternative.

**Materials Handling**
Within a typical CDF, contaminated dredged material is only handled once, during placement. In contrast, facilities constructed for clean dredged material are often constructed using the dredged material (i.e., the materials placed from one dredging operation are excavated and used to build up the dikes for the next operation).

At a facility used for a complex sediment remedial alternative, various materials may be handled on a continuing basis. Sediments can be dredged rapidly and placed into the facility over a relatively short period (weeks to months). Pretreatment and treatment equipment will require an extended period (months to years) to process the dredged sediments. As the pretreatment and treatment units operate, residues are created that may require immediate treatment, storage for later treatment, storage for transportation, or disposal onsite (see Chapter 9). The logistics of materials handling and internal transportation in such a facility may require detailed planning. Guidance on process plant designs in textbooks on chemical engineering might be useful in developing materials handling strategies.

**Storage of Chemicals, Reagents, and Treatment Residues**
A sediment remediation site, as illustrated in Figure 10-1, may require a number of storage locations for the chemicals and reagents used in sediment and water treatment and for residues of pretreatment and treatment technologies. Some of these materials may be hazardous, toxic, reactive, or combustible and require special storage containers. The number, size, location, and type of storage areas will be determined by the quantity and character of chemicals and reagents used, or of residues produced, and how these materials are to be rehandled, transported, or disposed.

**Dust Management**
Airborne contaminants can present a significant threat to worker health and safety, especially when dewatered sediments are being excavated and rehandled. Air monitoring may be required to determine if airborne contaminants are present and will aid in the selection of PPE. Dust particles, aerosols, and gaseous by-products from all construction activities, processing, and preparation of materials should be controlled at all times, including weekends, holidays, and hours when work is not in progress.

Provisions should be included in contracts to ensure that the contractor maintains all excavations, stockpiles, haul roads, permanent and temporary access roads, plant sites, spoil areas, borrow areas, and all other work areas within or outside the project boundaries free from particulates that could cause the air pollution standards to be exceeded or that could cause a hazard or a nuisance. Sprinkling systems, light bituminous treatment, or other equipment can be used to control particulates in the work area. To be efficient, sprinkling must be repeated at sufficient intervals to keep the disturbed area damp at all times. Particulate control should be performed as the work proceeds and whenever a particulate nuisance or hazard occurs.

**Energy/Power Generation and Distribution**
Some treatment technologies have significant energy requirements and may require special utility connections. If the distance to existing utilities and cost for connection are excessive, generators may be used to provide electrical power. Transportation and/or storage of fuels should also be considered during the design of the project.

**Site Closure and Post-Closure Maintenance**
As part of site closure, much of the equipment used onsite may require decontamination. Wash water from decontamination will have to be treated. Soil from the site that has become contaminated by contact with the sediments or residues, and materials that cannot be effectively decontaminated, such as plastic liners, may have to be disposed in a

licensed landfill or co-disposed with solid residues.

The placement of a cap and/or cover on dredged material in a CDF is not a simple construction activity. Typically, the site has to be cleared of vegetation and large root systems have to be unearthed. The site then has to be graded for positive drainage and the sediments compacted before any cap/cover materials can be placed. Long-term maintenance activities at a CDF would be essentially the same as those at a closed landfill, including:

- Periodic inspections and repairs of dikes and controls (i.e., cap/cover)
- Operation of leachate collection systems
- Operation of leachate treatment systems
- Management of plants and animals
- Groundwater monitoring.

Plant species grown on a cap/cover are selected to provide erosion protection and should be low maintenance and have shallow root systems. Site security may be required after closure for areas where leachate collection/treatment systems are operated. Dredged material in CDFs is not known to exhibit uneven settling and methane gas production, which are common problems in sanitary landfills. Closed CDFs may be used for a variety of productive purposes. CDFs around the Great Lakes have been used for harbor and airport expansion, park and recreational areas, and wildlife habitat (Miller 1990).

---

This page was generated on Friday, October 10, 2003

View the graphical version of this page at: http://www.epa.gov/grtlakes/arcs/EPA-905-B94-003/B94-003.ch10.html

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 11. SUMMARY AND CONCLUSIONS

### SUMMARY

Industrial and nonpoint pollution sources have historically contributed to diminished water quality in the Great Lakes and other water bodies in the United States. Although most point sources of pollution are now regulated and controlled, nonpoint sources, including contaminated bottom sediments, have been identified as a contributing factor to continuing water quality problems.

Areas of Concern (AOCs) with impaired beneficial uses in the Great Lakes waters have been identified by the Great Lakes Water Quality Agreement between the United States and Canada. Contaminated sediments are known to adversely impact water quality, promote contamination of fish flesh, and cause contaminant uptake in other organisms, including humans. Contamination in bottom sediments has also restricted the ability to maintain navigation channels and marine structures. The remediation of contaminated sediments is being considered in many of the Remedial Action Plans being prepared for Great Lakes AOCs.

Under the auspices of the Water Quality Act of 1987, section118, paragraph (c)(3), the USEPA was directed 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." To fulfill the requirements of the Act, the Great Lakes National Program Office initiated the Assessment and Remediation of Contaminated Sediments (ARCS) Program.

This document reflects the work effort of the ARCS Engineering/Technology Work Group. The primary purpose of this document is to provide guidance on the evaluation, selection, design, and implementation of technologies for sediment remediation. It is intended to be used in conjunction with other documents developed under the ARCS Program that address the chemistry and toxicity of contaminated sediments (the *ARCS Assessment Guidance Document* [USEPA 1994a]), assessment and modeling of contaminated sediment impacts (the *ARCS Risk Assessment and Modeling Overview Document* [USEPA 1993a]), a literature review of remediation technologies (Averett et al. 1990 and in prep.), an evaluation of methods for predicting contaminant losses during sediment remediation (Myers et al., in prep.), and others reporting on specific studies and demonstrations.

### Sediment Remediation Technologies

There are a number of technologies that may be used for the remediation of contaminated sediments. Some technologies, such as dredging and confined disposal, have been widely used for the removal and disposal of contaminated sediments from navigation projects. Many of the treatment technologies have been applied to soils, sludges, or oils, but not to sediments. Other technologies that might be used in sediment remediation are routinely applied in the mining and mineral processing industry or at wastewater treatment facilities.

A remedial alternative consists of a combination of technologies used in series or in parallel to alter sediment or sediment contaminant characteristics and achieve the remediation objectives. The technologies of a remedial alternative perform specific functions. In this document, the technologies have been functionally grouped into the following components:

- Nonremoval technologies
- Removal technologies

- Transport technologies
- Pretreatment technologies
- Treatment technologies
- Disposal technologies
- Residue management technologies

A sediment remedial alternative may be as simple as a single component, as with *in situ* capping, a nonremoval technology. An alternative may also have many components interacting and supporting one another.

A matrix of the sediment remediation components that ranks their state of development, relative potential for contaminant loss, and application costs is provided in Table 11-1. As shown, some components are made up of well-developed, proven technologies, such as removal, transport, and residue management. Other technologies are still in developmental stages or have been implemented only at the bench- or pilot-scale level. Many sediment treatment technologies, both *in situ* and *ex situ*, fall within the latter category.

**Nonremoval Technologies**
There are two general types of nonremoval technologies, those that isolate the sediments from the surrounding aquatic environment and *in situ* (or in-place) treatment. *In situ* capping and containment of contaminated sediments have been demonstrated at two Superfund sites in the Great Lakes--the Sheboygan and Manistique Rivers. Bottom sediments at a number of lakes and reservoirs have been treated to control the release of nutrients and limit eutrophication. *In situ* treatment methods for toxic contaminants have only been demonstrated on a limited scale, and the contaminant losses and operating costs are largely unknown.

**Removal Technologies**
There has been more full-scale experience with removal (i.e., dredging) than with any other remediation technology. For the two general types of dredges, mechanical and hydraulic, there are numerous equipment variations, including a number of dredges specifically developed to minimize the loss of contaminants, for which the removal component is relatively high. Dredging is typically one of the least costly components of a remedial alternative, and the dredging equipment can be selected to fit the requirements of other components.

**Transport Technologies**
Transportation modes, such as pipelines, railcars, trucks, and conveyors, are all well-developed technologies, although not all have been widely applied to sediments. For a simple remedial alternative, transportation may only involve the movement of sediments from the dredging site to the disposal site. For more complex remedial alternatives, sediments may be rehandled several times, and products (residues) of pretreatment and treatment technologies may require handling and transportation as well. The handling steps at each end of a transportation route are, in many cases, the most costly item of the transport component, as well as the source of most contaminant losses during transport. The costs and contaminant losses of the transport component are generally low in relation to other remediation components.

**Pretreatment Technologies**
The physical properties of sediments, in particular the amount of water and the size of sediment particles, represent one of the most challenging aspects of sediment remediation. These properties must be modified, and in some cases, used to advantage by the pretreatment technologies. Technologies commonly used in the mining and mineral processing industry can be used to prepare sediments for subsequent treatment processes and, in some cases, can separate sediments into specific fractions and thereby reduce the quantity of material requiring treatment or confined disposal. Other pretreatment technologies include passive dewatering methods used with dredged material from navigation projects and mechanical dewatering equipment more commonly used in wastewater treatment applications. The costs and contaminant losses from pretreatment technologies are moderate in relation to other remediation components, although estimates of these costs and losses from mining technologies are somewhat speculative.

**Treatment Technologies**
There are many technologies available for treating contaminated sediments. Treatment is generally the most costly component of a remedial alternative, and the component with the least amount of full-scale experience. Most of the treatment technologies that have been proposed for contaminated sediments were initially developed for soils, sludges, or other contaminated media. Many of the treatment technologies were developed for cleaning up chemical spills or waste oils with extremely concentrated contaminants and may be significantly less efficient with sediments having more dilute contaminant concentrations. Contaminant losses from most treatment technologies will be low in comparison to those from other remediation components, although the type and performance of controls associated with treatment technologies are quite varied.

**Disposal Technologies**

Technologies available for the disposal of sediments, treated sediments, and treatment residues range from unrestricted, open-water disposal to RCRA-licensed hazardous waste landfills. No single disposal method is appropriate for all materials, but confined disposal is the most commonly used technology for the disposal of contaminated sediments dredged for navigation or remediation. Remedial alternatives using almost any form of treatment will need a site for the storage and rehandling of sediments, and possibly the ultimate disposal of treatment residues. The availability and location of a suitable site for these activities is likely to be the most crucial feature in a sediment remedial alternative. Costs for disposal technologies are quite variable, although conventional confined disposal costs are moderate to low in comparison to those for treatment technologies. Methods for estimating contaminant losses from disposal technologies are well developed, although losses are variable.

### Residue Management Technologies

The last component of a sediment remedial alternative discussed in this document is the management of water, solid, organic, and air residues generated by other components. The character and quantity of these residues will depend on the component technologies selected for the remedial alternative. Water is likely to be the most important residue to manage because of its volume, although treatment technologies for wastewater are well developed. Treatment and disposal technologies for residues will, in most cases, be determined by regulatory considerations. Costs for residue management technologies may be incorporated into other component costs. Contaminant loss rates are generally low in comparison to those for other remediation components.

## Decision-Making Process

The process of developing a remedial alternative involves a number of activities, including:

- Determining a decision-making strategy
- Defining project objectives and scope
- Screening technologies
- Preliminary design
- Selection of preferred alternative
- Final design and implementation

This process is discussed in more detail in Chapter 2.

Chapters 3 through 9 of this document are dedicated to the remedial components listed above. For each component, available technology types and process options are briefly described and information needed for the formulation of remedial alternatives and selection of appropriate technologies is provided.

The first type of information needed to develop a remedial alternative is the technical features and requirements of the specific technologies. Each component of a remedial alternative must be evaluated to determine if it is compatible with the other components being considered. Some components have restrictions on site conditions or the physical properties of the materials they can accept. For example, most treatment technologies have very strict requirements for acceptable feed materials. Other remediation components (e.g., mechanical dredging) may have very few restrictions on the types of sediments that can be handled. The selection of a technology for any component cannot be made independently of those being considered for other components.

The second type of information is cost data. Cost estimates are used during all phases of project planning, design, and implementation. Available cost data provided in this document reflect January 1993 price levels. The accuracy of the available cost data depends on the level of operating experience with particular technologies. In some cases, the only available cost data are from applications of these technologies to media other than sediments (e.g., sludges, mined materials). Cost data for the most expensive technologies (e.g., treatment) are generally more speculative than for other technologies.

The third type of information is predictions of the amount of contaminant loss during implementation of the remedial alternative. Contaminant losses will occur with all components of a remedial alternative. Estimates of these losses are necessary to evaluate the environmental impacts of remedial alternatives and to compare the benefits of remediation vs. other options, including no action. These loss estimates may also be needed to evaluate the ability of a remedial alternative to maintain compliance with environmental laws and regulations. The tools for predicting contaminant losses from remediation technologies are at varying states of development, but available information suggests that losses occurring during the removal phase are greater than for other remediation components. This is primarily because losses from other components are more readily controlled.

## CONCLUSIONS

The ARCS Program conducted a series of studies, investigations, and demonstrations which examined the "state-of-the-art" for sediment remediation technologies. From the information and experience gathered during this program, the following general conclusions can be made:

- Feasible technologies for the remediation of contaminated sediments are available, although most of the treatment processes will require additional development for full-scale application.

  - The level of development varies widely from technologies that have been implemented on a full scale with sediments to those that are merely a theoretical series of equations on a piece of paper. Several technologies are developed to the point of having operating pilot-scale units available and now await the capital investment upon award of a remediation contract in order to construct the first full-scale unit that can process contaminated sediments. Other technologies that are well developed in other related industries (e.g., mineral processing) may require very little additional modification to be immediately applicable to treating contaminated sediments.

- Technologies for the removal, handling, transport, and disposal of contaminated sediments and residues are relatively well developed.

  - As more contaminated sediments are being remediated, additional modifications to these well-understood operations are anticipated; however, none of these changes will be of the magnitude of treatment technology development. Additional regulatory guidance is being developed, particularly for the testing of dredged material prior to disposal and for the design of confined disposal facilities in the Great Lakes.

- There is no panacea for sediment remediation. No single technology can work in all applications or remediate all possible contaminants.

  - Some technologies work on a broader range of contaminants than other, more contaminant-specific processes. Sediment washing and solidification may deal with a wider variety of both organic and inorganic contaminants than a thermally based destruction or extraction technique. Unfortunately, it is rare to find a contaminated sediment site in the Great Lakes where only one or two contaminants pose the sole environmental threat.

- The majority of contaminated sediments contain a diversity of pollutants in concentrations below the optimal levels for most treatment technologies. As a result, treatment technologies will operate with reduced removal or destruction efficiencies and may produce residues with restricted disposal options.

  - The combination of this conclusion and the immediately preceding one poses one of the greatest dilemmas in the application of treatment technologies to contaminated sediments. Applying a process that somehow deals with the organic contaminants present in a sediment may incur a substantial expense yet leave a residue that is still contaminated with levels of inorganic contaminants that do not allow any additional final disposal options than were available with the original "raw" sediment.

- The level of experience in sediment remediation, particularly with treatment processes, is very limited, and there is a high degree of uncertainty with the estimates of costs and contaminant losses for most of these technologies.

  - The ARCS Program has been able, along with the efforts of similar Canadian and Dutch programs, to advance the knowledge base of sediment treatment technologies. Reliable cost estimates are only developed through the experience that comes from the execution and observation of multiple full-scale remediation projects. As has been evidenced in the hazardous waste treatment field, costs for remediation take a long time to stabilize, if they ever reach a completely predictable range.

Depending on one's point of view, the above conclusions may project a pessimistic outlook on the implementability of most treatment technologies to contaminated sediments. Only a limited number of contaminated sediment sites have been remediated to date, and the technologies used for the majority of these sediments were containment in place and confined disposal. Considering the entire volume of contaminated sediments and the large number of individual sites in the Great Lakes, this pattern is not likely to change on a wide scale in the near future for a number of reasons, not the least of which is the high cost associated with most treatment technologies.

The feasibility of applying treatment technologies to contaminated sediments can be greatly improved by reducing the volume of materials to be processed. For some cases, this can be accomplished by selectively treating the sediments containing the highest contaminant concentrations (i.e., "hot spots") or by using pretreatment technologies to concentrate the contaminants into a small fraction of the original sediment volume.

The technical issues discussed in this document are only a part of what is limiting the remediation of contaminated bottom sediments in the Great Lakes and other water bodies. The broader limitations are the perception, both among the general public and government managers, of sediment contamination problems and the priority these sites receive for funding.

Contaminated sediments are an unseen problem, lying beneath rivers, harbors, and lakes that rarely display the signs of their impacts in readily visualized ways. Sediment contamination is a problem with boundaries that are not easily resolved, more often a continuum than a discrete zone with clear limits. The immense volume of contaminated sediments at some sites makes remediation seem impossible, and makes the remediation of a small part of this mass seem insignificant. With these perceived limitations, the presentation of the seriousness of sediment contamination problems and the solutions to the remediation of contaminated sediments must be innovative.

In recent years, a number of initiatives have been taken by various levels of government to overcome the above limitations. One of the most innovative efforts to remediate contaminated sediments is being conducted on the Grand Calumet River in northwestern Indiana. This effort has combined a series of enforcement actions by the USEPA Region 5 and Indiana Department of Environmental Management with navigation maintenance dredging by the Corps. Additional innovative approaches include the enforcement initiative in southeastern Michigan and the cooperative approach being taken along the Fox River in Wisconsin.

The philosophy that has arisen as a common thread among these initiatives, and which may be applicable to other sites with sediment contamination, is to seek an integrated solution composed of many individual pieces. Rather than looking for one authority or responsible party to solve the problem at one time, the effort is diversified into seeking out opportunities to implement sediment remediation in a systematic, piece-by-piece fashion involving government, industry, and the public. Using such an approach, an entire waterway can be remediated.

# Assessment and Remediation of Contaminated Sediments (ARCS) Program REMEDIATION GUIDANCE DOCUMENT

*US Environmental Protection Agency. 1994. ARCS Remediation Guidance Document. EPA 905-B94-003. Chicago, Ill.: Great Lakes National Program Office.*

## 12. REFERENCES

Abramowicz, D.A., M.R. Harkness, J.B. McDermott, and J.J. Salvo. 1992. 1991 *In Situ* Hudson River research study: A field study on biodegradation of PCBs in Hudson River sediments. Prepared by General Electric Corporate Research and Development, Schenectady, NY.

Acres International Ltd. 1993. The Welland River dredging and treatment demonstration. Prepared for Atlas Specialty Steels, Environment Canada, and Wastewater Technology Centre, Niagara Falls, Ontario. Acres International Ltd.

Albreck, A. 1994. Personal communication. Clark Dietz, Inc., Champaign, IL.

Allen, J.P. (In prep). Mineral processing pre-treatment of contaminated sediment. U.S. Department of Interior, Bureau of Mines, Salt Lake City Research Center, Salt Lake City, UT.

Aplan, F.F. 1980. Gravity concentration. Kirk-Othmer Encyclopedia of Chemical Technology, Third Edition. Volume 12. M. Grayson (ed). John Wiley & Sons, New York, NY.

Apogee Research, Inc. 1992a. Ohio guide to existing and potential financing sources for RAPs implementation. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office and U.S. Army Corps of Engineers, Bethesda, MD.

Apogee Research, Inc. 1992b. New York guide to financing RAP implementation. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office and U.S. Army Corps of Engineers, Bethesda, MD.

Apogee Research, Inc. 1993a. Milwaukee Estuary Area of Concern preliminary financial plan. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office and U.S. Army Corps of Engineers, Bethesda, MD.

Apogee Research, Inc. 1993b. Financial planning guide for Michigan Areas of Concern. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office and U.S. Army Corps of Engineers, Bethesda, MD.

Arterburn, R.A. 1976. The sizing and selection of hydrocyclones. Krebs Engineers, Menlo Park, CA.

Averett, D.E., B.D. Perry, E.J. Torrey, and J.A. Miller. (In prep.) Review of removal, containment and treatment technologies for remediation of contaminated sediment in the Great Lakes, 1994 update. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Averett, D.E., M.R. Palermo, M.J. Otis, and P.B. Rubinoff. 1989. New Bedford Harbor Superfund project, Acushnet River estuary engineering feasibility study of dredging and dredged material disposal alternatives. Report 11. Evaluation of conceptual dredging and disposal alternatives. Technical Report EL-88-15. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Averett, D.E., B.D. Perry, E.J. Torrey, and J.A. Miller. 1990. Review of removal, containment and treatment technologies for remediation of contaminated sediment in the Great Lakes. Miscellaneous Paper EL-90-25. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Barnard, W.D. 1978. Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operations, August 1978. Dredged Material Research Program Technical Report DS-78-13. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bedore, M.P., and D.W. Bowman. 1990. Disposal options for dredged material in the Detroit District, in coastal & inland water quality. In: Proc. of Seminar Conducted on February 6-7, 1990. Las Vegas, NV.

Berger, B.B. 1987. Control of organic substances in water and wastewater. Noyes Data Corporation, Park Ridge, NJ.

Blasland and Bouck Engineers. 1990. Final work plan/QAPP alternative specific remedial investigation Sheboygan River and Harbor: Final version of the draft work plan/QAPP utilized during pilot study activities conducted in 1989. Tecumseh Products Company, Sheboygan Falls, WI.

Bohlen, W.F., and J.M. Tramontaro. 1977. An investigation of the impact of dredging operations on suspended material transport in the Lower Thames River estuary. University of Connecticut, Groton, CT.

Brady, J.E., and G.E. Humiston. 1986. General chemistry--principles and structure. Fourth Edition. John Wiley & Sons, New York, NY.

Brannon, J. 1985. Effectiveness of capping in isolating contaminated dredged material from biota and the overlying water. Technical Report D-85-10. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Brannon, J., and M.E. Poindexter-Rollings. 1990. Consolidation and contaminant migration in a capped dredged material deposit. Sci. Tot. Environ. 91:115-126.

Brannon, J.M., J.C. Pennington, D. Gunnison, and T.E. Myers. 1990. Comprehensive analysis of migration pathways (CAMP): contaminant migration pathways at confined dredged material disposal facilities. Miscellaneous Paper D-90-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bronkala, W.J. 1980. Magnetic separation. In: Mineral Processing Plant Design. Second Edition. A.L. Mular and R. Bhappu (eds). Society of Mining Engineers, Littleton, CO.

Buchberger, C., and I. Orchard. 1992. Toronto Harbor contaminated sediment removal demonstration. In: Proc. of the International Symposium on Environmental Dredging. September 30-October 2, 1992, Buffalo, NY.

Building Systems Design. 1992. MCACES Gold Construction Cost Engineering System. Users manual prepared for U.S. Army Corps of Engineers, Atlanta, GA.

Burgher, B., M. Culpepper, and W. Zieger. 1987. Remedial action costing procedures manual. EPA/600/8-87/049. Prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Hazardous Waste Engineering Research Laboratory, Washington, DC.

Carpenter, B.H. 1986. PCB sediment decontamination-technical/economic assessment of selected alternative treatments. Contract Report 68-02-3992. Research Triangle Institute, Research Triangle Park, NC.

Carusone, C., and D. Hickmand. 1988. Options for the remediation of contaminated sediments in the Great Lakes. In: Report to the Great Lakes Water Quality Board, Sediment Subcommittee and Remedial Options Work Groups, Windsor, Ontario.

CDM. 1986. Mobile treatment technologies for Superfund wastes. Prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Emergency and Remedial Response, Washington, DC. Camp Dresser & McKee, Inc.

Chan, D.B., A. Kornel, and C. Rogers. 1989. Economics of the KPEG process for decontamination of PCBs in soil. In: Fifteenth Annual Research Symposium, Remedial Action, Treatment, and Disposal of Hazardous Wastes. U.S. Environmental Protection Agency, Cincinnati, OH.

Chapp, R. 1993. Personal communication. Millguard Environmental, Livonia, MI.

Church, H.K. 1981. Excavation handbook. McGraw Hill Co., New York, NY.

Churchward, V., E. Isely, and A.T. Kearney. 1981. National waterways study--overview of the transportation industry. U.S. Army Corps of Engineers, Institute for Water Resources, Water Resources Support Center, Fort Belvoir, VA.

City of East Chicago. 1985. An ordinance approving the wastewater discharge resolution for the East Chicago Sanitary District. Ordinance No. 3403. East Chicago, IN.

Clark, B.D., D.J. Rittall, D.J. Baumgartner, and K.V. Byram. 1971. The barged ocean disposal of wastes--a review of current practice and methods of evaluation. U.S. Environmental Protection Agency, Pacific Northwest Water Laboratory, Corvallis, OR.

Clausner, J.E. 1992. A single-point mooring system for direct pumpout of hopper dredges. Dredging Research Program Technical Note DRP-3-08. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Coe, H.S., and G.H Clevenger. 1916. Methods for determining the capacity of slime settling tanks. Volume 55. In: Trans. Amer. Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Collins, D.N., and A.D. Read. 1979. The treatment of slimes. Minerals Science and Engineering 3:2:19-31.

Colman, K.G. 1980. Selection guidelines for size and type of vibrating screens in ore crushing plants. Mineral Processing Plant Design. A.L. Mular and R. Bhappu (eds). Society of Mining Engineers, Littleton, CO.

Corbitt, R.A. 1990. Standard handbook of environmental engineering. McGraw-Hill, New York, NY.

Cullinane, M.J., D.E. Averett, R.A. Shafer, J.W. Male, C.L. Truitt, and M.R. Bradbury. 1986a. Guidelines for selecting control and treatment options for contaminated dredged material requiring restrictions. Puget Sound Dredged Disposal Analysis, U.S. Army Corps of Engineers, Seattle District, Seattle, WA.

Cullinane, M.J., L.W. Jones, and P.G. Malone. 1986b. Handbook for stabilization/solidification of hazardous waste. EPA/540/2-86/001. Hazardous Waste Engineering Research Laboratory, Cincinnati, OH.

Currie, J.V. 1991. Comply quick - seven fast, easy steps to comply with the hazardous materials transportation regulations. Currie Associates, Shrewsbury, MA.

d'Angremond, K., J. Brakel, A.J. Hoekstra, W.C.H. Kleinbloesem, L. Nederlof, and J. de Nekkar. 1978. Assessment of certain European dredging practices and dredged material containment and reclamation methods. Technical Report D-78-58. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Dahlstrom, D.A., and E.B Fitch. 1986. Thickening. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Dahlstrom, D.A., and C.E. Silverblatt. 1980. Experimental techniques in solid/liquid separation. Solid/Liquid Separation Equipment Scale-Up. Second Edition. D.B. Purchase (ed). Uplands Press Ltd., London.

Decision Sciences Corp. 1992. Promotional literature on REP/PC. Decision Sciences Corporation, St. Louis, MO.

Denning, R.A. 1980. Nomograph solution of solids transport problems. In: Proc. of the Ninth World Dredging Conference, Vancouver, Canada.

Dick, R.I. 1972. Sludge treatment, in physiochemical processes for water quality control. W.J. Weber, Jr. (ed). John Wiley & Sons.

Diekmann, J.E. 1993. Cost and schedule risk analysis guidance document. Prepared for the U.S. Army Corps of Engineers, Washington, DC.

Diez, L. 1994. Personal communication. USACE Chicago District, Chicago, IL.

Dorkin, J., P. Ross, M.S. Henebry, J. Miller, and M. Wetzel. 1989. Biological and toxicological investigations of Chicago area navigation projects. Contract Report to U.S. Army Engineer District, Chicago by Illinois Natural History Survey, Champaign, IL.

Dortch, M.S. (ed). 1990. Methods of determining the long-term fate of dredged material for aquatic disposal sites. Technical Report D-90-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Edmiston, K.J. 1983. International guide to hydrocyclones. World Mining 36:4:61.

Eleder, B. 1993. Personal communication. U.S. Environmental Protection Agency, Region 5, Chicago, IL.

ELI Eco Logic International Inc. 1992. Pilot-scale demonstration of contaminated harbour sediment treatment process. Prepared for Environment Canada and Environment Ontario, Rockwood, Ontario.

Engel, M. 1994. Personal communication. U.S. Army Engineer District, Chicago, IL.

ENR. 1993. Construction cost index history, 1906-1993. Engineering News Record. March 29, 1993, New York, NY.

Environment Canada. 1993. In: Removal and Treatment of Contaminated Sediments Workshop, January 21, 1992, Etobicoke, Ontario. Great Lakes Environment Office, Environment Canada, Toronto, Ontario.

Environmental Laboratory. 1987. Disposal alternatives for PCB-contaminated sediments from Indiana Harbor, Indiana. Miscellaneous Paper EL-87-9. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fitzpatrick, W. 1993. Removal of mercury contaminated sediments in an urban stream, Starkweather Creek, Madison, Wisconsin, USA. In: Proc. of 6th International Symposium, The Interactions Between Sediments and Water, Santa Barbara, CA. December 1993. Australian Journal of Marine and Freshwater Research.

Fitzpatrick, W. 1994. Personal communication. Wisconsin Department of Natural Resources, Madison, WI.

Fleming, E.C., D.E. Averett, M.G. Channell, and B.D. Perry. 1991. An evaluation of solidification/stabilization technology for Buffalo River sediment. Miscellaneous Paper EL-91-11. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Folsom, B.L., and D.R. Lee. 1985. Plant bioassay of dredged material. Technical Note EEDP-02-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Francinques, N.R., and D.E. Averett. 1988. New Bedford Harbor Superfund project, Acushnet River estuary engineering feasibility study of dredging and dredged material disposal alternatives. Report 1, Study Overview, Technical Report EL-88-15. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Francinques, N.R., M.R. Palermo, C.R. Lee, and R.K. Peddicord. 1985. Management strategy for disposal of dredged material: contaminant testing and controls. Miscellaneous Paper D-85-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fredette, T. 1993. Personal communication. U.S. Army Corps of Engineers, New England Division, Waltham, MA.

Fredette, T.J., J.E. Clausner, D.A. Nelson, E.B. Hands, T. Miller-Way, J.A. Adair, V.A. Sotler, and F.J. Anders. 1990a. Guidelines for physical and biological monitoring of aquatic dredged material disposal sites. Technical Report D-90-12. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fredette, T.J., J.E. Clausner, D.A. Nelson, E.B. Hands, T. Miller-Way, J.A. Adair, V.A Sotler, and F.J. Anders. 1990b. Selected tools and techniques for physical and biological monitoring of aquatic dredged material disposal sites. Technical Report D-90-11. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Grace Dearborn Inc. (In prep.). Pilot-scale demonstration of Darament[TM] enhanced bioremediation of sediment contaminated with polycyclic aromatic hydrocarbons. Submitted to The Wastewater Technology Centre. Prepared for Environment Canada, Vancouver, British Columbia.

Great Lakes United. 1989. Conference Proceedings: The Sediment Solution. Hel in Merrillville, Indiana on November 30-December 3, 1988, Buffalo, NY.

Grogan, T. 1993. First quarterly cost report--cost history, March 29, 1993. Engineering News Record 230:13. The McGraw-Hill Construction Weekly.

Gunston, B. 1970. Hydrofoils and hovercrafts, new vehicles for sea and land. Doubleday and Company, Inc., New York, NY.

Haliburton, T.A. 1978. Guidelines for dewatering & densifying confined dredged material. Technical Report DS-178-11. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hand, T.D., A.W. Ford, P.G. Malone, D.W. Thompson. and R.B. Mercer. 1978. A feasibility study of response techniques for discharges of hazardous chemicals that sink. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hawco. 1993. Manufacturer's literature. Hawco Manufacturing Co., Slaughter, LA.

Hayes, D.F. 1986. Guide to selecting a dredge for minimizing resuspension of sediment, environmental effects of dredging. Technical Note EEDP-09-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hayes, D.F. 1992. Anticipating sediment resuspension and contaminant release during environmental dredging operations. In: Proc. of the International Symposium on Environmental Dredging, September 30-October 2, 1992, Buffalo, NY.

Hayes, D.F., T.M. McLellan, and C.L. Truitt. 1988. Demonstration of innovative and conventional dredging equipment at Calumet Harbor, Illinois. Improvement of Operation and Maintenance Techniques Research Program. Miscellaneous Paper EL-88-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Herbich, D.F. 1992. Handbook of dredging engineering. First Edition. McGraw-Hill Book Company, New York, NY.

Herbich, J.B., and S.B. Brahme. 1991. Literature review and technical evaluation of sediment resuspension during dredging. Contract Report HL-91-1. Prepared for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Texas A&M University, College Station, TX.

Herbst, J.A., and J.L. Sepulvada. 1986. Particle size analysis. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Hill, D.O., T.E. Myers, and J.M. Brannon. 1988. Development and application of techniques for predicting leachate quality in confined disposal facilities: background and theory. DOTS. Miscellaneous Paper D-88-1. Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hopstock, D.M. 1986. Measurement of the electric and magnetic properties of minerals. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Hosokawa, Y. 1993. Remediation work for mercury contaminated bay--experiences of Minamata Bay project. In: Preprints from First International Specialized Conference on Contaminated Aquatic Sediments: Historical Records, Environmental Impact, and Remediation. June 14-16, 1993. International Association on Water Quality, Milwaukee, WS.

Huston, J. 1970. Hydraulic dredging, theoretical and applied. Cornell Maritime Press, Inc., Cambridge, MD.

Huston, J.W., and W.C. Huston. 1976. Techniques for reducing turbidity associated with present dredging procedures and operations. Contract Report D-76-4. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hutton, J.H., and R. Shanks. 1992. Thermal desorption of PCB-contaminated waste at the Waukegan Harbor Superfund site--a case study. Fourth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

IDR. Directory of dredge owners and operators and dredging industry buyer's guide (published annually). International Dredging Review. Fort Collins, CO.

IJC. 1982. Guidelines and register for evaluation of Great Lakes dredging projects. Report of the International Joint Commission, Dredging Subcommittee, to the Great Lakes Water Quality Board, Windsor, Ontario.

IJC. 1986. A forum to review confined disposal facilities for dredged material in the Great Lakes. Report of the International Joint Commission, Dredging Subcommittee, to the Great Lakes Water Quality Board, Windsor, Ontario.

IJC. 1988. Procedures for the assessment of contaminated sediment problems in the Great Lakes. Report of the International Joint Commission, Sediment Subcommittee, to the Great Lakes Water Quality Board, Windsor, Ontario.

IJC. 1990. Proceedings of the technology transfer symposium for the remediation of contaminated sediments in the Great Lakes Basin, October 25-28, 1988, Burlington, Ontario. Report of the International Joint Commission, Sediment Subcommittee, to the Great Lakes Water Quality Board, Windsor, Ontario.

IJC. 1993. Levels reference study: Great Lakes-St. Lawrence River basin. Submitted to the IJC by the Levels Reference Study Board, Chicago, IL.

Iwasaki, M., K. Kuioka, S. Izumi, and N. Miyata. 1992. High density dredging and pneumatic conveying system. pp.773-792 In: Proc. of the XIIIth World Dredging Congress (WODCON XIII); Bombay, India.

Jafvert, C.T., and J.E. Rogers. 1991. Biological remediation of contaminated sediments, with special emphasis on the Great Lakes. Workshop Report. Manitowoc, WS. USEPA/600/9-91/001. Environmental Research Laboratory, Athens, GA.

JBF Scientific Corp. 1978. An analysis of the functional capabilities and performance of silt curtains. TRD-78-39. U.S. Army, Office of the Chief of Engineers, Washington, DC.

Johnson, B.H. 1990. User's guide for models of dredged material disposal in open water. Technical Report D-90-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Johnson, C.N. 1994. Personal communication. U.S. Army Corps of Engineers, North Central Division, Chicago, IL.

Jones, W.J., R. Araujo, and J.E. Rogers. (In prep.a). Bench-scale evaluation of bioremediation for the treatment of sediments from the Ashtabula, Buffalo, Saginaw and Sheboygan Rivers. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Jones, W.J., R. Araujo, and J.E. Rogers. (In prep.b). Pilot-scale demonstration of bioremediation for the treatment of Sheboygan River sediments. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Kaszalka, D. 1993. Personal communication on March 9, 1993. Trinity Environmental Technologies, Inc.

Kennedy, R.H., and G.D. Cooke. 1982. Control of lake phosphorous with aluminum sulfate: dose determination and application techniques. Water Res. Bull. 18(3):389-395.

Kiang, Y.H., and A.A. Metry. 1982. Hazardous waste processing technology. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Kido, K.M., Yamada, and N. Ueda. 1992. Restoration of aquatic animals by dredging of Dokai Bay in Kitakyushu City, Japan. In: Proc. of the International Symposium on Environmental Dredging, September 30-October 2, 1992, Buffalo, NY.

Kikegawa, K. 1983. Sand overlying for bottom sediment improvement by sand spreader: Management of bottom sediments containing toxic substances. In: Proc. of 7th US/Japan Experts Meeting. Prepared for the U.S. Army Corps of Engineers, Water Resources Support Center by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Koba, H. 1985. Dispersion of sediment resuspension caused by dredge operation, in Management of Bottom Sediments Containing Toxic Substances: Proceedings of the 9th U.S./Japan Experts' Meeting, Jacksonville, FL.

Koerner, R.M., J. Fowler, and C.A. Lawrence. 1986. Soft soil stabilization study for Wilmington Harbor South dredged material disposal area. Miscellaneous Paper GL-86-38. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kovach, R. 1994. Personal communication. U.S. Environmental Protection Agency, Region 5, Chicago, IL.

Krizek, R.J., J.A. Fitzpatrick, and D.K. Atmatzidis. 1976. Investigation of effluent filtering syatems for dredged material containment facilities. Contract Report D-76-8. Northwestern University, Department of Civil Engineering, for the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kynch, G.J. 1952. A theory of sedimentation. Transactions. Volume 55. Faraday Society.

Lake Michigan Federation. 1989. Cleaning up contaminated sediments: a citizens guide. Chicago, IL.

Lee, C.R., and J.G. Skogerboe. 1983. Prediction of surface runoff water quality from an upland dredged material disposal site. In: Proc. of the International Conference on Heavy Metals in the Environment, Heidelberg, Germany.

Lee, C.R., and J.G. Skogerboe. 1987. Upland site management for surface runoff water quality. Environmental Effects of Dredging Program Technical Note EEDP-02-3. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C.R., R.K. Peddicord, M.R. Palermo, and N.R. Francinques. 1991. General decision-making framework for management of dredged material--example application to Commencement Bay, WA. Miscellaneous Paper D-91-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lerman, A. 1979. Geochemical processes water and sediment environments. John Wiley & Sons, New York, NY.

Lindeburg, M.R. 1992. Civil engineering reference manual. Sixth Edition. Professional Publications, Inc., Belmont, CA.

Long, B.W., and D.J. Grana. 1978. Feasibility study of vacuum filtration systems for dewatering dredged material. Technical Report D-78-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

MacDonald, R.D., R.J. Brison, and W.C. Hellyer. 1986. Flotation test procedures. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

MacKnight, Dr. S.D. 1992. Dredging of contaminated sediment between pre-dredging survey and treatment. In: Proc. of the International Symposium on Environmental Dredging, Buffalo, NY.

Mallory, C.W., and M.A. Nawrocki. 1974. Containment area facility concepts for dredged material separation, drying, and rehandling. DMMP Contract Report D-74-6. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Maynord, S., and R. Oswalt. 1993. *In-situ* capping/armoring. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McClellan, T.N., R.N. Harvis, D.F. Hayes, and G.L. Raymond. 1989. Field study of sediment resuspension characteristics of selected dredges. Technical Report HL-89-9. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McGraw-Hill. 1984. Dictionary of scientific and technical terms. Third Edition. S. P. Parker (ed). McGraw-Hill Book Company, New York, NY.

Metcalf & Eddy, Inc. 1979. Wastewater engineering: treatment, disposal, reuse. Second Edition. Revised by G. Tchobanoglous. McGraw-Hill, New York, NY.

Metcalf & Eddy, Inc. 1991. Wastewater engineering: treatment, disposal, reuse. Third Edition. Revised by G. Tchobanoglous and F.L. Burton. McGraw-Hill, New York, NY.

Miller, A.C., and B.S. Payne. 1992. The effects of increased commercial navigation traffic on freshwater mussels in the upper Mississippi River: 1990 studies. Technical Report EL-92-23. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Miller, A.C., and B.S. Payne. 1993a. Effects of increased commercial navigation traffic on freshwater mussels in the upper Mississippi River: 1991 studies. Technical Report EL-93-1. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Miller, A.C., and B.S. Payne. 1993b. Phase II studies: impacts of commercial navigation traffic on freshwater mussels at the W.H. Zimmer Station, 1991 studies. Technical Report EL-93-2. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Miller, A.C., K.J. Killgore, and B.S. Payne. 1987. Bibliography of effects of commercial navigation traffic in large waterways, environmental and water quality operational studies. Miscellaneous Paper E-87-1. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Miller, A.C., B.S. Payne, D.J. Hornbach, and D.V. Ragland. 1990. Physical effects of increased commercial navigation traffic on freshwater mussels in the upper Mississippi River: Phase I studies. Technical Report EL-90-3. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Miller, J.A. 1990. Confined disposal facilities on the Great Lakes. U.S. Army Engineer Division, North Central, Chicago, IL.

Miller, R.H. 1968. The hydro-dump barge, October 1968. In: Proc. of the World Dredging Conference, WODCON '68. Rotterdam, Holland.

Mills, C. 1985. Specific gravity fractionation and testing with heavy liquids. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Milwaukee Metropolitan Sewerage District. 1992. Chapter II: discharge regulations and enforcement procedures. Milwaukee Metropolitan Sewerage District, Milwaukee, WI.

Mudroch, A., and S.C. MacKnight (eds), 1991. Handbook of techniques for aquatic sediments sampling. CRC Press, Boca Raton, Fl.

Mular, A.L., and N.A. Jull. 1980. The selection of cyclone classifiers, pumps, and pump boxes for grinding circuits, mineral processing plant design. Second Edition. A.L. Mular and R. Bhappu (eds). Society of Mining Engineers, Littleton, CO. pp. 376-403.

Murphy, T., H. Brouwer, A. Moller, M. Fox, D. Jeffries, J. Thachuk, H. Savile, and H. Don. 1993. Preliminary analysis of *in situ* bioremediation in Hamilton Harbour. In: Proc. of Workshop on the Removal and Treatment of Contaminated Sediments. Environment Canada, Toronto, Ontario.

Myers, T.E. 1991. Polychlorinated biphenyl levels in the Saginaw confined disposal facility during disposal operations. Fall 1987. Miscellaneous Paper EL-91-4. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Myers, T.E., and J.M. Brannon. 1991. Technical consideration for applications of leach tests to sediments and dredged material, environmental effects of dredging program. Technical Note EEDP-02-15. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Myers, T.E., and M.E. Zappi. 1989. New Bedford Harbor Superfund project, Acushnet River estuary engineering feasibility study of dredging and dredged material disposal alternatives. In: Report No. 9, Laboratory-Scale Application of Solidification/Stabilization Technology. Technical Report EL-88-15. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Myers, T.E., and M.E. Zappi. 1992. Laboratory evaluation of solidification/stabilization technology for reducing the mobility of heavy metals in New Bedford Harbor Superfund site sediment. In: Stabilization and Solidification of Hazardous, Radioactive, and Mixed Wastes, Second Volume, ASTM STP 1123. T.M. Gilliam and C.C. Wiles (eds). American Society for Testing and Materials, Philadelphia, PA.

Myers, T.E., D.D. Reible, M.R. Palermo, T.J. Olin, D.E. Averett, J.L. Martin, and S.G. McCutcheon. (In prep.). Estimating contaminant losses from components of remediation alternatives for contaminated sediments. EPA905-R94-XXX. U.S.

Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Myers, T.E., J.M. Brannon, and C.B. Price. 1992. Recent developments in leachate testing and evaluation. Miscellaneous Paper D-92-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Neal, R.W., G. Henry, and S.H. Greene. 1978. Evaluation of submerged discharge of dredged material slurry during pipeline dredged operations. DMRP Technical Report D-78-44. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nielsen, R.K., and C.A. Myler. 1990. Low temperature thermal treatment (LT[3]) of soils contaminated with aviation fuel and chlorinated solvents. In: Proc. of Second Forum of Innovative Hazardous Waste Treatment Technologies: Domestic and International, Philadelphia, PA. May 15-17, 1990. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH.

Norfolk District. 1982. James River demonstration project. Final Report. U.S. Army Engineer District, Norfolk, VA.

O'Brien, R.P., and J.L. Fisher. 1983. There is an answer to groundwater contamination. In: Water/Engineering and Management.

Onondaga County Department of Drainage and Sanitation. 1983. Rivers and regulations relating to the use of the public sewer system. Onondaga County Department of Drainage and Sanitation, Syracuse, NY.

Palermo, M.R. 1986. Interim guidance for predicting the quality of effluent discharged from confined dredged material disposal areas, environmental effects of dredging program. Technical Note EEDP-04-1 through 4. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R. 1989. Capping contaminated dredged material in deep water. In: Proc. of the Specialty Conference Ports 89. American Society of Civil Engineers, Boston, MA.

Palermo, M.R. 1991a. Design requirements for capping. Technical Note DRP-5-03. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R. 1991b. Equipment and placement techniques for capping. Technical Note DRP-5-05. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R. 1991c. Site selection considerations for capping. Technical Note DRP-5-04. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R., and D.D. Reible. (In prep.) Guidance on the *in situ* capping of contaminated sediments. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Palermo, M.R., and V.R. Pankow. 1988. New Bedford Harbor Superfund project, Acushnet River estuary engineering feasibility study of dredging and dredged material disposal alternatives. In: Report 10, Evaluation of Dredging and Dredging Control Technologies. Technical Report EL-88-15. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R., and R.E. Randall. 1990. Practices and problems associated with economic loading and overflow of dredge hoppers and scows. October 1990. Technical Report DRP-90-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R., and E.L. Thaxton. 1988. Test for dredged material effluent quality. J. Environ. Eng. 114:6. American Society of Civil Engineers.

Palermo, M.R., T. Fredette, R.E. Randall, and J. Clausner. (In prep.). Guidance for subaqueous capping. Technical Report X-XX. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R, R.A. Shafer, J.M. Brannon, T.E. Myers, C.L. Truitt, M.E. Zappi, J.G. Skogerboe, T.C. Sturgis, R. Wade, D. Gunnison, D.M. Griffin, H. Tatum, and S. Portzer. 1989. Evaluation of dredged material disposal alternatives for U.S. Navy Homeport at Everett, Washington. Technical Report EL-89-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palermo, M.R., T. Fredette, and R.E. Randall. 1992. Monitoring considerations for capping. Technical Note DRP-5-07. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Palmer, C. 1993. Personal communication on March 9, 1993. Chemical Waste Management, Batavia, IL.

Pankow, V.R. 1987. Dredging applications of high density polyethylene pipe, September 1987. In: Proc. for the Nineteenth Dredging Seminar, Baltimore, MN.

Parker, C., and W. Sisk. 1991. Low temperature thermal stripping of organics--contaminated soils, society of military engineers technology transfer conference on environmental cleanup. Society of Military Engineers, Denver, CO.

Payne, M. 1993. Personal communication. Chemical Waste Management, Batavia, IL.

Penmetsa, R.V., and W.J. Greeney. 1993. STEP: Model for technology screening for hazardous-waste-site cleanup. Journal of Environmental Engineering. 119(2)231-247. American Society of Civil Engineers.

Pequegnat, W.E., B.J. Gallaway, and T.D. Wright. 1990. Revised procedural guide for designation survey of ocean dredged material disposal sites. Technical Report D-90-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Perry, R.H., and C.H. Chilton. 1973. Chemical engineers' handbook. Fifth Edition. Harold B. Crawford and Ross J. Kepler (eds). McGraw-Hill Book Company, New York, NY.

Petrovski, D. 1994. Personal communication. U.S. Environmental Protection Agency, Region 5, Chicago, IL.

Philips K., and J. Malek. 1984. Dredging as a remedial method for a Superfund site. In: Proc. of the Dredging Conference '84. Dredging and Dredged Material Disposal, Volume 2. American Society of Civil Engineers, New York, NY.

Poindexter, M.E. 1989. Monitoring dredged material consolidation and settlement at aquatic disposal sites, environmental effects of dredging programs. Technical Note EEDP-01-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Poindexter, M.E. 1990. Methodology for analysis of subaqueous sediment mounds. Technical Report D-90-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Portland Cement Association. 1991. Solidification and stabilization of wastes using Portland cement. Portland Cement Association, Skokie, IL.

Quensen, J.F., S.A. Boyd, and J.M. Tiedje. 1991. Anaerobic dechlorination and the bioremediation of pcbs, in biological remediation of contaminated sediments, with special emphasis on the Great Lakes. In: Report of a Workshop, Manitowoc, Wisconsin, July 17-19, 1990. EPA/600/9-91/001. Environmental Research Laboratory, Athens, GA.

Randall, R.E. 1992. Equipment used for dredging contaminated sediments. In: Proc. of the International Symposium on Environmental Dredging, September 30-October 2, 1992, Buffalo, NY.

Reithmann, R.E., and B.E. Burnnell. 1980. Application and selection of spiral classifiers. pp. 362-375. In: Mineral Processing Plant Design. Second Edition. A.L. Mular and R. Bhappu (eds). Society of Mining Engineers, Littleton CO.

Rexnord, Inc. 1986. Ashtabula River sediment belt filter press pilot study. Prepared for U.S. Army Corps of Engineers, Buffalo District, Buffalo, NY.

Robert Snow Means Company, Inc. 1993. Building construction cost data. Kingston, MS.

Rogers, C. 1993. Personal communication. U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Rokosch, W.D. 1992. Dredging of contaminated sediment between pre-dredging survey and treatment. In: Proc. of the International Symposium on Environmental Dredging, September 30-October 2, 1992, Buffalo, NY.

Sanderson, W.H., and A.L. McKnight. 1986. Survey of equipment and construction techniques for capping dredged material. Miscellaneous Paper D-86-6. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Saucier, R.T., C.C. Calhoun, Jr., R. M. Engler, T.R. Patin, and H.K. Smith. 1978. Executive overview and detailed summary. Technical Report DS-78-22. U.S. Army Engineer Waterways Experiment Station, Dredged Material Research Program, Vicksburg, MS.

Sato, E. 1984. Bottom sediment dredge "clean-up"--principles and results in management of bottom sediments containing toxic substances. In: Proc. of the 8th U.S./Japan Experts' Meeting, Waterways Experiment Station, Vicksburg, MS. pp. 403-418.

Schaefer, T.E., and P.R. Schroeder. 1988. Confined disposal guidance for small hydraulic maintenance dredging projects - design procedures. Environmental Effects of Dredging Program Technical Note EEDP-02-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schindler, T. 1992. The Carver-Greenfield process: established sludge-drying process touted for environmental market. Environmental Information Ltd., Minneapolis, MN.

Schroeder, P.R. 1983. Chemical clarification methods for confined dredged material disposal. Technical Report D-83-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schroeder, P.R., and M.R. Palermo. 1990. The automated dredging and disposal alternatives management system (ADDAMS). Environmental Effects of Dredging Program Technical Note EEDP-06-12. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schroeder, P.R., J.M. Morgan, T.M. Walski, and A.C. Gibson. 1984. The hydrologic evaluation of landfill performance (HELP) model: Volume I, user's guide for Version I. EPA/5-30-SW-84-009. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH, and Office of Solid Waste and Emergency Response, Washington, DC.

Seech, A., B. O'Neil, and L.A. Cornacchio. 1993. Bioremediation of sediments contaminated with polynuclear aromatic hydrocarbons (PAHs). In: Proc. of Workshop on the Removal and Treatment of Contaminated Sediments. Environment Canada's Great Lakes Cleanup Fund, Wastewater Technology Centre, Burlington, Ontario.

Semmler, J.A. 1990. PCB volatilization from dredged material, Indiana Harbor, Indiana. Environmental Effects of Dredging Technical Note EEDP-02-12. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Shields, F.D., and R.L. Montgomery. 1984. Fundamentals of capping contaminated dredged material. In: Proc. of the Specialty Conference: Dredging 84. American Society of Civil Engineers, Clearwater, FL.

Shuckrow, A.J., A.P. Pajek, and J.W. Osheka. 1981. Concentration technologies for hazardous aqueous waste treatment. EPA-600/2-81-019. U.S. Environmental Protection Agency, Washington, DC.

Simmers, J. 1994. Personal communication. U.S. Army Waterways Experiment Station, Vicksburg, MS.

Simmers, J.W., R.G. Rhett, and C.R. Lee. 1986. Upland animal bioassays of dredged material. Environmental Effects of Dredging Program Technical Note EEDP-02-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Snoeyink, V.L., and D. Jenkins. 1980. Water chemistry. John Wiley & Sons, New York, NY.

Somasundran, P. 1979. Processing mineral fines. Engineering and Mining Journal, December 1979. pp. 64-68.

Somasundran, K., and K.P. Ananthapadmanabhan. 1986. Experimental techniques in flotation basic research. Mineral Processing Handbook. N.L. Weiss (ed). Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Sorensen, J. 1994. Personal communication. U.S. Army Engineer District, Detroit, MI.

Souder, P.S., Jr., L. Tobias, J.F. Imperial, and F.C. Mushal. 1978. Dredged material transport systems for inland disposal and/or productive use concepts, June 1978. Dredged Material Research Program Technical Report D-78-28. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Spaine, P.A., J.L. Llopis, E.R. Perrier. 1978. Guidance for land improvement using dredged material, December 1978. Dredged Material Research Program Technical Report DS-78-21. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

St. Lawrence Centre. 1993. Selecting and operating dredging equipment: a guide to sound environmental practices. Prepared in collaboration with Public Works Canada and the Ministere de l'Environnement du Quebec, and written by Les Consultants Jacques Berube Inc. Cat No. En 40-438/1993E.

Stafford, E.A., J.W. Simmers, R.G. Rhett, and C.P. Brown. 1991. Interim report: collation and interpretation of data for times beach confined disposal facility, Buffalo, New York. LEDO Miscellaneous Paper D-91-17. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Stark, T.D. 1991. Program documentation and users guide: PCDDF89, primary consolidation and desiccation of dredged fill. Instruction Report D-91-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sturgis, T., and D. Gunnison. 1988. A procedure for determining cap thickness for capping subaqueous dredged material deposits. Technical Note EEDP-0109. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sumeri, A. 1989. Confined aquatic disposal and capping of contaminated bottom sediments in Puget Sound. In: Proc. of the WODCON XII, Dredging: Technology, Environmental, Mining, World Dredging Congress, Orlando, FL. May 2-5, 1989.

Tchobanoglous, G., H. Theisen, and R. Eliassen. 1977. Solid wastes: engineering principles and management issues. McGraw-Hill Publishers, New York, NY.

Teeter, A.M. 1988. New Bedford Harbor Superfund project, Acushnet River estuary engineering feasibility study of dredging and dredged material disposal alternatives. In: Report 2, Sediment and Contaminant Hydraulic Transport Investigations. Technical Report EL-88-15, Report 2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thibodeaux, L.J., C. Springer, and R.S. Parker. 1985. Design for control of volatile chemical emissions from surface impoundments. Hazardous Waste and Hazardous Materials 2(1):99-106.

Togashi, H. 1983. Sand overlaying for sea bottom sediment improvement by conveyer barge: Management of bottom sediments containing toxic substances. In: Proc. of 7th US/Japan Experts Meeting. Prepared for the U.S. Army Corps of Engineers, Water Resources Support Center by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Toronto Harbour Commission. 1993. Report on the treatment of the Toronto Harbour sediments at the THC soil recycling plant. Prepared for the Wastewater Technology Centre, Toronto, Ontario.

Truitt, C. 1987a. Engineering considerations for subaqueous dredged material capping--background and preliminary planning. Environmental Effects of Dredging Programs Technical Note EEDP-01-3. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Truitt, C. 1987b. Engineering considerations for capping subaqueous dredged material deposits--design concepts and placement techniques. Environmental Effects of Dredging Programs Technical Note EEDP-01-4. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Turner, T.M. 1984. Fundamentals of hydraulic dredging. Cornell Maritime Press, Centerville, MD.

UAB. 1993. Hazardous materials in intrastate commerce--notice of proposed rulemaking. Alabama Emergency Response and Remediation Training Newsletter, Number 13. University of Alabama at Birmingham, Center for Labor Education and Research, Birmingham, AL.

U.S. Bureau of Mines. 1987. Bureau of Mines cost estimating system handbook. Vol. 2--Mineral Processing. Compiled by the U.S. Bureau of Mines, BuMines IC 9143, Washington, DC.

USACE. 1970. Laboratory soil testing. Engineer Manual EM 1110-2-1906. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1973. Resident engineers management guide. Engineer Pamphlet EP 415-1-260. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1976. Ecological evaluation of proposed discharge of dredged or fill material into navigable waters (interim guidance for implementation of Section 404(b)(1) of Public Law 92-500). Miscellaneous Paper D-76-17. U.S. Army Corps of Engineers, Dredged Material Research Program, Waterways Experiment Station, Vicksburg, MS.

USACE. 1980a. Civil works construction cost index system (CWCCIS). Engineer Manual EM 1110-2-1304. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1980b. Cost estimates-planning and design stages. Engineer Manual EM 1110-2-1301. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1980c. Guidelines for designing, operating, and managing dredged material containment areas. Engineer Manual EM 1110-2-5006. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1982. Cost estimates-government estimate of fair and reasonable cost to contractor. Engineer Manual EM 1110-2-1302. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1983. Dredging and dredged material disposal. Engineer Manual EM 1110-2-5025. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1987a. Beneficial uses of dredged material. Engineer Manual EM 1110-2-5026. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1987b. Confined disposal of dredged material. Engineer Manual EM 1110-2-5027. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1987c. Environmental engineering for deep-draft navigation projects, Engineer Manual EM 1110-2-1202. U.S. Army Corps of Engineers, Washington, DC.

USACE. 1987d. Modifications and claim guide: fixed price construction contracts. Engineer Pamphlet EP 415-1-2. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1987e. Safety and health requirements manual. Engineer Manual EM 385-1-1. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1987f. Value engineering officer's operational guide. Engineer Pamphlet EP 11-1-3. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1988. Construction equipment ownership and operating expense schedule. U.S. Army Engineer District, Walla Walla, WA.

USACE. 1989. Waterborne Commerce of the United States, Part 3: Great Lakes. WRSC-WCUS-89-3. U.S. Army Corps of Engineers, Water Resources Support Center, New Orleans, LA.

USACE. 1992a. Civil works cost engineering. Engineer Regulation ER 1110-8-1 (Draft). U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE. 1992b. Quality assurance representative's guide. Engineer Pamphlet EP 415-1-261 (4 Volumes). U.S. Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC.

USACE Buffalo District. (In prep.). Pilot-scale demonstration of thermal desorption for the treatment of Ashtabula River sediments. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USACE Buffalo District. 1969. Dredging and water quality problems in the Great Lakes. 12 Volumes. U.S. Army Corps of Engineers Buffalo District, Buffalo, NY.

USACE Buffalo District. 1993. Pilot-scale demonstration thermal desorption for the treatment of Buffalo River sediments. EPA905-R93-005. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USACE Chicago District. 1984. Project files on Chicago Area confined disposal facility. U.S. Army Engineer District, Chicago, IL.

USACE Chicago District. 1986. Draft environmental impact statement, Indiana Harbor confined disposal facility and maintenance dredging, Lake County, Indiana. U.S. Army Engineer District, Chicago, IL.

USACE Chicago District. 1994. Pilot-scale demonstration of solvent extraction for the treatment of Grand Calumet River sediments. EPA905-R94-003. Prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USACE Detroit District. 1994. Pilot-scale demonstration of sediment washing for the treatment of Saginaw River sediments. EPA905-R94-019. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USACE/USEPA. 1984. General approach to designation studies of ocean dredged material disposal sites. U.S. Army Engineer Water Resources Support Center, Ft. Belvoir, VA.

USACE/USEPA. 1992. Evaluating environmental effects of dredged material management alternatives--a technical framework. EPA-842-B-92-008. U.S. Army Corps of Engineers and U.S. Environmental Protection Agency, Washington, DC.

USEPA. (In prep.a). Bench-scale evaluation of sediment treatment technologies summary report. EPA905-R94-011. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USEPA. (In prep.b). Concept plans for the remediation of contaminated sediment at five Great Lakes Areas of Concern. EPA905-R94-XXX. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USEPA. 1979. Process design manual for sludge treatment and disposal, September 1979. EPA 625/1-79-011. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Office of Research and Development, Cincinnati, OH.

USEPA. 1984a. Review of in-place treatment techniques for contaminated surface soils. Volume 1, Technical Evaluation. EPA-540/2-84-00a. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.

USEPA. 1984b. Outboard marine corporation record of decision. U.S. Environmental Protection Agency, Region 5, Chicago, IL.

USEPA. 1985a. Handbook: estimating sludge management costs. U.S. Environmental Protection Agency, Office of Research and Development. Published by Technomic Publishing Comp., Inc., Lancaster, PA.

USEPA. 1985b. Remedial action at waste disposal sites (revised). EPA/625/6-85/006. U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH.

USEPA. 1986a. Ocean dumping site designation delegation handbook. U.S. Environmental Protection Agency, Office of Marine and Estuarine Protection, Washington, DC.

USEPA. 1986b. Superfund remedial design and remedial action guidance. OSWER Guidance 9355.0-4A. U.S. Environmental Protection Agency, Office of Remedial Response, Washington, DC.

USEPA. 1987a. A compendium of technologies used in the treatment of hazardous wastes. EPA/625/8-87/014. U.S. Environmental Protection Agency, Center for Environmental Research Information, Cincinnati, OH.

USEPA. 1987b. Dewatering municipal wastewater sludges. EPA/625/1-87/014. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1988a. Guidance for conducting remedial investigations and feasibility studies under CERCLA. Interim Final. EPA/540/G-89/004. OSWER Directive 9355.3-01. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC.

USEPA. 1988b. Technology screening guide for treatment of CERCLA soils and sludges. EPA/540/2-88/004. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Emergency and Remedial Response, Cincinnati, OH.

USEPA. 1988c. The Superfund Innovative Technology Evaluation program: technology profiles. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Emergency and Remedial Response, Washington, DC.

USEPA. 1989a. Bioremediation of contaminated surface soils. EPA-600/9-89/073. Robert S. Kerr Environmental Research Laboratory, Ada, OK.

USEPA. 1989b. Guide for conducting treatability studies under CERCLA. EPA/540/2-89/058. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1989c. Innovative technology; slurry phase biodegradation. EPA/9200.5-252FS. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

USEPA. 1989d. Requirements for hazardous waste landfill design, construction and closure. EPA/625/4-89/022. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 1989e. Shirco infrared incineration system. Superfund Innovative Technology Evaluation Applications Analysis Report. EPA/540/A5-89/010. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1989f. Health and safety plan (HASP). OSWER Directive 9285-01. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

USEPA. 1989g. The Superfund Innovative Technology Evaluation Program: Technology Profiles. EPA/540/5-89/013. Risk Reduction Engineering Laboratory, Cincinnati, OH.

USEPA. 1990a. Chemical dehalogenation treatment: APEG treatment. In: Engineering Bulletin. Superfund EPA/540/2-90/015. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990b. CF systems organics extraction process-New Bedford Harbor, MA. Superfund Innovative Technology Evaluation Applications Analysis Report. EPA 540/A5-90/002. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 1990c. CF systems organics extraction system-New Bedford, Massachusetts. Technology Evaluation Report. EPA/540/5-90/002, January 1990. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1990d. Engineering Bulletin: slurry biodegradation. EPA/540/2-90/016. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990e. International waste technologies/Geo-Con *in situ* stabilization/solidification--applications analysis report. EPA/540/A-89/004. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, OH.

USEPA. 1990f. Mobile/transportable incineration treatment. In: Engineering Bulletin. EPA/540/2-90/014. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990g. Soil washing treatment. In: Engineering Bulletin. EPA/540/2-90/017. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990h Solvent extraction treatment. In: Engineering Bulletin. EPA/540/2-90/013. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990i. The lake and reservoir restoration guidance manual. EPA-440/4-90-006. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 1990j. Treating chlorinated wastes with the KPEG process. Project Summary. EPA/600/S2-90/026. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1990k. Engineering Bulletin: Solvent extraction treatment. EPA/540/2-90/013. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1990l. Feasibility study of remedial alternatives for the estuary and lower harbor/bay: New Bedford, Massachusetts. Volume II. Prepared by Ebasco Services, Inc. for U.S. Environmental Protection Agency, Region I, Boston, MA.

USEPA. 1991a. Chemfix Technologies, Inc. Solidification/stabilization process--applications analysis report. EPA/540/A5-89/011. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, OH.

USEPA. 1991b. Chemical oxidation treatment. Engineering Bulletin Superfund. EPA/540/2-91/025. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1991c. Engineering Bulletin: thermal desorption treatment. EPA/540/2-91/008. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1991d. Innovative treatment technologies--bioremediation. EPA/540/9-91/002. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

USEPA. 1991e. The Superfund Innovative Technology Evaluation program: technology profiles. Fourth Edition. EPA/540/5-91/008. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, and Office of Research and Development, Cincinnati, OH.

USEPA. 1991f. Innovative treatment technologies--overview and guide to information sources. EPA/540/9-91/002 U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

USEPA. 1991g. DuPont/Oberlin microfiltration technology: applications analysis report. EPA/540/A5-90/007. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, OH.

USEPA. 1991h. Test methods for evaluating solid waste - physical/chemical methods, SW-846. Revised methods. Third edition. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 1992a. Babcock and Wilcox cyclone furnace vitrification technology. Superfund Innovative Technology Evaluation applications analysis report. EPA/540/AR-92/017. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

USEPA. 1992b. Horsehead Resource Development Company, Inc. Flame reactor technology. Superfund Innovative Technology Evaluation applications analysis report. EPA/540/A5-91/005. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 1992c. Quality assurance management plan for the assessment and remediation of contaminated sediments (ARCS) program. U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, NV.

USEPA. 1992d. ReTech, Inc. Plasma centrifugal furnace--applications analysis report. EPA/5540/A5-91/007. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, OH.

USEPA. 1992e. The Carver-Greenfield process. Superfund Innovative Technology Evaluation demonstration bulletin. EPA/540/MR-92/002. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 1992f. The Carver-Greenfield process Dehydro-Tech Corporation. Superfund Innovative Technology Evaluation applications analysis report. EPA/540/AR-92/002. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 1992g. The Superfund Innovative Technology Evaluation program: technology profiles. Fifth Edition. Superfund EPA/540/R-92/077. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC, and Office of Research and Development, Washington, DC.

USEPA. 1992h. Standard operating safety guides. Publication 9285.1-03. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC.

USEPA. 1992i. Seminar publication organic air emissions from waste management facilities. EPA/625/R-92/003. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards Research Triangle Park, NC, and Office of Research and Development, Washington, DC.

USEPA. 1993a. ARCS risk assessment and modeling overview document. EPA905-R93-007. Prepared by ASCI for the U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USEPA. 1993b. VISITT--vendor information system for innovative technologies. EPA/542-R-93-001. Number 2. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

USEPA. 1993c. Seminars on bioremediation of hazardous waste sites: Practical approaches to implementation. EPA/600/K-93/002. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 1993d. Selecting remediation techniques for contaminated sediment. EPA-823-B93-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 1994a. ARCS assessment guidance document. EPA905-B94-002. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

USEPA. 1994b. SITE demonstration bulletin: the ECO logic thermal desorption unit. EPA/540/MR-94/504. U.S. Environmental Protection Agency, Center for Environmental Research Information, Cincinnati, OH.

USEPA/NCD. 1994. Great Lakes dredged material testing and evaluation manual. U.S. Environmental Protection Agency, Regions 2, 3, and 5, and U.S. Army Engineer Division, North Central, Chicago, IL.

USEPA/USACE. 1990. Draft ecological evaluation of proposed discharge of dredged material into ocean waters. EPA-503-8-90/002. U.S. Environmental Protection Agency, Office of Marine and Estuarine Protection, Washington, DC.

USEPA/USACE. 1994. Evaluation of dredged material proposed for discharge in waters of the U.S.--Testing manual (Inland Testing Manual). EPA 823-B-94-002. U.S. Environmental Protection Agency, Washington, DC.

van Oostrum, R.W. 1992. Dredging of contaminated sediment between pre-dredging survey and treatment. In: Proc. of the International Symposium on Environmental Dredging, Buffalo, NY.

van Veen, H.J., and G.J. Annokkée. 1991. Biological remediation of contaminated sediments in the Netherlands. In: C.T. Jafvert and J.E. Rogers. pp. 113-126.

Wastewater Technology Centre. 1993. Sediment treatment technologies database. Second Edition. Wastewater

Technology Centre, Site Remediation Division, Burlington, Ontario.

Watanabe, R. 1970. Utilization of the pusher barge line system in reclamation projects. In: Proc. of WODCON: World Dredging Conference. Canoga Park, CA. World Dredging Association, Irvine, CA.

Way, C.M., A.C. Miller, B.S. Payne, J. Wakeley. 1990. TRAFFIC: an information retrieval system to evaluate the environmental impacts of commercial navigation traffic, December 1990. Environmental Impact Research Program Technical Report EL-90-13. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Weber, W.J., Jr. 1972. Physicochemical processes for water quality control. John Wiley & Sons, New York, NY.

Weiss, N.L. (ed). 1986. SME mineral processing handbook. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY.

Wills, B.A. 1988. Mineral processing technology. Fourth Edition. Pergamon Press, Oxford, MA. pp. 353-376.

Wong, H.T. 1994. Personal communication. U.S. Army Engineer District, Detroit, MI.

Yagi, T., T. Konsei, and S. Miyazaki. 1975. Dredging, environmental effects and technology: Turbidity caused by dredging. In: Proc. of the Seventh World Dredging Conference, WODCON VII, San Francisco, CA.

Yang, E.C., D. Bauma, L. Schwartz, and J.D. Werner. 1987. A compendium of technologies used in the treatment of hazardous wastes. EPA/625/8-87/014. U.S. Environmental Protection Agency, Center for Environmental Research Information, Cincinnati, OH.

Youngblood, A., and S. Booth. 1992. Environmental remediation cost and risk estimating software summary. U.S. Department of Energy, Los Alamos National Laboratory, Los Alamos, NM.

Zappi, P.A., and D.F. Hayes. 1991. Innovative technologies for dredging contaminated sediments. Miscellaneous Paper EL-91-20. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. p. 55.

Zeman, A.J., S. Sills, J.E. Graham, and K.A. Klein. 1992. Subaqueous capping of contaminated sediments: annotated bibliography. NWRI Contribution No. 92-65. National Water Research Institute, Burlington, Ontario, Canada.

Zeman, A.J. 1993. Personal communication. Environment Canada, National Water Research Institute, Burlington, Ontario, Canada.

---

EPA Home | Privacy and Security Notice | Contact Us