United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/530/R-93/012
June 1993

PB93-237535

EPA

Technical Resource Document

Solidification/ Stabilization and its Application to Waste Materials

EPA/530/R-93/012
June 1993

TECHNICAL RESOURCE DOCUMENT SOLIDIFICATION/STABILIZATION AND ITS APPLICATION TO WASTE MATERIALS

by

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Columbus Division
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Work Assignment No. 0-15
Contract No. 68-C0-0003

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (USEPA)is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between improving the quality of life and minimizing the risks to the environment. These laws direct the USEPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory (RREL) is responsible for planning, implementing, and managing research, development, and demonstration programs in order to provide authoritative and reliable information that can be used by both regulators and the regulated in their common efforts to protect the environment from the hazards of industrial and municipal waste. In addition, RREL is also responsible for coordinating and disseminating the latest engineering and scientific technology developments aimed at mitigating the harmful effects of environmental contaminants.

This Technical Resource Document contains the latest information on the use of solidification/stabilization for the treatment of hazardous waste, assembled for EPA by Battelle in close consultation with a distinguished panel of experts eminently renowned in this field. It addresses several issues including such important questions as to when this technology is appropriate for a specific waste and when it is not. Our goal is to provide the user community with the most comprehensive information available to enable them to manage their waste in the most efficient, feasible, and safe manner and to maintain a harmonious relationship between man and his environment.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

Stabilization/solidification (S/S) processes are effective in treating a variety of difficult to manage waste materials for reuse or disposal. S/S has been identified as the Best Demonstrated Available Technology for treating a wide range of Resource Conservation and Recovery Act (RCRA) non-wastewater hazardous waste subcategories. S/S has been selected as the treatment technology of choice for 26% of the remedial actions complete at Superfund sites through fiscal year 1992.

The standard bulk material handling and mixing equipment used in many S/S processes make the technology appear simple. However, there are significant challenges to the successful application of S/S processes. The morphology and chemistry of S/S-treated waste are complex. Selection of the binder requires an understanding of the chemistry of the bulk material, the contaminants, and the binder. The S/S user must be fully aware of the complex interactions among the various components to ensure efficient and reliable results.

Battelle, under the direction of the U.S. Environmental Protection Agency, has prepared this Technical Resources Document (TRD) as a resource for the S/S user community and a guide to promote the best future application of S/S processes. An extensive body of information is available describing the theory and practice of S/S processes. However, no one document existed combining theory, practice, and regulatory aspects of S/S application to RCRA, Superfund, and similar waste materials. This TRD pulls a diverse range of materials into one comprehensive reference.

The TRD is intended for site managers considering S/S as an option for treating hazardous wastes. It provides technology transfer to persons responsible for selection and design of S/S treatment methods. Information about S/S technology is presented in detailed text descriptions supported by summary tables, checklists, and figures. It gives the user a summary of current S/S technology. The technology areas covered are binders and their binding mechanisms, waste interferences with S/S processes, S/S treatment of organic contaminants, air emissions for S/S processes, leaching mechanisms, long-term stability, reuse and disposal of S/S-treated waste, and economics. Information is also provided to clarify the limitations of S/S technology and ongoing research to fulfill future development needs.

This TRD was submitted in fulfillment of Work Assignment 0-15 of Contract #68-CO-0003 with Battelle, Columbus, under sponsorship of the USEPA. It covers a period from 11/01/90 through 05/30/92.

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ACKNOWLEDGMENTS

The authors wish to acknowledge the many helpful comments, constructive criticisms, and substantial contributions of the members of the Technical Review Panel: Paul Bishop, University of Cincinnati; Jesse Conner, Chemical Waste Management, Inc.; John Cullinane, Jr., USAE Waterways Experiment Station; Mile Gilliam, Oak Ridge National Laboratory; Peter Hannak, Union Carbide Chemicals and Plastics Company, Inc.; Hans van der Sloot, ECN, the Netherlands; and Trish Erickson and Calton Wiles, U.S. EPA Risk Reduction Engineering Laboratory (RREL). The EPA Work Assignment Manager was Charles Mashni of RREL.

1 INTRODUCTION

Solidification/stabilization (S/S) processes are effective in treating a variety of difficult-to-manage waste materials for reuse or disposal. They are flexible enough to accommodate mixtures of contaminants and economical enough to be used for large volumes of waste. Some common S/S applications are incinerator ash, wastewater treatment sludge, and low-level waste from nuclear power plants. S/S has been identified as the Best Demonstrated Available Technology (BDAT) for treating a wide range of Resource Conservation and Recovery Act (RCRA) nonwastewater listed and characteristic wastes. S/S has also been the treatment technology of choice for 26% of the remedial actions completed at Superfund sites through fiscal year 1992 (U.S. EPA, 1992).

This document is a technical resource for the S/S user community and a guide to promote the best future applications of S/S processes. The standard bulk materials handling and mixing equipment processes used in S/S processes make the technology appear simple. However, there are significant challenges to the successful application of S/S processes. This Technical Resources Document (TRD) describes S/S process screening procedures and summarizes the status of S/S processes to assist users and reviewers in their selection, planning, and application of S/S technology.

S/S is frequently the technology of choice for immobilizing soils and sludges containing one or more metal contaminants. S/S is often chosen also for waste with poor handling quality (e.g., a dense, viscous sludge) or for large volumes of waste that are difficult to treat using other technologies (e.g., power plant desulfurization sludge).

The morphology and chemistry of S/S-treated waste are complex. Therefore, selection of the binder requires an understanding of the chemistry of the bulk material, the contaminants, and the binder, as well as of the complex interactions among the various components, to ensure efficient and reliable results. Although there is no sure prescription for selecting a successful binder, a well-structured testing program guided by an understanding of the mechanisms involved in S/S systems will reduce uncertainty in the selection process.

1.1 BACKGROUND

1.1.1 Definition of Solidification and Stabilization

The term "solidification/stabilization" (S/S) refers to a category of waste treatment processes that are being used increasingly to treat a wide variety of wastes—both solid and liquid. Generally, S/S processes are designed and used to accomplish one or more of the following objectives:

- Reduce contaminant/pollutant mobility or solubility
- Improve the handling and physical characteristics of the waste by producing a solid with no free liquid
- Decrease the exposed surface area across which transfer or loss of contaminants may occur.

Numerous other terms, such as "immobilization" and "fixation," have been used to refer to S/S technology. "Solidification" and "stabilization" are preferred here because they encompass the variety of mechanisms that may contribute to contaminant immobilization by this technology. "Solidification" refers to a process in which materials are added to the waste to produce a solid. This may or may not involve a chemical bonding between the toxic contaminant and the additive. "Stabilization" refers to converting a waste to a more chemically stable form. This conversion may include solidification, but it almost always includes use of a physicochemical reaction to transform the contaminant to a less mobile or less toxic form. Note that biological processes such as bioremediation are not included in this definition of S/S (Wiles, 1987).

1.1.2 Position of S/S in the U.S. EPA Environmental Management Options Hierarchy

The U.S. Environmental Protection Agency's (U.S. EPA) hierarchy of hazardous waste management is shown in Figure 1-1. The hierarchy lists, in descending order of emphasis, technical alternatives for the management of hazardous waste. Pollution prevention and waste minimization programs should be instituted to reduce the volume of waste at the source or to recover, reuse, or recycle the waste. If the waste cannot be eliminated or reduced, destructive treatment methods should then be examined. For degradable contaminants, treatment technologies that destroy the contaminant are preferred.

First Choice (Pollution Prevention):
Reduce/Eliminate Waste Products at the Source

- Design Long-Lived, Low-Impact Products
- Use Less-Hazardous Input Materials
- Minimize Use of Non-Recoverable Input Materials and of Water
- Conserve Energy in Production Operations and Facility Operation
- Improve Process Technology and Practices

Second Choice (Pollution Prevention):
Reuse (Closed-Loop Recycling)

- Recover Chemicals
- Reuse Water
- Recover Waste Heat

Third Choice:
Recycle Off-Site

- Ensure Safe Transport to Recycling Operation
- Select Environmentally-Sound Recycling Technology

Fourth Choice:
Treat and Dispose of Unavoidable Wastes Safely

- Minimize Volume and Toxicity of Wastes
- Dispose of Safely

FIGURE 1-1. U.S. ENVIRONMENTAL PROTECTION AGENCY'S HIERARCHY OF HAZARDOUS WASTE MANAGEMENT

However, S/S processes have an important place in the hierarchy because of their ability to treat otherwise intractable wastes.

1.1.3 Application of Solidification/Stabilization

S/S processes are used to manage numerous types of wastes, such as those covered by Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) remediation projects. As shown in Table 1-1, S/S processes have been identified as the Best Demonstrated Available Technology (BDAT) for a variety of Resource Conservation and Recovery Act (RCRA) non-wastewater wastes. S/S processes have been applied to a variety of wastes, such as nuclear, municipal ash, and wastewaters and slurries.

In the case of contaminated soils and debris, S/S is a relatively inexpensive and versatile method of treating large amounts of material with a variety of contaminants. For example, a review of 487 Records of Decision (RODs) from the 1980s showed that 53 sites (11%) documented S/S as at least one component of the source control remedy (U.S. EPA, 1989a). In fiscal year (FY) 1988, S/S processes were used at 25% of the active Superfund sites (U.S. EPA, 1989b). Waste types treated in these projects included soil, sediment, sludges, liquids, and debris. Contaminant types included volatile organic compounds (VOCs) at 21 sites, polychlorinated biphenyls (PCBs) at 19 sites, and inorganics, including metals, asbestos and cyanide, at 43 sites (U.S. EPA, 1989a). It should be noted that more than one type of contaminant may have been present at a given site.

The ROD analysis indicated that, while wastes containing some VOC contamination are treated by S/S processes, the VOCs were not the prime target. Low levels of VOCs can be incorporated coincidentally in a waste treated to immobilize inorganic contaminants (see Section 4.4.3). However, whenever VOCs are present, the possibility of their release as air emissions during treatment needs to be considered. Sites contaminated with high levels of VOCs required pretreatment prior to S/S treatment. Of the sites using S/S processes on wastes with VOC contamination, 33 percent reported using pre-treatment; of those without VOCs, only 3 percent used pretreatment.

As shown in Table 1-1, S/S processes can be used for a number of types of sludge that contain inorganic contaminants and, in some cases, inorganics mixed with organics. In cases where high levels of organics are present, the waste is typically incinerated initially. S/S processes can be

TABLE 1-1. RCRA WASTES FOR WHICH SOLIDIFICATION/STABILIZATION IS IDENTIFIED AS BEST DEMONSTRATED AVAILABLE TREATMENT TECHNOLOGY (BDAT)

Code	Waste Description	BDAT Treatment/ Treatment Train	Reference
D001	Ignitable (40 CFR 261.21(a)(2))	S/S (one alternative)	55 FR 22714
D002	Other corrosives (40 CFR 261.22 (a)(2))	S/S (one alternative)	55 FR 22714
D003	Reactive sulfides (40 CFR 261.23 (a)(5))	S/S (one alternative)	55 FR 22714
D005	Barium	S/S (one alternative)	55 FR 22561
D006	Cadmium	S/S (except batteries)	55 FR 22562
D007	Chromium	S/S (one alternative)	55 FR 22563
D008	Lead	S/S	55 FR 22565
D009	Mercury (subclass)	S/S (<260 mg/kg total Hg)	55 FR 22572
D010	Selenium	S/S	55 FR 22574
D011	Silver	S/S	55 FR 22575
F006	Some wastewater treatment sludges	Alkaline Chlorination + Precipitation + S/S	54 FR 26600
F007	Spent cyanide plating bath solutions	Alkaline Chlorination + Precipitation + S/S	54 FR 26600
F008	Plating sludges from cyanide processes	Alkaline Chlorination + Precipitation + S/S	54 FR 26600

TABLE 1-1. RCRA WASTES FOR WHICH SOLIDIFICATION/STABILIZATION IS IDENTIFIED AS BEST DEMONSTRATED AVAILABLE TREATMENT TECHNOLOGY (Continued)

Code	Waste Description	BDAT Treatment/ Treatment Train	Reference
F009	Spent stripping and cleaning solutions from cyanide processes	Alkaline Chlorination + Precipitation + S/S	54 FR 26600
F011	Spent cyanide solutions from salt bath cleaning	Electrolytic Oxidation + Alkaline Chlorination + Precipitation + S/S	54 FR 26600
F012	Quenching wastewater treatment sludges from cyanide processes	Electrolytic Oxidation + Alkaline Chlorination + Precipitation + S/S	54 FR 26600
F019	Wastewater treatment sludges from coating of aluminum except for some zirconium phosphating processes	S/S	55 FR 22580
F024	Process wastes from the production of certain chlorinated aliphatic hydrocarbons	Incineration + S/S	55 FR 22589
F039	Leachates from listed wastes	S/S (metals)	55 FR 22607
K001	Bottom sediment sludge from the treatment of waste-waters from wood preserving processes that use creosote and/or pentachlorophenol	Incineration + S/S	54 FR 31153
K006	Wastewater treatment sludge from the production of chromium oxide green pigments (anhydrous or hydrated)	S/S (hydrated form only)	55 FR 22583

TABLE 1-1. RCRA WASTES FOR WHICH SOLIDIFICATION/STABILIZATION IS IDENTIFIED AS BEST DEMONSTRATED AVAILABLE TREATMENT TECHNOLOGY (Continued)

Code	Waste Description	BDAT Treatment/ Treatment Train	Reference
K015	Still bottoms from distillation of benzyl chloride	Incineration + S/S	55 FR 22535
K022	Distillation bottom tars from the production of phenol/acetone from cumene	Incineration + S/S	53 FR 31156
K028	Spent catalyst from the hydrochlorinator reactor in the production of 1,1,1-trichloroethane	Incineration + S/S	55 FR 22589
K046	Wastewater treatment sludges from the manufacturing, formulation, and loading of lead-based initiating compounds	Reactive - Deactivation Stabilization Nonreactive - Stabilization	55 FR 22593
K048	Dissolved air flotation float from the petroleum refining industry	Incineration + S/S	53 FR 31160 55 FR 22595
K049	Slop oil emulsion solids from the petroleum refining industry	Incineration + S/S	53 FR 31160 55 FR 22595
K050	Heat exchanger bundle cleaning sludge from the petroleum refining industry	Incineration + S/S	53 FR 31160 55 FR 22595
K051	API separator sludge from the petroleum refining industry	Incineration + S/S	53 FR 31160 53 FR 22595
K052	Tank bottoms (leaded) from the petroleum refining industry	Incineration + S/S	53 FR 31160 55 FR 22595
K061	Emission control dust/sludge from primary steel production in electric furnaces	S/S (<15% Zn)	55 FR 22599

TABLE 1-1. RCRA WASTES FOR WHICH SOLIDIFICATION/STABILIZATION IS IDENTIFIED AS BEST DEMONSTRATED AVAILABLE TREATMENT TECHNOLOGY (Continued)

Code	Waste Description	BDAT Treatment/ Treatment Train	Reference
K069	Emission control dust/sludge from secondary lead smelting	S/S	55 FR 22568
K083	Distillation bottoms from aniline production	Incineration + S/S	55 FR 22588
K087	Decanter tank tar sludge from coking operations	Incineration + S/S	53 FR 31169
K100	Waste leaching solution from acid leaching of emission control dust/ sludge from secondary lead production	Precipitation + S/S	55 FR 22568
K115	Heavy ends from the purification of toluenediamine in the production of toluenediamine via hydrogenation of dinitrotoluene	S/S	55 FR 26601
U051	Creosote	Incineration + S/S	55 FR 22582
U144	Lead acetate	S/S	55 FR 22565
U145	Lead phosphate	S/S	55 FR 22565
U146	Lead subacetate	S/S	55 FR 22565
U204	Selenious acid	S/S	55 FR 22574
U205	Selenium disulfide	S/S	55 FR 22574
U214	Thallium (I) acetate	S/S or Thermal Recovery	55 FR 3891
U215	Thallium (I) carbonate	S/S or Thermal Recovery	55 FR 3891
U216	Thallium (I) chloride	S/S or Thermal Recovery	55 FR 3891

TABLE 1-1. RCRA WASTES FOR WHICH SOLIDIFICATION/STABILIZATION IS IDENTIFIED AS BEST DEMONSTRATED AVAILABLE TREATMENT TECHNOLOGY (Continued)

Code	Waste Description	BDAT Treatment/ Treatment Train	Reference
U217	Thallium (I) nitrate	S/S or Thermal Recovery	55 FR 3891
P074	Nickel cyanide	Electrolytic Oxidation + Alkaline Chlorination + Precipitation + S/S	55 FR 26600
P099	Argenate (1-), bis(cyano-C)-potassium	Electrolytic Oxidation + Alkaline Chlorination + S/S	54 FR 26600
P013	Barium cyanide	S/S (one alternative)	55 FR 22561
P103	Selenourea	S/S	55 FR 22574
P104	Silver cyanide	Electrolytic Oxidation + Alkaline Chlorination + Precipitation + S/S	54 FR 26600
P110	Tetra ethyl lead	Incineration + S/S	55 FR 22568
P113	Thallic oxide	S/S or Thermal Recovery	55 FR 3888
P114	Thallium (I) selenite	S/S	55 FR 22574
P115	Thallium (I) sulfate	S/S or Thermal Recovery	55 FR 3888
P119	Ammonium vanadate	S/S	55 FR 3888
P120	Vanadium pentoxide	S/S	55 FR 3889

applied to decrease contaminant mobility in incinerator ash, if necessary. S/S is, in many cases, the only technology that can be applied to a difficult waste form. S/S processes can treat contaminated soil or lagoon sludge either in situ or after the material is excavated and have been successfully applied in the field to treat waste. S/S processes generally use simple, relatively inexpensive equipment and are cost-competitive with other treatment options. Availability of services from a number of vendors and an established record of field performance help minimize management and regulatory barriers to acceptance of the technology.

Laboratory experiments and field experience have demonstrated the ability of the S/S matrix to decrease contaminant mobility by a combination of physical and chemical mechanisms. The exact nature of these mechanisms is, however, not well understood. Long-term testing is difficult because environmental factors affecting the wastes are not defined. The measurement of long-term environmental exposure is cumbersome at best. Accelerated tests, if available, are not calibrated against real environmental effects. Methods need to be developed for measuring the combined effects of environmental factors. However, the main difficulties are the broad variety of wastes to be treated and the commercial secrecy surrounding some of the binder systems available on the market. Without an understanding of the mechanisms and chemistry involved, it is difficult to predict the long-term performance of a binder/waste combination.

Despite its flexibility and broad appeal, S/S treatment is not appropriate for all wastes. It is generally appropriate as a treatment alternative for material containing inorganics, semivolatile and/or nonvolatile organics. S/S treatment is typically not the preferred choice in technologies for treating wastes containing only volatile organics (see Section 4.4.3). Selection of S/S treatment for waste containing semivolatile and nonvolatile organics requires a site-specific treatability study or non-site-specific treatability study data generated on waste which is very similar (in terms of type of contaminant, concentration, and waste matrix) to that to be treated. The use of an aqueous leaching methodology such as the TCLP is clearly not a meaningful indication of the degree of immobilization for low-solubility organic contaminants. Therefore, the use of a nonpolar solvent extraction (e.g., the Total Waste Analysis (TWA)) has been recommended. However, this recommendation is still under consideration by EPA because it is unclear how the results of a solvent extraction relate to the environmental mobility of a contaminant in groundwater. Also, there are few if any data that demonstrate that the chemical interaction between an S/S binder and an organic contaminant is strong enough to resist leaching by an aggressive nonpolar extractant. Therefore, one of the potential pitfalls of using S/S technology to treat waste with significant nonpolar organic contaminants is the inability to adequately assess the extent of contaminant immobilization caused by S/S treatment.

A careful treatability testing program, guided by expert knowledge, is typically required to formulate, test, and apply an S/S treatment system. The need for treatability study data and the importance of conducting appropriate leachability tests as part of the study, are mandatory if organics are present in the waste.

1.2 PURPOSE AND SCOPE

1.2.1 Objectives

This Technical Resources Document (TRD) is intended to be a user's guide, emphasizing technology transfer and promoting the best possible future uses of S/S processes. It addresses the following questions:

- When are S/S processes the preferred treatment technology?
- How do I evaluate alternative S/S processes to select the correct one?
- What are the correct and incorrect ways of using S/S processes?
- How do I design the correct process?

The specific details and approach of each waste treatment project vary, depending on the needs and circumstances of the specific project. It is not possible to prescribe the details of a specific S/S project because there are so many variables. However, some generalized procedures for S/S implementation can be defined. Applying these procedures will enhance uniformity and consistency, thus helping to overcome difficulties sometimes encountered during the application of S/S technology. As the phrase "Technical Resources Document" implies, this document is a technical resource for the S/S user community. Technical information relating to S/S is summarized throughout the text. Where the information is lengthy, references are provided to other documents to allow the reader access to more detailed background and technical information pertaining to S/S.

The document provides guidance in conducting S/S treatability studies in Chapter 2. High-quality treatability studies are an important step in the selection and optimization of an S/S treatment technology. Chapter 2 addresses the following aspects of each phase of an S/S treatability study, starting with the sampling and waste characterization phase and ending with the field demonstration phase:

- Information requirements
- Acceptance criteria
- Technology screening and testing procedures
- Sequence of activities
- Decision points

Chapter 3 is a review of analysis and test methods. Chapter 4 is a compilation of technical resources information on S/S processes, divided into 10 different sections. Chapter 5 is a discussion of S/S technology shortcomings and limitations. Chapter 6 is a description of ongoing research and a discussion of fruitful areas for further research. Chapter 7 provides bibliographic data for the references cited in the text. Appendix A consists of information checklists to provide users with guidance in planning and conducting S/S treatability studies.

Overall, the TRD gives an appraisal of S/S technology, with a "how-to" theme for technology screening. It does not address design issues or provide detailed instructions, because these are project-specific and cannot be prescribed based on generic information. For example, the TRD describes the options for pretreating waste to develop material with particle size distribution and other properties suitable to S/S treatment. However, selection of the pretreatment approach is site specific.

1.2.2 Scope

This section broadly characterizes the categories of wastes and the types of processes covered in this document.

1.2.2.1 Waste Types

As stated in Section 1.1, S/S processes have been applied to a wide variety of wastes, both hazardous and nonhazardous, nuclear and nonnuclear, inorganic and organic, liquid and solid.

The primary wastes of interest in this document are wastes regulated under CERCLA, RCRA, and other environmental laws or acts. CERCLA soils and sludges are emphasized because CERCLA technology screening and performance requirements are the most detailed. RCRA is discussed because S/S treatment is identified as BDAT for many RCRA wastes (Table 1-1).

Because the principal aim of this document is to provide information on materials covered by environmental regulation, some classes of wastes are not addressed. Aqueous wastes contaminated with organics and/or metals are not covered. Nuclear wastes, which are regulated by the U.S. Nuclear Regulatory Commission (NRC) rather than the U.S. EPA, are not specifically addressed in the TRD. However, the large body of literature on nuclear S/S technology provides an important resource (Kibbey et al., 1978), and much of the S/S technology developed by the nuclear community is applicable to EPA-regulated wastes. Mixed wastes are not specifically discussed in this document; however, S/S technologies may be applicable to these wastes. For example, liquid radioactive and hazardous tank wastes have been stabilized with a cement-based system that satisfies EPA's hazardous waste regulations and U.S. Department of Energy long-term performance criteria (Peek and Woodrich, 1990).

1.2.2.2 Processes

S/S technology includes many classes of immobilization systems and applications; example classes include inorganic binders or organic binders, low-temperature processes (e.g., pozzolanic) or high-temperature processes (e.g., vitrification), in situ applications or ex situ applications, and S/S as a sole treatment technology or as a component of a treatment train. The scope of this TRD specifically excludes only vitrification and the formation of ceramics, which involve the application of very high temperatures

(>1,500-°F). Vitrification is discussed in a separate U.S. EPA guidance document currently under preparation [bibliographic citation needed].

1.2.3 Audience

This document is intended for persons planning or applying S/S processes to hazardous waste management. The document describes the treatability testing and project planning approach leading to selection of an effective S/S technology and gives technical background on S/S treatment methods. It is intended to provide technology transfer to persons responsible for selection and design of S/S treatment methods. Information about S/S technology is presented in detailed text descriptions supported by summary tables, checklists, and figures to introduce users who are unfamiliar with S/S technology to the key concepts. The tables, checklists, and figures also serve as a ready reference for experts.

1.2.3.1 CERCLA Applications

For CERCLA projects, the users of the TRD may include responsible parties (RPs), Remedial Project Managers (RPMs), contractors, and technology vendors. Each has a different role in designing, conducting, and evaluating S/S process testing and selection under CERCLA, as described below.

Currently, RPs plan and manage clean up at approximately half of the Superfund sites. At enforcement sites, RPs are responsible for planning and executing S/S process testing and evaluation under federal or state oversight.

RPMs perform planning and oversight of the remediation. Their role in treatability investigations depends on the designated lead organization (federal, state, or private). Their activities generally include scoping the treatability study, establishing the data quality objectives, selecting a contractor, issuing a work assignment, overseeing the execution of the study, and informing or involving the public as appropriate.

Treatability studies for S/S process testing and evaluation are generally performed by remedial contractors or technology vendors. Their roles in treatability investigations include preparing work plans and other supporting documents, complying with regulatory requirements, executing the study, analyzing and interpreting the data, and reporting the results.

The RPs, RPMs, contractors, and vendors participate in identification of proposed response action, technology screening, development of remedial action alternatives, and evaluation of remedial action alternatives. The TRD provides S/S process-specific information to assist users through the CERCLA planning process.

1.2.3.2 RCRA Applications

Technology screening at RCRA treatment facilities is driven by the regulations, the specific technologies available at the facility, and the permit conditions. A treatment facility probably has one or more specific immobilization technologies in place with a menu of permitted treatment options available (U.S. EPA, 1989b). Consequently, screening at a RCRA TSD facility means determining whether each proposed waste is treatable by the available permitted immobilization technology. The criterion for satisfactory treatability is the ability of the treated waste to pass all the required tests for acceptance for disposal. The TRD will help RCRA TSD facility operators and engineers match wastestreams to S/S treatment options, design treatability studies, and select test methods. It also will help generators of characteristically hazardous waste who treat their waste to remove the requirements for Subpart C disposal.

1.3 REGULATORY CONSIDERATIONS

This section is intended to provide a brief introduction to the major regulatory considerations for S/S. Due to the complexity of the regulations, this discussion does not attempt to be comprehensive, but rather provides an overview of the regulatory framework within which S/S is generally applied. It is very important for anyone considering the use of S/S treatment to consult the regulatory agencies that have authority over that waste. State and local regulations may vary widely, and implementation of regulatory requirements is often developed on a site-specific basis, particularly in the case of Superfund sites.

1.3.1 Regulatory Framework

Cleanup and disposal of hazardous wastes are regulated primarily by two federal laws and their amendments.

First is the Resource Conservation and Recovery Act of 1976 (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA). These give EPA authority to regulate disposal of hazardous waste and set standards for treatment.

The second major law regulating hazardous waste is the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986. CERCLA regulates the cleanup of spilled materials and abandoned hazardous waste sites.

Generally, CERCLA sites are not regulated by RCRA directly. However, CERCLA Section 121(d)(2) requires that Superfund response actions comply with other environmental laws that are applicable or relevant and appropriate requirements (ARARs) (U.S. EPA, 1989c). Determination of ARARs is site-specific. If portions of RCRA regulations constitute ARARs, then these regulations apply to the Superfund sites.

1.3.2 RCRA Land Disposal Restrictions

The part of RCRA that most affects the use of S/S is that related to the Land Disposal Restrictions (LDRs), also referred to as "landban." The LDRs were included in RCRA as part of the Hazardous and Solid Waste Amendments (HSWA) of 1984 following a growing concern that hazardous waste being disposed in the ground (such as in a landfill) would eventually be released into the environment despite containment efforts. Under HSWA, land disposal of hazardous waste is prohibited unless it has been treated first. U.S. EPA is required to establish treatment standards for each type of RCRA hazardous waste. The RCRA definition of "land disposal," or "placement," includes but is not limited to:

> any "placement" of hazardous waste in a landfill, surface impoundment, waste pile, injection well, land treatment facility, salt dome formation, salt bed formation, underground mine or cave, and concrete bunker or vault. (RCRA 3004(k))

LDRs apply only to wastes that are land-disposed after the effective date of the restrictions. That is, the LDRs do not require that wastes land-disposed prior to the date of the restrictions be removed and treated.

However, wastes being treated under CERCLA remedial response actions may still fall under the land disposal restrictions if RCRA regulations apply as ARARs.

As discussed above, U.S. EPA has established three types of LDR treatment standards (U.S. EPA, 1989c), specified in 40 CFR Part 268:

a. A concentration level to be achieved prior to disposal of the waste or treatment residual (the most common type of treatment standard)

b. A specified technology to be used prior to disposal, or

c. A "no land disposal" designation when the waste is no longer generated, is totally recycled, is not currently being land disposed, or no residuals are produced from treatment.

Treatment standards are established on the basis of the Best Demonstrated Available Technology (BDAT) rather than on risk-based or health-based standards. "Best" is defined as the technology that offers the greatest reduction of toxicity, mobility, or volume of the waste. To be "demonstrated," a treatment technology must be demonstrated to work at a full-scale level, as opposed to bench-scale or pilot-scale. "Available" means that a technology is commercially available. S/S has been identified as BDAT for a variety of waste codes. These waste codes are listed in Table 1-1.

The majority of LDR treatment standards promulgated to date specify concentration levels. For wastes with treatment standards expressed as concentrations, any technology that can achieve the required concentration-based levels may be used (i.e., the BDAT used by U.S. EPA to set the standards is not the required technology). To establish a concentration level(s) for a specific waste code, U.S. EPA selects a subset of the hazardous constituents found in the waste (known as "BDAT constituents") and sets treatment standards for each of these constituents. Although the waste may contain additional constituents, only the treatment standards for the "BDAT constituents" must be met before the wastes can be land-disposed. The residues from treatment of an originally listed waste (e.g., ash or scrubber water) are also listed RCRA hazardous wastes (because of the "derived from" rule), and are therefore also prohibited from land disposal unless they meet the treatment standards for the waste code of the original listed waste from which they derive (U.S. EPA, 1989d). Separate standards are established for wastewaters and nonwastewaters.

If a treatment standard is promulgated as a specified technology, that technology must be used to treat the waste unless an Equivalent Treatment Method Petition is approved by U.S. EPA. To be granted, the petition must demonstrate that the alternative technology achieves an equivalent measure of performance.

Sometimes, both a concentration standard and a treatment standard apply to the same waste code. When this is the case, the two standards usually address different contaminants in that waste. Generally, the technology-based treatment is applied first, then the waste is tested for the concentration and further treatment is applied if necessary to meet the concentration-based standard.

U.S. EPA recognized that not all wastes can be treated to the LDR treatment standards and that alternative treatment standards and methods of land disposal may provide significant reduction in the toxicity, mobility, or volume of wastes and may be protective of human health and the environment. The LDRs therefore provide the following compliance options to meeting the restrictions discussed above:

- Treatability Variance: This option is available when U.S. EPA has set a treatment standard as a concentration level, but because a generator's waste differs significantly from the waste used to set the standard, the promulgated treatment standards cannot be met or the BDAT technology is inappropriate for that waste. (For the purposes of the LDRs, CERCLA site managers are considered generators of hazardous waste.) Under a treatability variance, U.S. EPA approves an alternative treatment standard that must be met before that waste can be land-disposed.

- Equivalent Method Petition: This option is available when U.S. EPA has set a treatment standard that specifies a technology (e.g., incineration). Generators may use a different technology (e.g., chemical treatment) if they can demonstrate that this technology will achieve a measure of performance equivalent to that of the specified technology.

- No Migration Petition: This option may be used to meet any of the four types of LDR restriction. Generators may land-dispose of wastes that do not meet the LDR restriction if they can demonstrate that no hazardous constituents above health-based levels will migrate from the disposal unit or injection zone for as long as the wastes remain hazardous.

- Delisting: This option may be used to demonstrate that a waste is nonhazardous and therefore not subject to any of the RCRA subtitle C hazardous waste regulations, including the LDRs. Delisting only applies when the CERCLA waste is a listed RCRA hazardous waste. Characteristic wastes need not be delisted, but they must be treated to no longer exhibit the characteristic before they can be considered nonhazardous. Generators must demonstrate that (1) the waste does not meet any of the criteria for which the waste was listed as a hazardous waste; and (2) other factors, including additional constituents, do not cause the waste to be hazardous.

1.3.3 Application of Land Disposal Restrictions to CERCLA Sites

CERCLA Section 121(d)(2) specifies that on-site Superfund remedial actions shall attain "other Federal standards requirements, criteria, limitations, or more stringent State requirements that are determined to be legally applicable or relevant and appropriate (ARAR) to the specified circumstances at the site" (U.S. EPA, 1989d). In addition, the National Oil and Hazardous Substances Contingency Plan (NCP) requires that on-site removal actions attain ARARs to the extent practicable. Off-site removal and remedial actions must comply with legally applicable requirements.

For LDRs to be applicable to a CERCLA response, the action must constitute placement of a restricted RCRA hazardous waste. Therefore, the CERCLA site manager must answer these three questions:

1. Does the response action constitute placement?
2. Is the CERCLA substance being placed also a RCRA hazardous waste?
3. Is the RCRA waste restricted under the LDRs?

With respect to the first question, if the waste is transported off site and placed in a land disposal unit as defined by RCRA (landfill, surface impoundments, waste pile, injection well, land treatment facility, salt dome formation, underground mine or cave, concrete bunker, or vault), placement occurs. On-site disposal of wastes is often less well defined. U.S. EPA uses the concept of "areas of contamination" (AOCs), which are viewed as the equivalent of RCRA units to determine if LDRs apply. An AOC is delineated by areal extent of contiguous contamination. Such contamination must be continuous, but may contain varying types and concentrations of hazardous substances (for example, a waste source such as a waste pit, landfill, or pile, and the surrounding contaminated soil). For on-site disposal, placement occurs when wastes are moved from one AOC into another. Examples of placement include consolidation of wastes from different AOCs into a single AOC, or excavation from an AOC for treatment in a separate unit such as an incinerator or tank that is within the AOC followed by redeposit into the same AOC. Placement does not occur when wastes are left in place or moved within a single AOC (for example, treatment in situ, capping in place, or processing within the AOC — but not in a separate unit such as a tank — to improve structural stability).

The second question entails determining whether the CERCLA substance is a RCRA hazardous waste. Site managers are not required to presume that a substance is a RCRA hazardous waste unless there is affirmative evidence to support such a finding. There are two types of RCRA wastes: listed wastes (those waste types or compounds specifically listed in 40 CFR Part 261) and characteristic wastes (wastes exhibiting the characteristics of ignitability, corrosivity, reactivity, or toxicity, as defined in 40 CFR Part 261). Information on the source, prior use, and process type is usually required and can be obtained from facility business records or examination of processes used at the facility.

In addition to the two categories of RCRA wastes, three principles may apply:

- The "derived from" rule
- The "mixture rule"
- The "contained in" interpretation

First, the "derived from" rule (40 CFR 261.3(c)(2)) states that any solid waste derived from the treatment, storage, or disposal of a listed RCRA waste is also a listed waste, regardless of the concentration of hazardous constituents. For example, ash and scrubber water from incineration of a listed waste are hazardous on the basis of the derived-from rule. However, wastes derived from a characteristic waste are hazardous only if they exhibit the characteristic.

Another principle is the "mixture rule" (40 CFR 261.3(a)(2)). Under this rule, when any solid waste and a listed hazardous waste are mixed, the entire mixture is a listed hazardous waste. Mixtures of solid wastes and characteristic hazardous wastes are hazardous only if the mixture exhibits a characteristic.

The third principle is the "contained in" interpretation (Office of Solid Waste Memorandum dated November 13, 1986). Under this interpretation, any mixture of a nonsolid waste and a RCRA-listed hazardous waste must be managed as a hazardous waste as long as the material contains (i.e., is above health-based levels of) the listed hazardous waste. For example, if soil or groundwater contains a listed hazardous waste, that soil or groundwater must be managed as a RCRA hazardous waste as long as it "contains" the waste.

If a waste is a RCRA-listed hazardous waste, a "derived from" waste, or a mixture of a listed waste and a solid waste, the waste must be delisted in order to be exempted from the RCRA system. Characteristic wastes need not be delisted, only treated to no longer exhibit the characteristic. A "contained in" waste also does not have to be delisted; it only has to no longer "contain" the hazardous waste.

If the answers to the first two questions determined that placement will occur and that the waste is a RCRA hazardous waste, the third step is to determine applicability of the landbans as specified by the treatment standards promulgated in 40 CFR Part 268. If treatment standards have been promulgated for the waste in question, the landbans apply and the waste must be treated in accordance with these standards. For several of these standards the BDAT used to derive the standard is S/S.

1.3.4 Toxic Substances Control Act

The Toxic Substances Control Act (TSCA) regulates numerous toxic chemicals, many of which are not commonly encountered in hazardous waste. However, one group of compounds that is regulated under TSCA — polychlorinated biphenyls (PCBs) — is a fairly common type of contaminant at Superfund sites. PCB-containing wastes (other than the California List Wastes) — for example, liquids that contain both PCBs above 50 ppm and RCRA hazardous wastes —

generally require cleanup when the total PCB levels are greater than 50 ppm. However, 40 CFR 761.120(a)(1) excludes spills that occurred prior to May 4, 1987, from the scope of the U.S. EPA's PCB Spill Policy. The U.S. EPA recognizes that old spills require site-by-site evaluation because of the likelihood that the site involves more pervasive PCB contamination than fresh spills, and because old spills are generally more difficult to clean up than fresh spills (particularly on porous surfaces such as concrete). Therefore, spills that occurred before May 4, 1987, are to be decontaminated to requirements established at the discretion of the U.S. EPA, usually through its regional offices.

1.3.5 Other Environmental Regulations

In addition to RCRA, CERCLA and TSCA, other environmental legislation may be applicable to the use of S/S:

- The Clean Water Act regulates the discharge of liquid effluents to waters of the U.S.
- The Clean Air Act regulates the release of pollutants into the air.
- The Safe Drinking Water Act controls levels of pollutants in drinking water and regulates underground injection wells.
- The Occupational Safety and Health Act regulates exposure of workers to toxic substances and harmful work practices.
- State and/of local regulations pertaining to hazardous wastes, which may be more stringent than the federal regulations.

In the event that S/S produces effluents or conditions which fall under the jurisdiction of one or more of these acts, compliance would be required. As noted at the beginning of this section, consultation with all cognizant regulatory officials responsible for a particular waste or site is advised before undertaking treatment.

2 SOLIDIFICATION/STABILIZATION (S/S) TECHNOLOGY SCREENING PROCEDURES

2.1 INTRODUCTION

2.1.1 Overview

The process of technology selection, evaluation, and optimization is frequently referred to as "technology screening." A treatment technology that has been properly screened prior to full-scale implementation has the highest probability of success in the field.

This chapter provides guidance on the S/S technology screening process and the steps needed to select and test an appropriate S/S process for each waste type. Figure 2-1 shows the major steps in the technology screening process and their order of implementation. Sections 2.2 through 2.8 correspond to each of these major steps.

Sections 2.2 through 2.4 describe activities that must be undertaken before conducting treatability studies. Section 2.2 discusses the fundamental information requirements for characterizing the waste, including guidance on waste sampling. An example of a Sampling and Analysis Plan is provided in Appendix B. Section 2.3 addresses the need for, and issues related to, establishing S/S treatability performance objectives or acceptance criteria. Regulatory, technical, and institutional requirements are discussed, and an approach for setting performance criteria is presented. Section 2.4 overviews the generic technology screening process leading to the selection of S/S rather than other types of technologies and references documents offering more detail on this subject.

Sections 2.5 through 2.8 describe in detail each of the tiers of treatability testing for S/S processes. Section 2.5 addresses waste/binder compatibility screening. Section 2.6 discusses laboratory screening of waste/binder mixtures, including binder screening and optimization. Section 2.7 addresses bench-scale performance testing, and Section 2.8 discusses pilot-scale testing. During each sequential tier of treatability testing, the testing becomes more specific to the individual waste form.

Three points relating to the technology screening process (Figure 2-1) are emphasized:

- The screening process often requires several iterations through some or all of the steps.

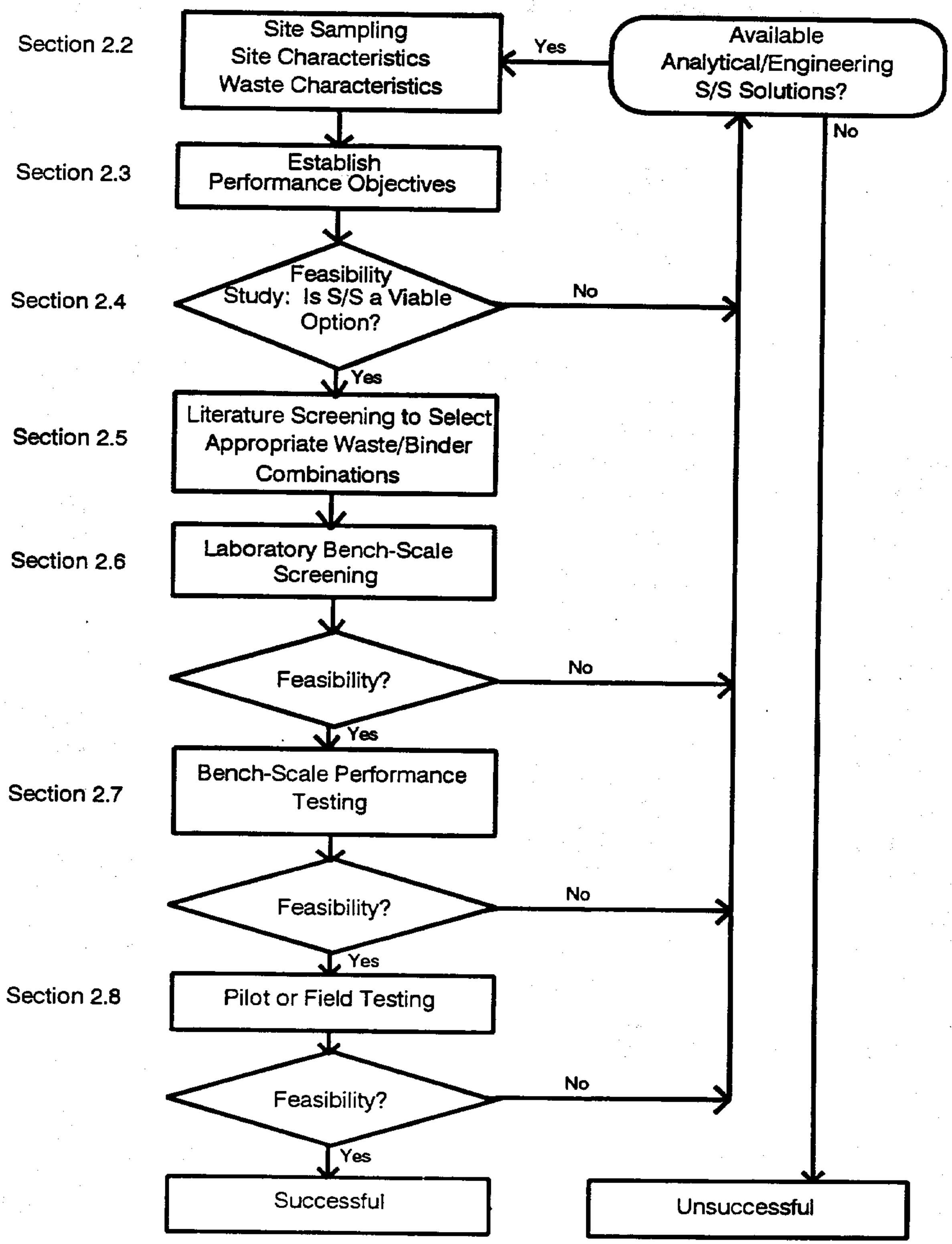

FIGURE 2-1. SOLIDIFICATION/STABILIZATION TECHNOLOGY SCREENING

A decision point occurs at the end of each step, and, depending on the outcome of the analysis, it may be necessary to return to an earlier stage of the screening process, modify the approach, and repeat one or more steps.

- The screening process must be flexible. Project-specific circumstances require a flexible approach because not all projects have the same set of needs and resources. Under certain circumstances it may be prudent to skip steps or entire sequences of steps. For example, minimal or even no treatability testing might be required for a well-developed S/S process applied to a simple waste. Project-specific resource limitations may also indicate the need to eliminate certain steps. In designing each treatability study, procedural decisions will have to be made based on the trade-offs of the various alternatives. Eliminating various steps in the technology screening procedure can reduce the likelihood of successful technology application; the party responsible for the treatability study must evaluate the risk associated with eliminating such steps.

- In the event that, during treatability testing, S/S appears not to be feasible (i.e., certain critical performance goals are not being achieved), then it may be advisable to return to an earlier step in the screening process and repeat the screening procedure using a different approach or a different set of assumptions. For example, perhaps a completely different binder type should be tested, or the waste should be pretreated prior to S/S. Unsuccessful S/S treatability studies are not uncommon, but technical deficiencies can frequently be overcome by testing different binders or by modifying the S/S process.

2.1.2 <u>The Need for Treatability Studies</u>

Treatability studies provide valuable site-specific data needed to select and implement the appropriate remedy. The Remedial Investigation/Feasibility Study (RI/FS) interim final guidance document (U.S. EPA, 1988a) specifies nine evaluation criteria for use in analyzing alternatives. Treatability studies can address seven of these criteria:

- Overall protection of human health and the environment

- Compliance with applicable or relevant and appropriate requirements (ARARs)

- Implementability
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Cost
- Long-term effectiveness

The other two criteria affecting the evaluation and selection of the remedial alternative – community and state acceptance – can influence the decision to conduct treatability studies on a particular technology.

Treatability studies should be conducted by individuals or groups with the proper expertise and training. These may include research laboratories, universities, S/S vendors, or treatability vendors. EPA (1990a) provides a compilation of vendors qualified to perform S/S treatability studies and indicates the types of media and contaminant groups in which the firms are experienced.

Several documents provide varying levels of guidance on the design and conduct of treatability studies. For example, U.S. EPA (1989e) provides generic guidance for conducting treatability studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in the context of the RI/FS process and the preparation of the Record of Decision (ROD). The guidance, which is not specific to any technology, includes a discussion of planning documentation and data quality objectives. A related draft document (U.S. EPA, 1990b) provides generic treatability study guidance under CERCLA on S/S technology for inorganic contaminants. Other technology-specific treatability guides have been or are in the process of being published for soil washing, aerobic biodegradation, soil vapor extraction, chemical dehalogenation, solvent extraction, and thermal desorption. An example of a facility-specific guidance document is Barth and McCandless (1989), which outlines S/S treatability testing procedures for U.S. EPA's Center Hill Research Facility. All of these documents supplement information contained in this chapter and should be consulted for appropriate levels of guidance.

2.2 SITE-SPECIFIC BASELINE INFORMATION REQUIREMENTS

The purpose of this section is to discuss the information requirements for technology screening, which are presented in five subsections: Waste Sampling, Waste Acceptance (the acceptability of the waste at the treatability or analytical laboratory in terms of compliance with applicable permits and other requirements), Waste Characterization, Site Characterization, and Quality Assurance/Quality Control (Sections 2.2.1 through 2.2.5). Figure 2-2 presents the sequence of information collection steps. Initially, preliminary characterization of the waste is needed to support preliminary decisions about the use of S/S and waste acceptability at the test facility. This information is also used to determine appropriate worker protection provisions for waste sampling. Information for preliminary characterization is usually available from remedial investigation (RI) studies if the waste is from a CERCLA site or from other historical records or testing. The RI studies generally do not provide enough information to determine appropriateness of S/S; therefore, additional waste sampling is required to support a waste-specific determination of the appropriateness of various treatability approaches. If the waste is not acceptable at the testing facility, the project cannot proceed until the problem is resolved. In Section 2.2.6, Table 2-6 briefly outlines guidance on site-specific baseline information needs.

2.2.1 Waste Sampling

The principal objective of waste sampling is to obtain waste samples for analysis and treatability testing that are representative both of the waste as a whole, and of the extremes of waste composition ("hot spots"), which can be used for worst-case testing. This can be accomplished in several ways, as described in Section 2.2.1.1. It is also important to obtain a sufficient number of samples and volume of sample to satisfy the analytical and bench-scale testing requirements, because repeat sampling can be expensive and undesirable.

2.2.1.1 Composites vs. Hot Spots

Many factors affect site sampling. This document is not intended to provide complete coverage of the many reports that should be referred to for guidance regarding sampling strategies and collection and preservation

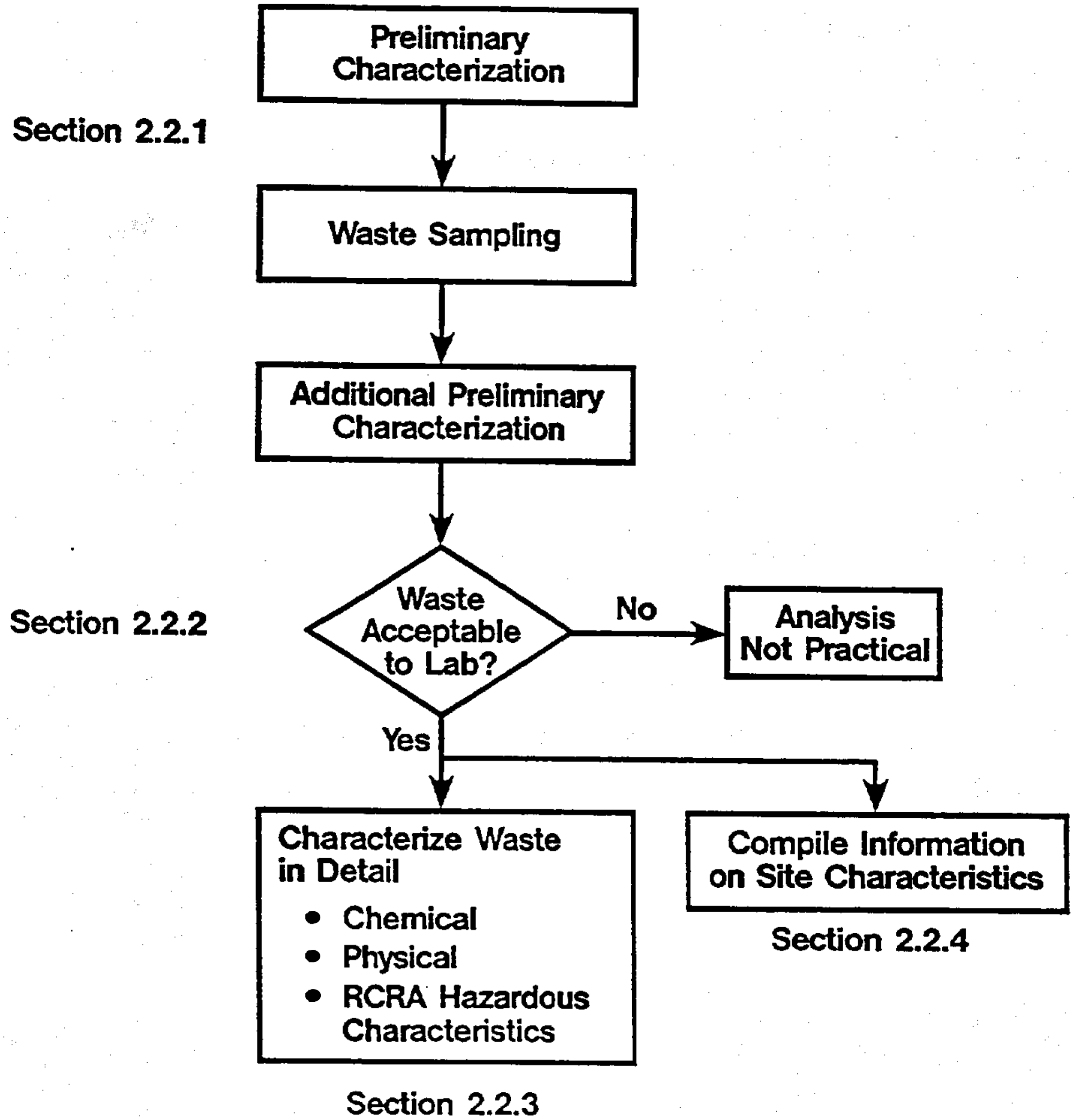

FIGURE 2-2. INFORMATION COLLECTION STEPS IN THE TECHNOLOGY-SCREENING PROCESS

requirements. Such documents include an EPA soil sampling quality assurance document (U.S. EPA, 1989f), EPA's Solid Waste Test Method Manual, commonly referred to as SW-846 (U.S. EPA, 1986a), Conner (1990, Chapter 17), and U.S. EPA (1989e). A sampling technique developed by U.S. EPA Region 10 especially for S/S treatability studies has been shown to be very effective (U.S. EPA Region 10, 1200 Sixth Avenue, Seattle, WA, (206) 442-5810). The discussion that follows emphasizes several issues applicable to sampling for S/S treatability studies.

Prior to detailed sampling, historical records or a grab sample should be used to determine whether the waste can be sampled safely. The waste material should be surveyed to determine the necessary sampling apparatus and the procedures that must be used. Also, some analytical data should be available at this point to determine the appropriate level of personal protective equipment.

As indicated in Section 2.2.1, the principal objective of the sampling activity is to obtain waste samples that are representative of the waste as a whole (in terms of both chemical and physical characteristics) and that are collected in sufficient quantity to permit all the necessary analytical tests to be conducted. Representativeness is crucial but difficult to quantify (U.S. EPA, 1989f). The two approaches to achieving representativeness are as follows:

- Combine samples from a wide range of sampling locations both vertically and spatially to produce a single composite sample that represents the "overall average." A variation of this approach would include compositing the subset of samples with the highest target contaminant levels to produce a "worst-case composite" for bench-scale testing. However, if S/S treatment is applied in batches, combining samples would not represent high-concentration areas that could occur in a particular batch.

- Collect samples from a wide range of locations but do not composite. Analyze samples individually and select the "hot spots" for subsequent bench-scale testing.

Both approaches have advantages and disadvantages. Compositing samples may be more appropriate when (1) a batch-mixing system is to be used in the field or treated samples are to be composited prior to analysis or (2) the primary purpose in conducting the treatability study is to compare stabilization with some other completely different treatment process. In the latter case, the waste needs to be uniform to ensure comparability. Also, wastes that are already contained in barrels are usually sampled by compositing.

The "hot spot" approach may be more appropriate when a continuous flow-through mixing system such as a pug mill is employed, or when the process will be applied to in situ waste. The composite approach risks overlooking the zones of unusually elevated contaminant or interferant concentrations that may cause the process to fail to satisfy its performance criteria. On the other hand, the "hot spots" may be difficult to define for complex waste forms and may lead one in the direction of an unnecessarily expensive S/S process. The issue is sufficiently complex that an expert system would be needed to sort out all the variables and point to the preferred approach for each individual case. The logic used in selecting samples for treatability studies will be examined by the regulatory authority before accepting test results.

The amount of sample collected should be adequate to satisfy the needs of the waste acceptance, waste characterization, bench-scale screening, and performance testing activities and should include a suitable quantity to be archived for possible later use. One RCRA-permitted facility typically uses 130 kg as the rule of thumb (Barth and McCandless, 1989). This includes about 110 kg for testing and an additional 20% safety margin.

Nonpermitted facilities can perform treatability tests under the treatability study exemption (40 CFR 261.4). However, these facilities are limited to a total of 1000 kg of waste in the facility at one time. Therefore, the testing facility may be reluctant to accept unnecessarily large quantities of sample, particularly if they are performing treatability studies for more than one client.

One possible solution that allows collection of larger quantities of sample is to hold the sample at the site and ship batches to the test facility as needed. Generally, at least 10 kg of sample is needed to provide enough sample to test; however, it is important to be sensitive to the 1000 kg limit.

In practice, sample quantity needs will vary from project to project, depending on the size of the waste material, the complexity of waste chemistry, QA/QC requirements, and the binder to be used. Other factors affecting sample volume requirements cannot be known beforehand.

2.2.1.2 Statistical Approaches

It should be emphasized that sampling in support of S/S treatability studies encompasses more than the usual soil or waste sampling undertaken in RI studies at a Superfund site. It is important that the samples are adequately sized and representative. Since wastes may be found in diverse locations and physical states, each sampling routine should be designed to fit the waste and the situation. Wastes to be treated with S/S may occur as nonhomogeneous mixtures in stratified layers or as poorly mixed conglomerates. For such wastes it is particularly important to have a carefully assessed, well-planned, and well-executed sampling routine to ensure that samples are representative. For example, wastes stored in surface impoundments with stratified sludges and covered by wastewater, would probably require samples of the wastewater, the sludges, and the soil beneath the sludges. Additional information on sampling plans can be found in the ASTM Standard Guide for General Planning of Waste Sampling (ASTM-D-4687-87).

Cost is an important factor in determining the extent of sampling. Involvement of a statistician knowledgeable in sample design can help to minimize cost by ensuring that the samples are collected in the most efficient way so as to provide adequate information for statistical analysis of the results.

Sampling for S/S must address four areas, depending on the specific needs of the treatability study and regulatory requirements:

- Chemical composition of the untreated waste
- Physical properties of the untreated waste
- Process control sampling (U.S. EPA, 1990b)
- Quality assurance/quality control (QA/QC) representativeness and accuracy

The first two areas of sampling apply to all S/S treatability studies. However, sampling for process control applies only to pilot-scale studies and to the actual S/S remedial operation.

Assessment of the chemical composition and physical properties of wastes in S/S treatability studies typically is based on a limited number of field measurements. However, the variability of field measurements can be quite complex. This variability is compounded by several factors such as measurement uncertainty, field heterogeneities (e.g., in soil and water properties), and sampling variability. In cases where decisions must be made from highly variable data, it is crucial that the information upon which the decisions are based be obtained from samples that are selected through the use of statistical sampling design procedures. There are at least three important purposes for statistical sampling design:

- to ensure that the sampling is representative
- to provide numerical estimates for decision making that have quantifiable error limits
- to improve sampling efficiency (i.e., to provide estimates that are precise enough at the lowest possible cost)

The design steps for selecting field sampling locations, measurements, and data analyses for S/S treatability studies are similar to those described by other authors for environmental monitoring of chemicals (Keith, 1988; Gilbert, 1987). These five steps can be summarized as follows:

1. Define the sampling zones, sampling frames, and variables(s) of interest.
2. Define a general sample collection strategy for each sampling zone.
3. Develop a statistical model and statistical sampling objectives for each sampling zone.
4. Specify the estimation and/or testing procedures to be employed and their desired statistical properties.
5. Select the sampling design parameters to achieve the desired statistical properties.

The "sampling zone" refers to the specific waste area that must be characterized, typically a contaminated soil body or waste accumulation. The "sampling frame" then refers to the complete set of potential sampling units (e.g., soil grab samples or core samples) that make up the sampling zone. Each sampling objective must be related to a specific variable that can be measured on every sampling unit (e.g., waste sample, soil sample, water sample). In this way, each objective can be stated in terms of the measured variable and some summary value across the entire sampling zone, such as an average value or a maximum value. Generally, a variety of physical, chemical, and biological properties (e.g., soil moisture, pH, and chemical concentrations) can be measured on each collected sample.

The "sampling strategy" specifies the general method, such as systematic, random, or stratified random, by which sampling locations will be selected. However, establishing the sampling strategy for a particular zone describes the final sampling plan only in general terms. To lay out the specific sampling plan in each zone, the number and locations of samples need to be clearly defined in terms of several sampling design parameters. The "statistical properties" of the sampling design, such as estimation precision, are then a function of these parameters. Examples of design parameters for a monitoring program are as follows: number of sampling locations, number of replications, grid configuration and orientation, sampling times, and measurement precision. If wastes are present in stratified layers such as in a lagoon or waste pit, the depths at which samples are taken will be important to the sample design.

After establishing the sampling frame and variable(s) of interest for each sampling zone, an appropriate mathematical model should be selected to describe the anticipated statistical properties of the measured values. It is important that a knowledgeable statistician be involved in both sample design and model selection. The sampling objectives for each zone can then be refined and restated in terms of the variables and parameters of the statistical model. For every sampling objective, the estimation and inference procedures to be employed must be stated clearly and referenced. Generally, these procedures will involve either estimating of parameter values for the statistical model or testing a statistical hypothesis about the parameter values.

Some examples of mathematical models commonly used in environmental assessments and S/S treatability studies are listed below:

- Gaussian (Normal) Model - used to estimate the average of some characteristic of the waste (e.g., average concentration in soil of a specified contaminant); estimator is the arithmetical average of the measured data.

- Lognormal Model - used to estimate the median of some characteristic of the waste; this model is less sensitive to outlier data than the Gaussian model; estimator is the antilog of the average of the log-transformed data.

- Binomial Model - used to estimate proportions of some characteristic of the waste (e.g., fraction of the waste where the concentration of a contaminant is above a specified threshold); estimator is a sample proportion calculated by comparing measured data to the specified threshold.

Data quality objectives can then be established at levels that make possible reliable decision-making about the chemical and physical properties of the waste from the sampling results. From a sampling design point of view, determining the desired quality of the data amounts to setting requirements for the statistical performance of the selected estimation and inference procedures. Once the data quality objectives have been determined, the specific sampling plan can be established by setting the number of samples, replications, etc. required to satisfy the data quality objectives.

For example, a data quality objective for a particular study might be to assess the waste for the average concentration of a toxic metal (e.g., mercury) in the waste to within an error of plus-or-minus 20%. Using the properties of the mathematical model, the statistician can easily determine the minimum number of samples required to satisfy the data quality objective. It is often useful to have the statistician prepare a table relating different sample sizes to the corresponding statistical confidence levels, so that sampling costs can be controlled by trading off resources available against confidence required.

2.2.2 Waste Acceptance

Waste acceptance involves analyzing a representative subsample to determine compliance with existing facility permits for the laboratory where subsequent analytical and bench-scale testing is to occur and to screen waste for the safety of facility personnel. The primary issue here is that S/S treatment in the field usually involves close contact between workers and the waste, and there are types of waste that may be too toxic to permit either the laboratory or field operations to be conducted safely. Such wastes are screened from further consideration as a candidate for S/S treatment at this point. Less toxic materials can be handled by nonpermitted facilities if they have a treatability study exemption (40 CFR 261.4 (f)(4)).

A representative subsample of the untreated waste must undergo chemical analysis before being shipped to the analytical or bench-scale testing facility (or facilities) to meet U.S. Department of Transportation (DOT) shipping requirements and to demonstrate compliance with existing facility permits, permit exclusions for treatability studies, and/or Health and Safety Plans. Problematic constituents include dioxins, furans, radionuclides, and excessive levels of PCBs or cyanide. In addition, there may be applicable DOT pre-shipment requirements and hazardous waste manifest or driver certification requirements that must be satisfied during shipping. In addition, even if the waste does not present an unacceptable degree of hazard at a permitted laboratory or test facility, it may present health or safety problems for workers in the field during the full-scale S/S treatment. The potential for this type of situation should also be assessed (U.S. EPA, 1990b).

2.2.3 Waste Characterization

The purpose of this section is to provide a brief overview of the various waste types and contaminants and their suitability for treatment with S/S technology. Industrial wastes include a wide variety of materials, both hazardous and nonhazardous. The wastes may come from various types of industries such as manufacturing, chemical production, petroleum refineries, or power production. These wastes typically include materials such as sludges, spent cleaning materials, pickle liquors, plating wastes, and combustion residues. Many of these wastes are complex mixtures that cannot be categorized easily. Table 2-1 lists generic wastes under broad industrial groupings. These generic waste types are not all amenable to S/S treatment but are presented to illustrate the types of industrial wastes encountered in practice. S/S processes are generally used to treat sludges or contaminated soils. Major producers of hazardous sludge include private industries,

TABLE 2-1. GENERAL INDUSTRIAL WASTE CATEGORIES

Industry	Waste category or source
Automobile	Automobile assembly wastes, foundry plant wastes, neutralized pickle liquors, treated plating wastes, treatment plant wastes
Chemical	Acids, alkalies, metal-containing sludges, treatment plant sludge
Chemical cleaning	Spent cleaning solutions
Dredging	Contaminated dredge spoils
Food processing	Biological treatment sludges
Leather tanning and finishing	Biological treatment sludges, metal-containing sludges
Metal finishing and major appliance	Dissolved metal solutions, pickle liquors, rinse water neutralization sludge, treatment plant sludge
Municipal	Sewage sludges, water treatment sludges
Nonferrous metals	Air pollution control (APC) dust and sludges, lime/limestone wet scrubber sludge, waste pickle liquors, water treatment sludge
Paint and painting	Metal pickling and cleaning wastes, paint sludges
Pharmaceutical	Biological treatment sludge, filter cake, spent carbon
Plastic and rubber	Biological treatment sludge, metal-containing sludge
Pollution control	APC sludges, general spent activated carbon, spent resins, water treatment plant sludges
Power	Fly ash, lime/limestone scrubber sludges, boiler cleaning solutions
Pulp and paper	Biological treatment sludges, spent clay and fibers
Refinery and petrochemical	American Petroleum Institute oil/water/sludge mixtures, biological treatment sludge, spent lime sludges
Sanitary landfill	Landfill leachates
Steel	APC dust and sludges, metal fines, scale pit sludge, waste pickle liquors, water treatment sludge
Textile	Biological treatment sludges, metal-containing sludges

Reprinted from: Conner, J. R. 1990. *Chemical Fixation and Solidification of Hazardous Wastes.* Van Nostrand Reinhold, New York. pp. 267-268. Used by permission of Van Nostrand Reinhold.

utility companies, and water/wastewater treatment plants. Waste types can be broadly categorized under a variety of hazardous waste regulations.

2.2.3.1 Regulatory Framework

One major waste type considered in this document is wastes covered by CERCLA (see Section 1.3.) Hazardous substances under CERCLA are broadly defined and include a wide variety of materials. The concept of "hazardous substances" under CERCLA is defined with reference to all of the major federal environmental statutes. Approximately 700 elements, compounds, and waste streams are designated as "hazardous substances" under CERCLA (40 CFR 302.4) by virtue of their regulation under one or more of these other environmental statutes. However, petroleum, natural gas, natural gas liquids, liquefied natural gas, and synthetic gas usable for fuel are excluded from the definition of "hazardous substances" under CERCLA.

Hazardous wastes that are covered by the Resource Conservation and Recovery Act (RCRA) are defined in the regulations specified in 40 CFR Part 261. Such wastes are either "listed wastes" or "characteristic wastes," as discussed in the following paragraphs (see also Section 1.3).

"Listed wastes" are specific chemicals or specific types of wastes listed in 40 CFR Part 261 Subpart D. Each listed waste is assigned a hazardous waste identification number. Hazardous wastes from nonspecific sources (e.g., spent halogenated solvents used in degreasing) are listed in 40 CFR 261.31. Hazardous waste from specific sources (e.g., distillation bottoms from the production of acetaldehyde from ethylene) are listed in 40 CFR 261.32. Discarded commercial chemical products, off-specification materials, container residues, and spill residue (i.e., specific chemicals) are listed in 40 CFR 261.33.

Wastes that are not specifically listed may be considered hazardous because they have one or more of the four characteristics defined in 40 CFR 261 Subpart C. These hazardous characteristics – ignitability, corrosivity, reactivity, and toxicity – are defined in 40 CFR Part 261 Subpart C.

The Toxic Substances Control Act (TSCA) provides a regulatory framework for dealing comprehensively with risks posed by the manufacture and use of chemical substances. Under TSCA, U.S. EPA is authorized to regulate the manufacture, processing, distribution, use, and disposal of a chemical or a mixture of chemicals. The U.S. EPA can place restrictions on specific compounds or groups of compounds if they pose an unreasonable risk to health or the environment. Polychlorinated biphenyls (PCBs) are one group of compounds the U.S. EPA has chosen to regulate under TSCA. The disposal requirements for PCBs given in 40 CFR 761.60 apply to cleanup of PCB-contaminated wastes or soils at CERCLA sites.

2.2.3.2 Contaminant Characteristics and Treatment Types

Contaminant classes in wastes include metals and metal compounds, organics of various types, and other constituents such as anions. The class of contaminants in a waste will influence the type of S/S treatment that can be applied to the waste.

Metal and metal compounds include native metal, salts of metals, and metal anions such as arsenate, molybdate, or selenate. Metal contaminants cannot be destroyed by chemical or thermal methods. Therefore, they are either extracted from the waste and concentrated into a more manageable form via a soil washing/extraction technology or are immobilized via S/S. Although immobilization is theoretically possible for most metals, the difficulty and cost of such treatment varies greatly according to numerous factors, such as form, speciation, quantity, and concentration of the metal. Some examples of metals and groups of metals tested for S/S treatment are listed in Table 2-2.

Certain organic-contaminated wastes, such as heavy sludges or soil contaminated with organics, are also amenable to S/S treatment. This is true particularly if the organics are present with metals or anions, are minor components of the waste, or are nonvolatile and/or viscous (see Table 2-3). Given the wide variety of organic compounds, it is not possible to prepare a comprehensive list of organic compounds amenable to S/S treatment. However, Table 2-4 lists some organic wastes that have been considered as candidates for S/S treatment. Solidification/stabilization, either directly or following incineration, has been identified as the Best Demonstrated Available Technology (BDAT) for some organic wastes (see Table 1-1). However, wastes with significant quantities of organic material, particularly volatile organic material, typically are treated better with other types of treatment technology. Organic materials can frequently be extracted or destroyed by chemical or thermal processes. Organics can be difficult to stabilize with inorganic S/S binders and can, in fact, interfere with the setting reactions (see

TABLE 2-2. EXAMPLES OF SOME METAL WASTES TESTED FOR SOLIDIFICATION/ STABILIZATION TREATMENT

Contaminant	Waste Type
Aluminum	Metal finishing
Aluminum (and other metals)	Aluminum anodizing sludge
Antimony (and other metals)	Battery manufacturing flue dust
Arsenic	Phosphoric acid filter cake
Arsenic	Fly ash
Arsenic	Herbicide waste
Arsenic	Phosphoric acid filter cake
Barium	Various
Cadmium (and zinc)	Salt slurry
Cadmium (and other metals)	Battery plant sludge
Cadmium (and other metals)	Contaminated soil
Chromium (and other metals)	Chromium plating sludge
Chromium (and other metals)	Aluminum anodizing sludge
Chromium (and other metals)	Chromic acid rinse
Chromium (and other metals)	Contaminated soil
Copper	Catalyst
Copper	Catalyst substrate
Copper (and zinc)	Filter press cake
Copper (and tin)	Foundry sand
Copper (and other metals)	Metal finish
Copper (and other metals)	Clarifier sludge
Lead	Portland cement kiln dust
Lead (and other metals)	Battery plant sludge
Lead (and other metals)	Battery manufacturing flue dust
Lead (and other metals)	Contaminated soil
Mercury	Chlor-alkali mercury cell
Nickel (and other metals)	Battery plant sludge
Nickel (and other metals)	Metal finishing sludge

TABLE 2-2. EXAMPLES OF SOME METAL WASTES TESTED FOR SOLIDIFICATION/ STABILIZATION TREATMENT (Continued)

Contaminant	Waste Type
Nickel (and metals)	Contaminated soil
Silver	Various
Sodium	Metal finishing salt sludge
Tin (and metals)	Battery manufacturing flue dust
Zinc (and cadmium)	Metal salt slurry
Zinc (and copper)	Clarifier sludge
Zinc (and copper)	Filter press cake
Zinc (and metals)	Battery plant sludge
Zinc (and metals)	Contaminated soil
Mixed metals	Paint sludge
Mixed metals	Foundry sludge
Mixed metals	Ore processing leaching residue
Mixed metals	Printing wastewater treatment sludge
Mixed metals	Printing wastewater treatment filter cake
Mixed metals	Paint waste incinerator ash
Mixed metals	Electrochemical machining waste
Mixed metals	Biosludge from chemical process waste treatment
Mixed metals	Clarifier sludge
Mixed metals	Lagoon sludge
Mixed metals	Wastewater treatment filter cake
Mixed metals	Neutralized acids
Mixed metals	Foundry and baghouse dust

Note: Degree of solidification/stabilization achieved was not reported.
Sources: Conner, 1990, pp. 269-271; and U.S. EPA, 1989g.

TABLE 2-3. EXAMPLES OF SOME METAL AND ORGANIC MIXED WASTES TESTED FOR SOLIDIFICATION/STABILIZATION TREATMENT

Contaminant	Waste Type
Aluminum, paraffins, and water	Waste lubricant
Barium and organics	Coke dust
Chromium and organics	Tannery waste
Chromium and organics	Drilling mud
Oil, cadmium, chrome, and lead	Refinery sludge
Oil, lead, chromium, and arsenic	Refinery sludge
Oil, lead, PCB, and arsenic	Contaminated soil
PAH and organics	Contaminated soil
PCB and VOC	Contaminated soil
Metals and oil	Spent oil re-refining bleach clay
Metals and oil	Metal finishing buff wash
Metals, oil, and sulfur	Synthetic oil sludge
Metals and organics	Weathered oil waste
Metals and organics	Coating manufacture waste sludge
Metals and organics	Coating manufacture wastewater treatment sludge
Metals and organics	Wastewater treatment plant sludge
Metals and organics	Hazardous waste landfill leachate
Metals and organics	Landfill leachate
Metals and organics	Mixed lagoon sludge
Metals and organics	Printing waste sludge
Metals and organics	Solder stripping solution
Metals and organics	Wire manufacture vinyl waste
Metals and organics	Tannery lagoon biosludge

Note: Degree of solidification/stabilization achieved was not reported.
Sources: Conner, 1990, pp. 269-271; U.S. EPA, 1989g.

TABLE 2-4. EXAMPLES OF SOME ORGANIC WASTES TESTED FOR SOLIDIFICATION/STABILIZATION TREATMENT

Contaminant	Waste type
Carbon tetrachloride and carbon disulfide	Waste sludge
Chlorinated hydrocarbons	Petrochemical manufacturing waste
Creosote	Waste sludge
Kepone	Contaminated soil
Naphthalene compounds	Waste sludge
Oil and grease	Contaminated soil
Oil and grease	Oil, soap, and grease in water
Oil and grease	Oil sludge
Pesticides	Sludge
PCB	PCB oil
PCB	Contaminated soil
Silicones	Silicone waste
Solvents	Rubber waste
Solvents	Paint waste
Synthetic rubber	Rubber waste
Vinyl chloride and ethylene chloride	Sludge
Organics	Paint wastewater treatment sludge
Organics	Paint waste sludge
Organics	Acrylic/epoxy paint wash
Organics	Mixed lagoon sludge
Organics	Oil refining caustic waste

TABLE 2-4. EXAMPLES OF SOME ORGANIC WASTES TESTED FOR SOLIDIFICATION/STABILIZATION TREATMENT (Continued)

Contaminant	Waste type
Organics	Tall oil resin waste
Organics	Organic phase of landfill leachate
Organics	Lacquer solvent still bottoms
Organics	Synthetic resin waste
Organics	Tannery waste
Organics	Phenolic resin waste

Note: Degree of solidification/stabilization achieved was not reported.
Sources: Conner, 1990, pp. 269-271; U.S. EPA, 1989g.

Section 4.4.3 for a detailed discussion of the issues concerning the stabilization of organic contaminants).

On the other hand, fluid oil- and solvent-based wastes, such as used solvents, distillation bottoms, and refinery wastes, are candidates for S/S treatment only in specialized applications where solidification is required temporarily for safety in transportation or storage, or in spill control work. These wastes are normally incinerated if they are hazardous.

Other constituents of concern in S/S include several additional nonmetal inorganic species. Table 2-5 lists examples of some inorganic species tested for S/S treatment.

2.2.3.3 Sampling and Analysis

Waste characterization for S/S treatability studies goes beyond the requirements of the RI and is usually done after the RI has been completed. This characterization phase involves analyzing untreated waste samples for chemical, physical, and hazardous characteristics. The minimum amount of waste characterization for CERCLA sites is screening for substances on the

TABLE 2-5. EXAMPLES OF OTHER INORGANIC WASTES TESTED FOR SOLIDIFICATION/STABILIZATION TREATMENT

Contaminant	Waste type
Acid waste	Metal finishing solution
Acid (and metals)	Sludge
Acid waste (and organics)	Sludge
Boron fluoride	Pilot plant waste
Caustic waste	Aluminum drawing waste
Cyanide (and metals)	Plating sludge
Fluoride (and metals)	Calcium fluoride sludge
Fluoride (and organics)	Mixed petroleum refining wastes
Oxalates, sulfides (and organics)	Spent pulping liquor

Note: Degree of solidification/stabilization achieved was not reported.
Sources: Conner, 1990, pp. 269-271; and U.S. EPA, 1989g.

Hazardous Substances List. Actual chemical analysis for each of these compounds may not be necessary if site records clearly show certain substances to be absent. However, some confirmation analyses may be necessary. The objective is to determine with confidence the primary target contaminants and any waste substrates or characteristics that may interfere significantly with the S/S process.

Two additional objectives for collecting waste characterization data are that such data are useful in selecting the most suitable binding agent for the waste and in predicting the ultimate performance of the waste/binder mixture. While at present these objectives are not always achievable, they underscore the need for an accurate and statistically designed database of waste characteristics information for each waste type being evaluated.

The amount of new data that must be generated as part of the S/S treatability study can frequently be minimized by examining waste and site history and any characterization data that may have been already generated. If data exist and are reliable, they may eliminate or reduce the need for additional testing. At a minimum, background information on waste history will allow the subsequent analytical activities to be more focused, emphasizing target contaminants and problem constituents.

Types of characterization data that may be required for the untreated waste include chemical, physical, or physicochemical (i.e., relating to the form of the contaminant as opposed to its bulk concentration). A number of frequently used testing methodologies are compiled in Chapter 3, and their applicability to untreated waste is indicated. The reasons for generating characterization data include:

- To gather information on substances that interfere with common S/S processes.
- To establish baselines for comparison with chemical data on the treated waste.
- To gather information on U.S. EPA hazard characteristics.
- To establish the target contaminants and their physicochemical form.

One of the primary reasons for collecting characterization data is to establish the target contaminants in the waste, in terms of both identity and concentration. At a minimum, the waste should be characterized using a "total waste analysis" or the equivalent, including:

- Elemental analysis (metals)
- Volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs)
- Base, neutral, and acid compounds (BNAs) (see Chapter 3 for methods)

The minimum analysis should also include leaching data to define the soluble portion of the contaminant in the waste, yielding an understanding of contaminant partitioning in the waste. If possible, it is desirable also to have some information on physicochemical form. This is true particularly for metals, whose reactivity with various binding agents can vary significantly depending on the species present. Because detailed microcharacterization can be expensive, the analysis program should be thought out carefully. Examples of microcharacterization data include valence state information for elements such as arsenic (As) or chromium (Cr), solid phase characterization, elemental analysis, and structural characterization. Section 3.5 provides a brief overview of procedures for microcharacterization. Detailed microcharacterization is typically used only in research and development projects.

Characterization of wastes from CERCLA sites should include at least substances on the Hazardous Substances List (both organics and metals). Also, if not collected as part of the baseline data discussed above, data on the soluble (leachable) contaminants in the waste need to be generated to establish the target contaminants whose leachabilities must be reduced during the S/S process. Also needed are data on the RCRA hazard characteristics of the waste. The four types of hazard characteristics are toxicity, ignitability, reactivity, and corrosivity. If present, the hazard characteristics for ignitability, reactivity, and/or corrosivity may preclude stabilization or at least indicate the need for pretreatment.

Baseline data can include a variety of parameters and, by definition, are needed to assess how the parameters change during S/S treatment. Such data may be either chemical (e.g., pH, Eh, total and leachable contaminants) or physical (e.g., specific gravity, permeability, physical state, total solids, particle size distribution, presence of debris, dustiness, viscosity, etc.). Perhaps the most important baseline data at this stage are data that demonstrate the hazardous nature of the waste and thus constitute the basis for the S/S treatment. The hazardous classification may be based upon either soluble (e.g., Toxicity Characteristic Leaching Procedure [TCLP]) or total (acid-digestible) contaminant concentrations. If the waste is not legally hazardous and if there is no other regulatory-driven need to stabilize the waste, there may be no need to proceed with the S/S project.

Another characterization data category is constituents that may interfere with the S/S process. These include a great variety of constituents, depending on the binding agent contemplated. Examples are oil and grease and soluble salts such as halide for cement-based technologies (see Section 4.3).

Along with the chemical data, there is a need for physical properties and textural characteristics data, because heterogeneous wastes containing large blocks or boulders may be difficult to process without pretreatment. Also included in this category are other parameters that will aid in the selection of the binding agent or the design of the S/S process. Examples are particle size and water content.

2.2.4 Site Characterization

Information on site characteristics is an important aspect of the technology screening process. The following types of information are highly useful:

- Baseline information on the geology, hydrology, weather, etc., may constrain the design of the field treatment system, influence project timing, and have other effects.
- Site layout and proximity to needed resources also affect engineering design and, therefore, project cost.
- Information on site history may provide valuable insight about the waste, including the types of chemicals that were used at the site and the general location where they were released or disposed of. Knowledge of site operations can also suggest metal speciation (e.g., presence of anionic forms of metal).

Overall site-specific concerns with regard to a remedial action project are geared toward evaluating waste containment potential. Important site parameters in this regard include the following (modified from Colonna et al., 1990).

- Area of the site
- Permeability of the area soils, both for a review of leaching capabilities and for possible liner/cap material
- Amount and type of rocks and debris

- Existing groundwater contamination
- Baseline information on uncontaminated or upgradient groundwater
- Groundwater flow regimes
- Velocity and direction of both groundwater and ambient air
- Site drainage
- Site meteorology
- Proximity to populated areas
- Location and sensitivity of receptors
- Access routes to and from the site, including any United States Department of Transportation (U.S. DOT) restrictions
- Available work area/stockpiling area on the site
- Final disposal options and their site-specific implications
- Postremediation use of the site
- Sensitive environmental areas within the work site, such as floodplains or marshes
- Waste product volume increase and its implications for the capacity of the site to contain final product if on-site disposal is required/preferred
- Potential for fugitive dust
- Ability to mix the materials adequately on the site
- Availability of the binder materials and additives in the amounts required for the entire site

Most of the site information needs can be categorized as relating to water table, climate, soil characteristics, site layout, or logistics (U.S. EPA, 1989b).

In some cases, the waste site cannot provide sufficient area for the expected processing, binder stockpiling, and temporary or final waste disposal. Some kinds of processing require stockpiling of untreated excavated wastes, the processed wastes, and the binder. These materials may have to be covered to reduce exposure to wind and precipitation. Binders increase the volume of the waste product, and this added volume could present difficulties if the S/S product is buried in the original waste site excavation. Solutions to problems posed by limited area must be developed on a site-specific basis. Delivery of preweighed amounts of the binder directly to the process site is a possible solution. The binder then can be added directly to the mixing area rather than being stockpiled in bulk containers.

The presence of an elevated water table extending into the potential disposal zone in the waste area creates four problems:

1. A water table poses the possibility of existing groundwater contamination.

2. Excess water (especially flowing water) can cause excavation difficulties.

3. A water table creates the potential need for dewatering a saturated waste material prior to its processing.

4. Also, if on-site disposal is selected, there is a higher potential for leaching of the disposed waste, and there probably will be a requirement for a permanent groundwater monitoring system and collection of leachate.

All four of these problems have significant cost implications and must be resolved before the final technology selection is made (Colonna et al., 1990).

2.2.5 Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) is an important aspect of waste sampling and characterization. The results of the chemical analyses must be valid and statistically significant.

The U.S. EPA's quality assurance policy requires that every monitoring and measurement program have a written and approved Quality Assurance Project Plan (QAPjP). These requirements are specified in Costle (1979a and 1979b). The specified QA/QC requirements apply to all environmental data collection, monitoring, and measurement efforts authorized or supported by the U.S. EPA. It is important that anyone undertaking an S/S treatability study understand U.S. EPA QA/QC objectives and requirements in order to achieve data quality.

Another objective of the QA/QC program is to assess and identify measurement errors that may enter the data collection and measurement system at various phases of the project during sampling, sample handling/ preparation, and analysis. The U.S. EPA Superfund Treatability Study Protocol (U.S. EPA, 1990b) and the documents cited therein provide an overview of U.S. EPA QA/QC guidelines for treatability studies, including a discussion of the following:

- Preparation of the Quality Assurance Project Plan (QAPjP)
- Data quality objectives (DQO)
- The need to identify the sources and types of errors that may occur during the sampling, analysis, and treatability measurement process
- The need for quality control samples
- Data quality indicators, measurement errors, and documentation

2.2.6 Guidance for Site-Specific Information Requirements

Table 2-6 lists several guidelines pertaining to the sampling and analysis activities that support the S/S technology screening process, as discussed in Section 2.2. For many remedial action projects involving S/S, particularly those involving relatively simple sites, not all of the guidance in Table 2-6 will necessarily apply. For large, complex projects, there may be additional issues and concerns not listed in Table 2-6.

2.3 PERFORMANCE OBJECTIVES

Treatability performance objectives or performance standards are specified values of the properties of S/S-treated wastes as determined by specific tests or measurements. The properties tested are those that are legally mandated and/or considered crucial for predicting the efficacy and long-term reliability of S/S. Every remedial action project needs a clearly defined set of measurable performance objectives. The success or failure of

TABLE 2-6. GUIDANCE FOR COLLECTING BASELINE INFORMATION

Sampling Guidelines

1. Consistent with agency guidance (see section 2.2.1). Issues such as sampling techniques, sample preservation and storage, holding times, chain-of-custody, etc.

2. Sampling locations statistically randomized for representativeness.

3. Samples composited prior to analysis for representativeness.

4. Debris, large rock fragments, vegetative material, etc., removed, unless they are not to be separated from the waste prior to treatment in the field.

5. "Hot spot" samples collected for worst-case analysis.

Waste Acceptance Criteria

1. Waste complies with transportation and facility (bench-scale treatability testing and/or analytical laboratory) permits as well as with health and safety plans.

Waste Characterization

1. Total waste analysis for target contaminants.

2. TCLP and other appropriate leaching data on untreated waste for establishing baseline leaching data and determining the presence of RCRA toxicity characteristic.

3. RCRA and other hazard characteristic tests as appropriate including the following:

   - ignitability
   - corrosivity
   - reactivity
   - toxicity
   - infectivity
   - (radioactivity)

4. Other chemical analyses to establish baselines and possible S/S interferences, for example

   - pH
   - redox potential
   - salt content
   - oil and grease content
   - leaching tests

TABLE 2-6. GUIDANCE FOR COLLECTING BASELINE INFORMATION (Continued)

5. Total contaminant analysis at the same time as a soluble (leachable) contaminant analysis, on the same subsample. This is to ensure that the subsample used to generate the soluble data does not contain a low contaminant level because of sample heterogeneity (avoid false negatives).

6. Baseline physical characteristics of the untreated waste:

   - physical state
   - paint filter test and/or liquid release test
   - specific gravity
   - permeability
   - particle size
   - dustiness
   - bulk density
   - phase separation
   - moisture content
   - porosity
   - health hazards

7. Other data on physicochemical form of the target contaminants — X-ray diffraction, scanning electron microscopy, optical microscopy, valence states of redox-sensitive contaminants such as As and Cr, organometallics (e.g., tetraethyl lead, butyl tin compounds), nickel-carbonyl, etc.

8. Total waste volume measured or calculated.

9. Presence and amount of debris that may interfere with S/S.

10. Textural characteristics of the waste:

    - oily, liquid
    - dry granular
    - sludge
    - clayey
    - hard massive, etc.

11. Heterogeneity of target contaminant distribution in the waste.

TABLE 2-6. GUIDANCE FOR COLLECTING BASELINE INFORMATION (Continued)

QA/QC

1. Suitable QA/QC program, with built-in mechanisms to define data quality objectives, to evaluate sources of error, and to provide suitable documentation.

2. Analytical laboratories should possess appropriate qualifications or certifications.

3. Sufficient amount of analytical replication to permit a statistical analysis of the results (e.g., confidence intervals to address sample heterogeneity).

4. Use of a second analytical laboratory for interlaboratory verification on a portion of the more critical analytical measurements.

Baseline Site Characteristics

1. Fundamental site characterization data:

   - geology
   - hydrology, surface water and groundwater
   - geochemistry, soils
   - climatology, meteorology (especially temperature, wind, and rainfall)

2. Knowledge of the proportion of waste that occurs above the groundwater table.

3. Compatibility of site with heavy field equipment, for example

   - topography, slope, presence of obstacles
   - ability to excavate
   - available space
   - storage areas
   - characteristics consistent with any special requirements such as dikes, berms, and groundwater diversion or suppression systems
   - surface water drainage, etc.

TABLE 2-6. GUIDANCE FOR COLLECTING BASELINE INFORMATION (Continued)

4. Proximity of site to necessary resources, for example

- water	- equipment rentals
- supplies	- access routes
- chemicals	- disposal facility
- electricity	- waste to be tested

5. Proximity of site to possible receptors, for items such as

- noise	- volatiles
- fugitive dust	- odors

6. Proximity of site to sensitive environmental areas, for example

- floodplains	- protected species breeding grounds
- wetlands	- populated areas

7. Measurement of baseline contaminant levels in various media (air, water, soil, etc.) to determine if contaminants were released during the field demonstration.

8. Availability of backfill, if necessary.

the project depends to a large degree upon the ability to satisfy these objectives.

Performance objectives are a function of the compliance requirements selected for the site, the test methods used to evaluate the performance of the stabilized waste, and the analytical procedures (models) used to relate test data to performance objectives (Barich and Mason, 1992). The performance objectives are established early in the process of planning the treatability study. Specifying performance objectives goes hand-in-hand with selecting the tests to conduct because the objectives are expressed as results for specific tests. The performance objectives constitute acceptance criteria: if treatment by S/S cannot meet these criteria at the bench scale, S/S alone probably cannot provide sufficient treatment to meet site cleanup goals. Once test methods and performance objectives are determined, the criteria to be used in interpreting test results can be derived readily (U.S. EPA, 1990b).

Before specific treatability performance objectives are set, the data quality needs of the project must be defined (Section 2.2.5). The early implementation of an appropriate QA/QC program and the establishment of DQOs will ensure that data of known and documented quality are generated. For a detailed discussion of DQOs, see U.S. EPA (1987a). Guidance on DQOs in the treatability study process can be obtained in U.S. EPA (1989e).

Treatability performance objectives can be grouped into two general types. Regulatory performance objectives (Section 2.3.1) are those based on applicable or relevant and appropriate requirements (ARARs) for the site. All other performance objectives may be classified as technical/institutional (Section 2.3.2). These relate to the characteristics of the S/S-treated waste for which explicit regulatory standards do not exist. Examples include cost effectiveness, a requirement for the S/S-treated waste to support vehicular traffic, and resistance of the treated waste to biodegradation. U.S. EPA, 1989e, Chapter 3, provides additional guidance.

2.3.1 Regulatory Requirements

The regulatory requirements pertinent to treatability testing of S/S are those standards that the remedial alternative will have to meet when implemented at full scale. The regulatory framework for RCRA wastes is clearly defined in the regulations. The CERCLA regulatory framework is derived from site-specific ARARs about which general guidance is given below. An ARAR search needs to be conducted early on in the conduct of the feasibility study and well before the onset of the treatability testing. ARARs can be numerous, and a process has been established by the U.S. EPA to identify ARARs for Superfund projects (Section 121, Superfund Amendments and Reauthorization Act [SARA] of 1986, Public Law 99-499). The various ARARs often have different goals. Multiple goals make it increasingly expensive and increasingly difficult to comply with all the goals.

2.3.1.1 CERCLA

There are several types of ARARs under CERCLA: action-specific, chemical-specific, and location-specific. Action-specific ARARs are technology- or activity-specific requirements or limitations related to various activities. Chemical-specific ARARs are usually numerical values that establish the amount or concentration of a chemical that may be in or discharged to the ambient environment. Location-specific requirements are restrictions placed on the concentrations of hazardous substances or the conduct of activities solely because they occur in a special location.

Detailed guidance on the ARAR search is given in U.S. EPA (1988b). Some aspects of ARAR identification that apply to S/S treatability standards are discussed here.

Most federal laws that contain location-specific ARARs are institutional or administrative in nature. These laws regulate the types of activities that may take place in particular types of locations such as seismic fault zones, floodplains, or critical habitats for endangered species. State and local regulations are more likely to provide location-specific ARARs for treatability testing. Pertinent regulations would include discharge limits or nondegradation standards for particular water bodies and basin-wide air quality standards (U.S. EPA, 1990b, Chapter 3).

Relevant technology (action)-specific ARARs must be identified. At present, there are few explicit performance standards for S/S-treated wastes. The U.S. Nuclear Regulatory Commission (NRC) has established performance standards for stabilized nuclear wastes (both high-level and low-level), but these are not applicable to nonnuclear materials. Hazardous wastes that are disposed of on land may be regulated under RCRA, and standards for treatment of such wastes are currently being promulgated. Wastes that are stabilized by in situ techniques, such as deep mixing, may not fall under the purview of RCRA rules. Wastes that are excavated, treated, and land-disposed of either on or off the site (i.e., they undergo "placement") may be regulated by RCRA rules. Land-disposed RCRA wastes usually need to demonstrate a minimum unconfined compressive strength of 50 psi (U.S. EPA, 1986b), but the actual target value for a specific site may be higher or lower depending on site-specific requirements. In addition, technology- and action-specific treatment standards for a number of RCRA waste classes are named in the RCRA land disposal restrictions (LDRs).

For many waste classes, including inorganics and some organic contaminants, treatment standards are expressed as percent reduction in contaminant leaching, as measured by pre- and post-treatment TCLP tests. Note, however, that there has been a tendency in RODs to express treatment standards, even for metal contaminants, in terms of reduction of total contaminant levels. This poses complications for the application of S/S technology because, under normal circumstances, S/S neither destroys nor removes the contaminant, but instead immobilizes it. These standards are directly applicable to laboratory screening and bench-scale testing of these waste classes; they can be used to gauge the efficiency of S/S treatment during treatability studies. For many organic contaminants, RCRA treatment standards are expressed as destruction-removal efficiency (DRE), where the efficiency of the treatment technology is measured by pre- and post-treatment total (as opposed to soluble) contaminant concentrations. (U.S. EPA, 1990b, Chapter 3). Results of TCLP tests on post-treatment samples may be influenced by dilution of waste due to binder addition. Reduced contaminant concentration in leachate may not reflect reduced mobility of the contaminant unless results have been corrected for dilution effects.

At many CERCLA sites, the materials requiring treatment cannot be assigned to specific RCRA waste classes. Contaminated soil and debris are often the materials of concern. For such sites, an appropriate regulatory performance standard can be derived by the procedure used to establish a treatability variance under RCRA (U.S. EPA, 1989b). The U.S. EPA has set target cleanup ranges for wastes contaminated by the principal classes of organic and inorganic contaminants (Table 2-7). For an organic contaminant, the appropriate treatability performance objective is determined as follows: If the total concentration for the contaminant in the untreated waste falls below the "threshold concentration," then the total concentration of the contaminant in the S/S-treated waste must fall within the "concentration range." If the original total concentration of the contaminant exceeds the threshold value, then the difference between the total concentrations of the contaminant in the treated and untreated wastes must fall within the "percent reduction range." The relevance of these guidelines when treatment is by S/S is unclear, however, because S/S neither destroys nor removes the contaminant, but instead immobilizes it. The same logic applies for metallic contaminants, but the criteria are based on the contaminant concentration in the TCLP

TABLE 2-7. ALTERNATIVE TREATMENT LEVELS FOR SOIL AND DEBRIS CONTAMINATED WITH RESTRICTED RCRA HAZARDOUS WASTES[a]

Structural Functional Groups	Concentration Range (ppm)	Threshold Concentration (ppm)	Percent Reduction Range	Technologies that Achieved Recommended Effluent Concentration Guidance[b]
Organics	Total Waste Analysis[c]	Total Waste Analysis[c]		
Halogenated nonpolar aromatics	0.5-10	100	90-99.0	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Dioxins	0.00001-0.05	0.5	90-99.9	Dechlorination, soil washing, thermal destruction
PCBs	0.1-10	100	90-99.9	Biological treatment, dechlorination, soil washing, thermal destruction
Herbicides	0.002-0.02	0.2	90-99.9	Thermal destruction
Halogenated phenols	0.5-40	400	90-99	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Halogenated aliphatics	0.5-2	40	95-99.9	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Halogenated cyclics	0.5-20	200	90-99.9	Thermal destruction
Nitrated aromatics	2.5-10.0	10,000	99-99.99	Biological treatment, soil washing, thermal destruction

TABLE 2-7. ALTERNATIVE TREATMENT LEVELS FOR SOIL AND DEBRIS CONTAMINATED WITH RESTRICTED RCRA HAZARDOUS WASTES[a] (Continued)

Structural Functional Groups	Concentration Range (ppm)	Threshold Concentration (ppm)	Percent Reduction Range	Technologies that Achieved Recommended Effluent Concentration Guidance[b]
Organics	Total Waste Analysis[c]	Total Waste Analysis[c]		
Heterocyclics	0.5-20	200	90-99.9	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Polynuclear aromatics	0.5-20	400	95-99.9	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Other polar organics	0.5-10	100	90-99.9	Biological treatment, low-temperature stripping, soil washing, thermal destruction
Inorganics	TCLP	TCLP		
Antimony	0.1-0.2	2	90-99	Immobilization
Arsenic	0.27-1	10	90-99.9	Immobilization, soil washing
Barium	0.1-40	400	90-99	Immobilization
Chromium	0.5-6	120	95-99.9	Immobilization, soil washing
Nickel	0.5-1	20	95-99.9	Immobilization, soil washing
Selenium	0.005	0.08	90-99	Immobilization
Vanadium	0.2-22	200	90-99	Immobilization

TABLE 2-7. ALTERNATIVE TREATMENT LEVELS FOR SOIL AND DEBRIS CONTAMINATED WITH RESTRICTED RCRA HAZARDOUS WASTES[a] (Continued)

Structural Functional Groups	Concentration Range (ppm)	Threshold Concentration (ppm)	Percent Reduction Range	Technologies that Achieved Recommended Effluent Concentration Guidance[b]
Inorganics	TCLP	TCLP		
Cadmium	0.2-2	40	95-99.9	Immobilization, soil washing
Lead	0.1-3	300	99-99.9	Immobilization, soil washing
Mercury	0.0002-0.008	0.06	90-99	Immobilization

[a] Source: U.S. EPA 1990c (Superfund LDR Guide No. 6A-2nd Edition).

[b] Other technologies may be used if treatability studies or other information indicates that they can achieve the necessary concentration or percent-reduction range.

[c] TCLP also may be used when evaluating waste with relatively low levels of organics that have been treated through an immobilization process.

leachate, rather than the total contaminant concentration (U.S. EPA, 1990b, Chapter 3).

Finally, an ARAR search may identify chemical-specific ARARs that should be evaluated during treatability testing. Numerical standards that may be ARARs have been promulgated under several federal laws. These include the Clean Water Act (water quality criteria for protection of human health and ambient water quality criteria), the Safe Drinking Water Act (maximum contaminant levels [MCLs] and MCL goals), and RCRA. If the S/S-treated wastes may be disposed of off-site, then the TCLP test and the RCRA characteristic tests should be specified; their acceptance criteria will constitute one set of performance objectives. Chemical-specific air quality standards may also apply and the ARARs cannot be exceeded. Because materials processing and the potential for volatilization are much different between bench- and full-scale, air quality standards are unlikely to form the basis for quantitative bench-scale tests (U.S. EPA, 1990b, Chapter 3).

For most S/S projects, resource limitations dictate that the treatability testing program be restricted to a subset of the contaminants present on the site. The contaminants to be evaluated should be selected according to the following characteristics (U.S. EPA, 1990b, Chapter 3):

- Toxicity or carcinogenicity - select the most harmful contaminants.
- Mobility - select the most soluble contaminants.
- Geochemistry - select a representative contaminant from each of the major functional types present.
- Concentration - all factors being equal, select the contaminants present at the highest concentrations.

Generally, if the number of contaminants being evaluated in treatability testing exceeds four or five at any one time, it becomes increasingly difficult to satisfy the performance objectives for all of the contaminants. If the ROD has been signed and site cleanup goals have been specified, the contaminants named therein should be monitored throughout the treatability study. Examples of regulatory performance objectives for CERCLA S/S studies are summarized in Table 2-8.

TABLE 2-8. EXAMPLES OF REGULATORY ARARs

1. Total contaminant treatment standards for disposal
2. Soluble contaminant treatment standards for disposal

   a. routine leaching procedure (e.g., TCLP)/
   b. other leaching procedure (e.g., ANSI/ANS/16.1)

3. Mobility criteria from geochemical transport model
4. Land activity restrictions (e.g., in seismic fault zones, floodplains, critical habitats of endangered species)
5. "Placement" restrictions (e.g., 50 psi unconfined compressive strength criterion)
6. Air emissions standards
7. Noise restrictions
8. Compliance with the Clean Water Act or Safe Drinking Water Act
9. Compliance with state and local regulations and laws.

2.3.1.2 RCRA

The factors for accepting stabilized waste at a treatment, storage, and disposal (TSD) facility under RCRA are much less complex than for CERCLA. The principal criteria (U.S. EPA, 1989b) are as follows:

- Paint Filter Test (PFT) for free liquid
- Adherence to TCLP maximum concentration limits (see Table 2-9)
- Screens for hazardous waste characteristics
  - ignitability
  - corrosivity
  - reactivity
  - radioactivity
- Compliance with LDRs (see Section 1.3 for a discussion of the nature and applicability of RCRA Land Disposal Restrictions).

TABLE 2-9. TOXICITY CHARACTERISTIC CONSTITUENTS AND REGULATORY LEVELS

EPA HW No.[a]	Constituent (mg/L)	Regulatory Level
D004	Arsenic	5.0
D005	Barium	100.0
D018	Benzene	0.5
D006	Cadmium	1.0
D019	Carbon tetrachloride	0.5
D020	Chlordane	0.03
D021	Chlorobenzene	100.0
D022	Chloroform	6.0
D007	Chromium	5.0
D023	o-Cresol	200.0[b]
D024	m-Cresol	200.0[b]
D025	p-Cresol	200.0[b]
D026	Cresol	200.0[b]
D016	2,4-D	10.0
D027	1,4-Dichlorobenzene	7.5
D028	1,2-Dichloroethane	0.5
D029	1,1-Dichloroethylene	0.7
D030	2,4-Dinitrotoluene	0.13[c]
D012	Endrin	0.02
D031	Heptachlor (and its hydroxide)	0.008
D032	Hexachlorobenzene	0.13[c]
D033	Hexachloro-1,3-butadiene	0.5
D034	Hexachloroethane	3.0
D008	Lead	5.0
D013	Lindane	0.4

TABLE 2-9. TOXICITY CHARACTERISTIC CONSTITUENTS AND REGULATORY LEVELS (Continued)

EPA HW No.[a]	Constituent (mg/L)	Regulatory Level
D009	Mercury	0.2
D014	Methoxychlor	10.0
D035	Methyl ethyl ketone	200.0
D036	Nitrobenzene	2.0
D037	Pentachlorophenol	100.0
D038	Pyridine	5.0[c]
D010	Selenium	1.0
D011	Silver	5.0
D039	Tetrachloroethylene	0.7
D015	Toxaphene	0.5
D040	Trichloroethylene	0.5
D041	2,4,5-Trichlorophenol	400.0
D042	2,4,6-Trichlorophenol	2.0
D017	2,4,5-TP (Silvex)	1.0
D043	Vinyl chloride	0.2

[a] Hazardous waste number

[b] If o-, m-, and p-cresol concentrations cannot be differentiated, the total cresol (D026) concentration is used. The regulatory level for total cresol is 200 mg/L.

[c] Quantitation limit is greater than the calculated regulatory level. The quantitation limit therefore becomes the regulatory level.

2.3.2 Technical and Institutional Requirements

In addition to regulatory requirements, other factors may shape the treatability performance objectives. Technical/institutional objectives are developed from constraints imposed by administrative factors, by the site itself, or by the waste to be treated. These objectives address special problems that may detract from the implementability of the S/S process or from the long-term performance of S/S-treated waste at the site. For successful remediation, developing such objectives and solving these problems may be as important as meeting applicable regulatory requirements.

Table 2-10 lists potential types of performance objectives that fall outside of the regulatory domain. For some objectives, such as cost-effectiveness and controlling the production of hazardous vapors, quantitative acceptance criteria may not exist. For many nonregulatory tests, quantitative performance standards for particular site conditions can be developed.

Some of the performance objectives listed in Table 2-10 for S/S-treated wastes have been studied in depth. Tests for these properties are widely performed and have been applied successfully in evaluating S/S-treated wastes. Examples of such properties are waste volume increase, sulfate or sulfide content, and leachability, as measured by various tests (see Chapter 3). The importance of other properties in maintaining the integrity of S/S-treated wastes is not well understood. The corresponding tests may be considered research tests and their results subject to various interpretations (U.S. EPA, 1990b, Chapter 3).

2.3.3. Approach for Setting Performance Criteria

The laboratory tests to be performed and performance criteria for these tests to meet are chosen at the same time. One should not begin the testing program without a clear definition of what results will constitute success and failure. The available physical, leaching, chemical, biological, and microcharacterization tests and their typical applications are discussed in Chapter 3.

Every bench-scale treatability study should consider tests of leaching, unconfined compressive strength, and free liquids. These tests are likely to form at least a portion of the basis for any regulatory evaluation of the S/S-treated waste.

TABLE 2-10. EXAMPLES OF TREATABILITY PERFORMANCE OBJECTIVES BASED ON NONREGULATORY FACTORS[a]

Objective	Potential generic test(s)
<u>Qualitative Objectives</u>	
Demonstrate basic feasibility	Leaching test One or more physical tests
Reagent costs not to exceed a given amount	Optimize mix; calculate binder cost per volume stabilized
Assay for off-gassing of volatile compounds	Measure temperature of fresh mixture Monitor air with organic vapor detector while mixing
Ensure thorough mixing	Microscopy; visual examination of fractured monoliths Observation of binder miscibility, wetting during mixing
Identify soil containing interfering minerals	X-ray diffraction
Treat a minimum proportion of contaminated material on site	Assay site for debris and large particles; determine handling needs
<u>Quantitative Objectives</u>	
Prevent unfavorable reactions between waste and binder	Potential reactivity of aggregates Petrographic examination of aggregates for concrete
Create a pumpable mix	Liquid waste consistency/ classification (see Table 3-3)
Ensure complete microencapsulation of contaminants	Collect, analyze any bleed water
Volume increase not to exceed a threshold value	Calculate volume change from treated, untreated waste bulk densities

TABLE 2-10. EXAMPLES OF TREATABILITY PERFORMANCE OBJECTIVES BASED ON NONREGULATORY FACTORS (Continued)

Objective	Potential generic test(s)
Ensure sufficient long-term structural integrity	Compressive strength Resistance to wet/dry and freeze/thaw stressing
Determine ability of S/S-treated waste to support heavy equipment soon after placement	Trace development of bearing capacity with cone penetrometer
Determine ability of cured S/S monolith to support vehicular traffic	Flexural strength test California bearing ratio Proctor compaction of subbase (and stabilized material, if it is a friable soil-cement)
Assure resistance to sulfate attack on S/S monolith	SO_4 content of waste
Prevent fracturing of S/S monolith	Shrink/swell potential of subbase material
Curtail fugitive dust emissions during full-scale fixation	Particle size analysis Moisture content of wastes
Minimize contaminant leaching	Leaching tests
Determine long-term leach behavior	Acid neutralization capacity Resistance to redox change Chemistry of surrounding soil and groundwater Accelerated aging/weathering tests
Minimize leachate toxicity	Aquatic bioassays
Resist biodegradation of organic contaminants or asphaltic binders	Biodegradation tests
Reduce contaminant load or concentration at the receptor to below threshold value	Leaching tests Permeability Transport modeling

[a] U.S. EPA, 1990b

The currently accepted version of the TCLP leaching test is usually required. However, depending on the anticipated disposal setting and environmental or human health risks, TCLP may not be adequate and additional leaching tests may be needed. The types of contaminants and their level of hazard and concentration, the planned disposal or reuse scenario, and the S/S approach used all influence the selection of leaching tests. Additional leaching tests are particularly important if there is a need to characterize the fundamental mechanisms involved (e.g., for risk analysis to receptor populations).

Beyond these basic regulatory requirements, further testing is initially projected on the basis of site hydrologic conditions. If an aqueous driving force for leachate production exists, additional leach testing should be considered. In addition, it may be necessary to evaluate contaminant transport using a modeling approach. Additional background and guidance on this issue is provided in U.S. EPA (1989e, Section 3.3). An aqueous driving force may not exist. For example, the final remedial design may specify that the S/S-treated waste be placed above the seasonal high-water table and an impervious cap and runon/runoff controls be constructed. In such cases, leaching and physical integrity tests will usually suffice to demonstrate whether the S/S process can be considered reliable for the site. Attenuation by engineering controls or natural processes is not usually considered in this case (U.S. EPA, 1989e, Chapter 3).

Strength and freedom from free liquids are two other frequently applied performance criteria. Other types of measurements should be planned based on site-specific factors such as those listed in Tables 2-8 and 2-10. Selection of testing depends on waste characteristics, disposal or reuse scenario, type of S/S progress, and scientific objectives of the program.

2.4 INITIAL TECHNOLOGY SCREENING

After the performance objectives for a treatability project have been identified, it is necessary to determine what treatment technology or technologies have the potential of complying with those performance objectives. This section briefly discusses the screening process whereby S/S is compared with other treatment alternatives and the most appropriate technology or technologies are selected for further evaluation to determine compliance with the performance objectives. Various terms have been applied to this technology screening process, including "feasibility study" (FS) for remedial actions and "economic evaluation/cost analysis" (EE/CA) for removal actions. The screening process is described in other publications, such as U.S. EPA (1988c), and it is beyond the scope of this TRD to describe the process in detail. Therefore, an overview of the basic elements of the process is given in Section 2.4.1 and rules of thumb for screening problematic waste types for S/S technology are provided in Section 2.4.2.

2.4.1 Technology Screening/Feasibility Study Process

In the broadest sense, the majority of wastes are potentially treatable with S/S. Pretreatment can be used to transform an untreatable waste form to a form that can be treated with S/S. However, for certain wastes, the pretreatment requirements may make the technology impractical based on cost or other criteria, and there clearly are situations where a different type of technology will be more effective or appropriate.

2.4.1.1 CERCLA Technology Screening

The first step in the technology screening process is to identify candidate remedial alternatives (treatment/removal technologies or treatment trains). A number of different technologies have been developed. Many technologies are applicable only to certain types of wastes. For example, U.S. EPA (1988c) lists the following broad categories of treatment technologies:

- Fluidized bed incineration
- Rotary kiln incineration
- Infrared thermal treatment
- Wet air oxidation
- Pyrolysis-incineration
- Vitrification (in situ, ex situ)
- Chemical extraction
- Glycolate dechlorination
- Solidification/stabilization

- Chemical reduction/oxidation
- Biodegradation
- In situ biodegradation

Treatment technologies continually are being developed, modified and refined. In selecting a remedial alternative (which includes selecting the treatment technologies), an analysis is performed with respect to a number of different evaluation criteria. The process described in the National Contingency Plan entails a detailed analysis of each remedial alternative with respect to nine different evaluation criteria in three main categories. These criteria are presented below. All selected remedies should provide the best trade-offs among the Primary Balancing Criteria and must, at a minimum, attain the Threshold Criteria. The Modifying Criteria are evaluated following the public comment period.

Threshold Criteria:

- Overall Protectiveness of Human Health and the Environment. This criterion evaluates the adequacy of protection that the remedy provides while describing how risks are eliminated, reduced, or controlled through treatment, engineering controls, and/or institutional controls.

- Compliance with Applicable or Relevant and Appropriate Requirements. This criterion addresses whether a remedy would meet all of the ARARs of federal and state environmental statutes and/or provide grounds for invoking a waiver.

Primary Balancing Criteria:

- Reduction of Toxicity, Mobility, or Volume Through Treatment. This criterion addresses the anticipated treatment performance of the remedy.

- Short-Term Effectiveness. This criterion refers to the speed with which the remedy achieves protection, as well as the remedy's potential to create adverse impacts on human health and the environment during the remedial action.

- Long-Term Effectiveness and Permanence. This criterion evaluates the magnitude of residual risk and the ability of the remedy to maintain reliable protection of human health and the environment over time once the remedial action has been completed.

- Implementability. This criterion examines the technical and administrative feasibility of executing a remedy, including the availability of materials and services needed to implement the chosen solution.

- Cost. This criterion includes the capital and operation and maintenance costs of the remedy.

Modifying Criteria:

- State Acceptance. This criterion indicates whether, based on its review of the planned remedial alternative, the state concurs with, opposes, or has no comment on the preferred alternative.

- Community Acceptance. This criterion evaluates the reaction of the public to the remedial alternatives and to the U.S. EPA's Proposed Plan.

A similar approach is employed using EPA's Engineering Evaluation/Cost Analysis (EE/CA) for selecting CERCLA removal actions/approaches. In this case, the technology screening takes place in two stages, as shown in Figure 2-3. First, all alternative remedial actions are compared based on timeliness and effectiveness to protect human health and the environment. Then, the smaller subset of remedial actions that satisfy these criteria are evaluated based on (a) technical feasibility, (b) cost, and (c) administrative and managerial feasibility. The process may be iterative and may have several different possible outcomes, which are discussed further in Section 2.4.3.

Another factor considered during technology screening is the position of the remedial action/technology in terms of the hierarchy of hazardous waste management (Section 1.1.2). Remedial actions that allow recycling, reuse, or recovery of the waste or some portion of the waste are preferable to treatment and disposal. For example, all other factors being equal, smelting or soil washing would be preferable to S/S for wastes containing appropriately high metal contents because some contaminants would be recovered and could then be recycled. However, it is important to consider the full system effects when making the comparison. One example is the need for pretreatment and the residuals generated, such as liquid waste produced during soil washing.

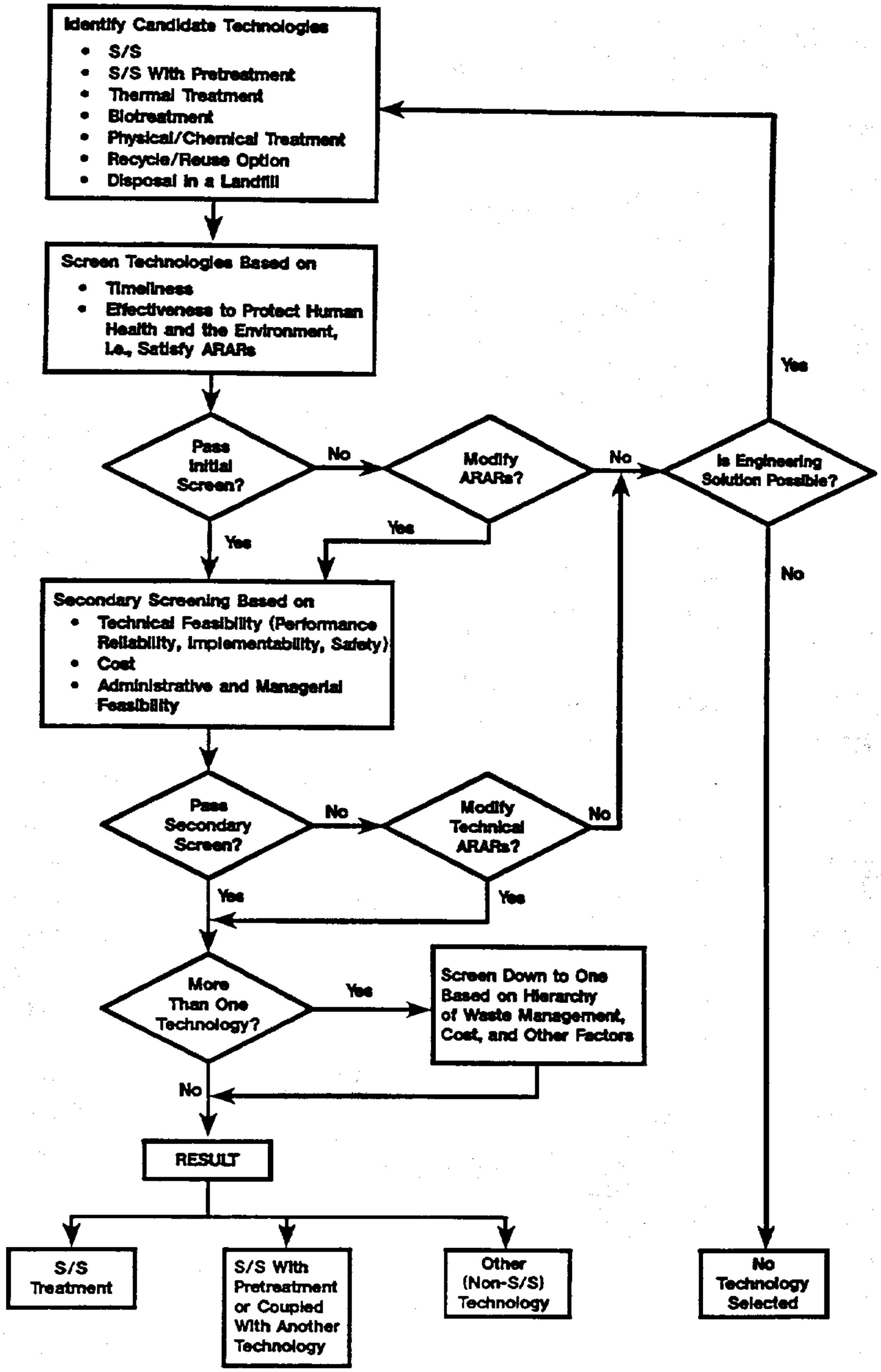

FIGURE 2-3. GENERAL TECHNOLOGY SCREENING PROCEDURE

2.4.1.2 Technology Screening at RCRA TSD Facilities

Remediation under CERCLA and RCRA corrective action are driven primarily by regulations, waste characteristics, and site characteristics and have the full range of available treatment technologies as options. In contrast, RCRA treatment, storage and disposal (TSD) facilities are driven by the regulations and by the specific permitted technologies available at the facility. Any one treatment facility probably has one or more specific immobilization technologies in place with a limited menu of pretreatment options available (U.S. EPA, 1989b).

The RCRA TSD facility personnel need to select, screen, and test treatment technologies to process waste streams while complying with permit conditions. Some flexibility may be gained by using pretreatment options or process modifications.

The criterion for satisfactory treatability is the ability of the treated waste to pass all the required tests for disposal. A flowchart for determining the potential suitability of S/S for waste treatment at a RCRA TSD facility is provided in Figure 2-4. Once the waste has been found to be potentially suitable for S/S, the approach for bench-scale screening is as outlined in Figure 2-5. This approach is basically a simplified version of the tiered approach for S/S treatability testing described in Sections 2.5 through 2.7.

2.4.2 General Criteria for Not Using S/S

Because the applicability of S/S processes to site-specific wastes depends on several variables, specifying criteria for not using S/S is difficult or impossible without site-specific data. However, it is possible to generalize about criteria that indicate potential S/S inapplicability. Table 2-11 summarizes the types of waste that are generally not amenable to S/S processes or that could pose problems.

2.4.3 Outcome of Technology Screening

The outcome of the technology screening process is a determination of one of the following (Figure 2-3):

- Waste can be treated with S/S without pretreatment.

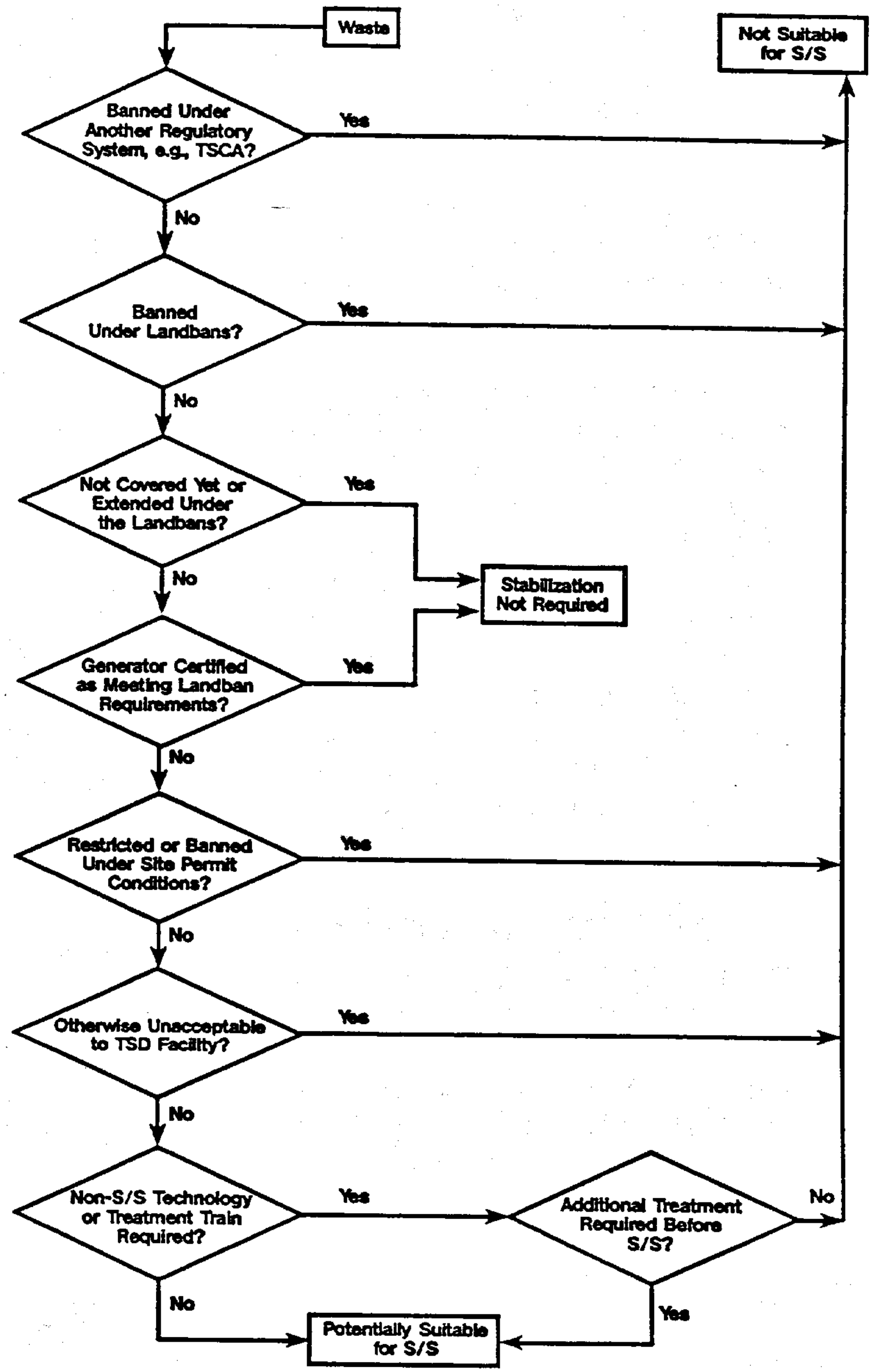

FIGURE 2-4. DETERMINING WHETHER S/S IS APPLICABLE AT A RCRA TSD FACILITY (from U.S. EPA, 1989b)

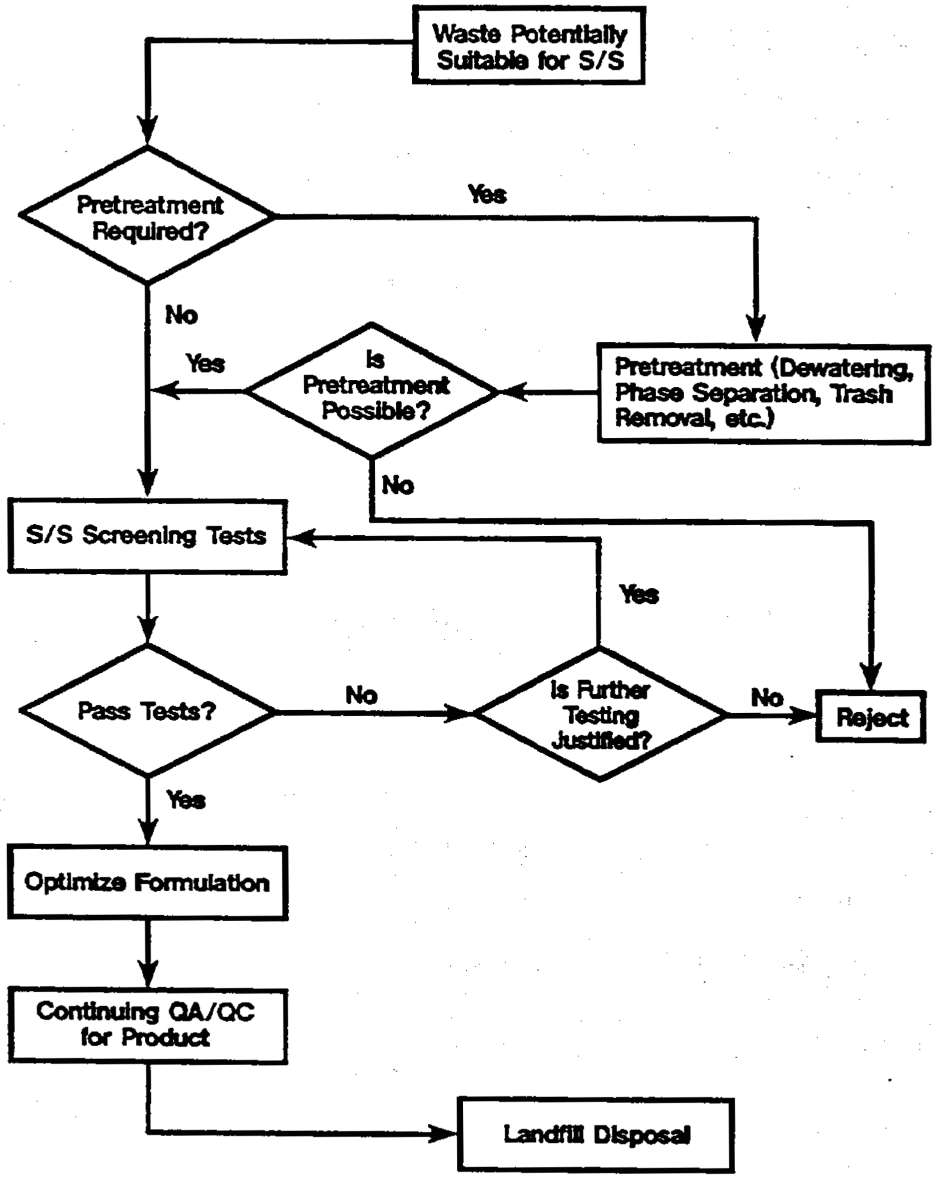

FIGURE 2-5. S/S DECISION TREE AT A RCRA TSD FACILITY (from U.S. EPA, 1989b)

TABLE 2-11. APPLICABILITY OF SOLIDIFICATION/STABILIZATION TO SITE-SPECIFIC WASTE

A. WASTES THAT ARE UNSUITABLE FOR S/S[a]

1. Wastes that are readily treatable by recycling, reuse, or recovery technology, all other factors being equal.

2. Wastes that are treatable using a destructive technology, all other factors being equal.

3. Wastes that contain land-banned constituents (unless land disposal can be avoided) and other high-hazard materials (e.g., dioxins, high levels of PCBs, pesticides, etc.).

4. Waste for which the ARARs cannot be satisfied with existing S/S technology (unless ARARs are modified).

5. Wastes that have unacceptable physical characteristics such as being too solid or viscous to mix or handle.

6. Wastes where waste volume expansion would exceed reuse space constraints.

7. Wastes that are treatable using a much less expensive technology, all other factors being equal.

B. WASTES THAT POSE COMPLICATIONS FOR S/S

1. Wastes with volatile organics (pretreatment is usually required).

2. Wastes that contain a large number of different types of contaminants.

3. Wastes that are situated such that field S/S will be difficult or expose local receptors to unacceptable risk.

4. Wastes with large amounts of interfering/incompatible constituents (pretreatment necessary).

5. Wastes that contain organics as the primary contaminants.

[a] S/S is not recommended for these wastes unless no other option exists.

- Waste can be treated with S/S with pretreatment or coupled with a different technology (treatment train).
- Waste can be treated with some type of technology other than S/S.
- No treatment technology is currently available for the waste.

Wastes that can be treated "as is" with S/S are those whose target contaminants are expected to respond favorably to S/S using at least one known binding agent. Such wastes should not have properties that would interfere with the S/S process.

Wastes requiring pretreatment include materials that are hazardous by virtue of ignitability, corrosivity, reactivity, infectiousness, presence of radionuclides, or some other property that would normally preclude secure land burial. Such wastes cannot be solidified or stabilized and disposed of in landfills without adequate pretreatment. Wastes that present specific problems, such as excessive escape of volatile organics of concern during treatment, may also fall into this category and require either pretreatment to reduce the volatiles or the use of additives in the S/S treatment formulation to inhibit emissions during S/S processing. Another example of a reason to pretreat a waste prior to S/S would be to remove an interference with the S/S technology. Conversely, S/S may itself also be the pretreatment step, for example, to improve material handling characteristics prior to treatment by a different technology.

Finally, wastes for which S/S is currently not a practical option include highly hazardous materials (because S/S does not convert metals or break organics down into basic chemicals), wastes containing excessive interferants that will not respond to treatment, and mixed wastes with complex chemistries that require several pretreatment steps prior to S/S. Such wastes become too expensive to process when compared with the cost for transportation and secure land burial in a RCRA-permitted facility. In many cases, these types of wastes will be treatable using a different type of technology. In rare cases, the waste will simply be untreatable. If allowed within regulations such as landban, the waste may be disposed of. If the disposal option is foreclosed, additional research will be needed.

2.5 WASTE/BINDER COMPATIBILITY LITERATURE SCREENING

After it has been determined that S/S is a potentially applicable technology for a specific waste (Section 2.4), surveying the technical literature to identify applicable binder types is a good starting point for the treatability study. The literature screening should result in the selection of two to four candidate binders for further evaluation at the laboratory bench-scale screening tier (Section 2.6).

The literature-screening step basically conforms to the remedy screening step, as outlined in U.S. EPA (1989e). Technical information resources, including information from reports, guidance documents, vendor information, and electronic databases, are useful reference materials. Any available performance and cost information should also be obtained for all binders being considered. A flowchart illustrating the waste/binder compatibility literature screening processes, as well as the organization of this section, is presented in Figure 2-6. The objective of this screening step is to identify, as simply and as inexpensively as possible, those binder types most suited for the site-specific waste and its contaminants and for the related waste disposal scenario.

2.5.1 Identify Available Binders

The selection of two to four binders for further evaluation is not a requirement, but is recommended because it improves the probability of a successful treatability study and requires minimal additional time and cost. This literature screening step is also intended to minimize potentially expensive trial-and-error bench-scale testing in the laboratory.

If a single binder or binder system has been preselected for bench-scale testing, then the literature screening step is no longer relevant. However, if that binder system proves to be ineffective in bench-scale screening (Section 2.6), then it will be necessary to select and test additional binder systems before it can be concluded that S/S is an inappropriate treatment technology.

2.5.2 Screening Process

The principal criteria for waste/binder compatibility literature screening are to determine (a) interferences and chemical incompatibilities,

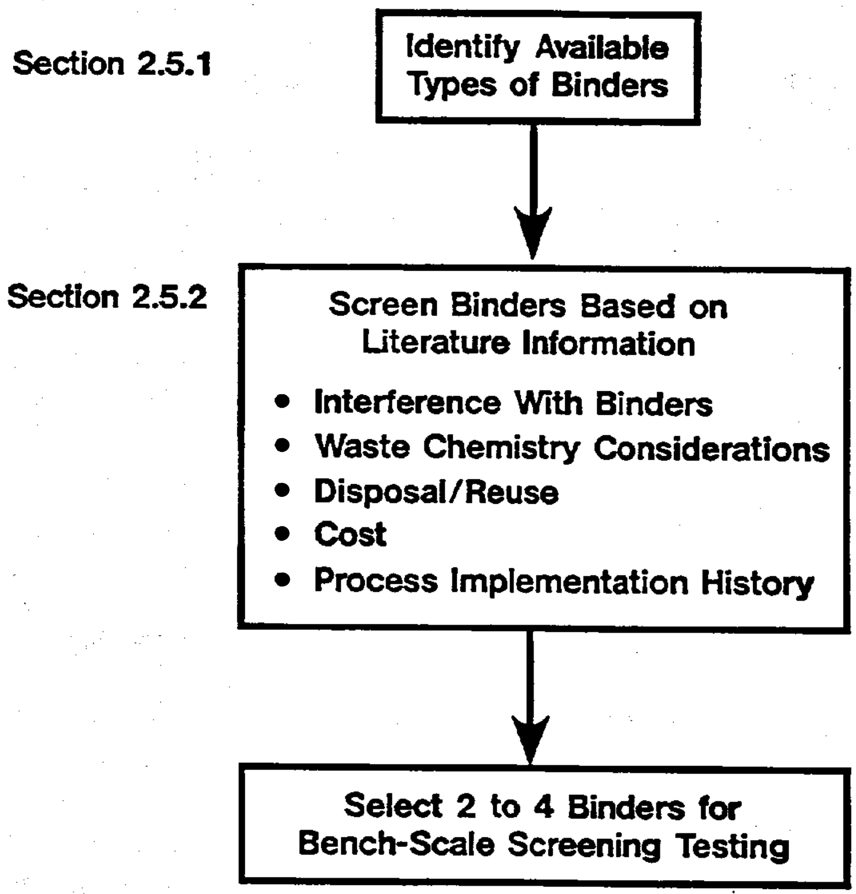

FIGURE 2-6. WASTE/BINDER COMPATIBILITY LITERATURE SCREENING

(b) metal chemistry considerations, (c) compatibility with the disposal or reuse environment, (d) cost, and (e) process track record. Ideally, an expert system should be developed to provide systematic evaluation of these issues. However, a fully usable system for complex waste forms has yet to be developed. The literature screening criteria are summarized below.

2.5.2.1 Interferences and Chemical Incompatibilities

Proper S/S treatment using pozzolanic binders may be inhibited in the presence of certain chemical constituents, such as high concentrations of oil, grease, and other organics, as well as chlorides and other soluble salts. Certain S/S processes will not function properly if the chemical environment is not adequately controlled. For example, sodium sulfide is incompatible with acids, which not only impair S/S but also may result in the release of toxic hydrogen sulfide gas. These and other types of waste/binder incompatibilities are summarized in Section 4.3 and in references cited therein. Material Safety Data Sheets (MSDSs) for individual waste components provide another potentially useful source of data on interferences and chemical incompatibilities.

2.5.2.2 Metal Chemistry Considerations

Metal chemistry is complex and has not been examined in any systematic manner as it pertains to S/S treatment and the chemical mechanisms of immobilization of contaminated soils. Section 4.2.2 and U.S. EPA (1990b, Appendix D) summarize some of the relevant chemical reactions. When alkaline binding agents such as cement, pozzolanic binders, or soluble silicates are used, the formation of metal hydroxides, oxides, and possibly silicates will be an important S/S mechanism. When sodium sulfide is used, extremely insoluble sulfide salts may form with numerous metals. In addition, metal carbonates, phosphates, and sulfates occasionally can be important in some systems.

Numerous chemical complexities exist. Chemical conditions, such as high pH (see Section 4.1.1) that are favorable for the immobilization of certain metals (e.g., Ni and Zn) actually may be detrimental to others. For example, As and Cr form soluble anionic species at high pH. Also, the solubility of many metal hydroxides is affected by their amphoteric behavior (solubility increases at both high and low pH). The minimum solubility for one metal may be several pH units different from the minimum solubility for another. Geochemical equilibrium modeling may be necessary to resolve issues related to complex waste chemistries.

2.5.2.3 Organic Chemistry Considerations for Target Contaminants

If organic contaminants are present, the binder selection must also be based upon compatibility with the organic contaminants. Section 4.2.2.2 discusses some of the types of binders and additives that are used frequently for immobilizing organic contaminants. These include such materials as activated carbon and modified clays. In general, generic binders such as Portland cement do a poor job of immobilizing organics, with the exception of highly polar compounds in low-to-moderate concentrations.

When evaluating the feasibility of applying S/S technology to wastes containing significant concentrations of organic contaminants, there are a number of issues that should be examined, as discussed in detail in Section 4.4. First and foremost is whether a destruction or extraction technology is available and applicable to the waste. All other factors being approximately equal, destruction or extraction technologies are preferred to S/S because they eliminate or remove the contaminant as opposed to just immobilizing it. Other issues that should be considered before concluding that S/S is the preferred approach for wastes containing organic contaminants are: (a) the volatility of the organics and whether air emissions may occur during excavation, mixing, and/or curing; (b) the solubility of the organics in water and the meaningfulness of conducting aqueous leach tests as a measure of the degree of immobilization of the organics by S/S treatment; and (c) whether the organic contaminants may degrade or transform to other by-products during S/S treatment and the toxicity of those by-products.

2.5.2.4 Compatibility with the Disposal or Reuse Environment

The ultimate planned use of the S/S-treated waste has a bearing on binder selection. Although many treated wastes may be disposed of in a municipal landfill, monofill, or some other subsurface burial site, others may be reused as fill, road base, or construction material. For still others, the method of treatment will be direct incorporation of the untreated waste, such as sandblasting grit, into a composite, such as asphalt. Numerous disposal and/or reuse options exist, but these are constrained by legal and institutional concerns. Reuse options, as opposed to disposal options, are nonroutine and subject to intense scrutiny to demonstrate environmental protection. Ultimate use options need to be anticipated and factored into the binder screening process along with product compatibility considerations.

For example, if the waste disposal location lies in the saturated zone, binder selection must consider the probability of water reaching the waste. Low permeability, adequate compressive strength, and stability in the groundwater geochemical environment will be important criteria. Also, engineering controls of disposal site hydrogeology may be incorporated to supplement binder performance criteria. Waste disposal site and waste performance considerations all relate to the protection of public health and the environment.

2.5.2.5 Cost

Cost is an additional binder screening criterion, although this criterion should be applied only after the interference, chemistry, and disposal/reuse environment issues have been considered. Because economic considerations are secondary to performance considerations, cost should be used only to screen binders that are significantly less economical or whose benefits clearly do not justify the added expenditure.

2.5.2.6 Process Track Record

Finally, process track record may be a discriminating factor in the selection of binders for bench-scale testing. Several databases have been developed that may be referred to as sources of information on successful treatability studies. Conner (1990) contains numerous tables of performance data from previous treatability studies, organized by metal. Means et al. (1991a) contains, on a disk in PC-DOS spreadsheet format, a tabulation of more than 2,500 performance data from S/S treatability studies. The database can be sorted by metal, waste type, binder type, or other delineators. Note, however, that published performance data from previous treatability studies generally are of limited value in designing future treatability studies because seldom do those publications provide the level of detail necessary to permit replication of the experiment. Also, subtle variations in waste chemistry can lead to very different treatability results.

Although process track record may be one of the factors used to select binders for bench-scale testing, its inclusion here is not intended to discourage the use of innovative or experimental binders or S/S technology, which may prove very useful in certain circumstances.

2.6 LABORATORY BENCH-SCALE SCREENING OF THE WASTE/BINDER MIXTURES

2.6.1 Purpose

The result of the waste/binder compatibility literature screening described in Section 2.5 will be a list of binders or binder additive systems that are promising candidates for S/S treatment. If only one binder is identified, then it should be tested as described in this section to determine whether it has merit; otherwise it will be necessary to identify an alternative binder.

Because the technology screening to this point has been based on the literature review and generic information from previous S/S projects, the analysis now needs to be made specific to the actual waste being studied. Waste/binder mixes should be tested in the laboratory to determine relative performance. Because analytical testing is expensive, it is impractical to conduct a full set of performance tests on all of the waste/binder mixtures. Therefore, the testing at this stage takes the form of "screening" as opposed to detailed performance testing and is limited to the minimum required to indicate process applicability.

The bench-scale screening process described in Section 2.6 essentially equates to the "remedy selection" screening step in U.S. EPA's guidance for treatability testing under CERCLA (U.S. EPA, 1989e). Note that for certain S/S projects, where there is a high level of confidence that a given binder will easily satisfy the project's performance goals, this bench-scale screening step may be deemed unnecessary. This might be the case in situations where waste properties are simple and straightforward, and where the selected binder has a demonstrated track record for the waste being stabilized. However, because of the numerous possible subtleties in S/S process implementation and the possible effects of site-specific water properties on binder performance, it is highly recommended that bench-scale screening be conducted whenever possible.

The general steps of the bench-scale screening process are summarized in Figure 2-7. As this figure indicates, several iterations may be necessary. Candidate binders identified from Section 2.5 are screened using simple bench-scale treatability tests. If the performance data do not discriminate sufficiently among binders, then additional screening criteria, such as ease of implementation in the field and cost, also may be considered at this stage. The binder or binder system that is ultimately selected will undergo more thorough bench-scale performance testing as described in Section 2.7.

2.6.2 Approach

Bench-scale screening entails mixing relatively small amounts of waste with binders for testing individual parameters or indicators of S/S technology performance. These laboratory tests, which are used to determine whether the "chemistry" of the process works, are usually performed in batch (e.g., "jar tests") with treatment parameters varied one at a time. Because small volumes and inexpensive reactors such as bottles or beakers are used, bench-scale screening tests can be an economical way to test a relatively large number of performance and chemistry variables. It is also possible to evaluate a treatment train made up of several technologies and to generate limited amounts of residuals for evaluation.

2.6.2.1 Experimental Design

At the screening stage a large number of treatment options are possible. For this reason, it is important to efficiently design the laboratory experiments. The important experimental questions to be answered can generally be expressed as hypotheses that are supported or disproved based on the experimental data. Decisions about how many and what kinds of data to measure are made most reliably on the basis of statistical experimental design procedures used to reduce the effects of experimental errors in the measured data. The area of experimental design has been well developed (e.g., Cochran and Cox, 1957; Hicks, 1973). The six fundamental steps in developing a statistical experimental design are as follows:

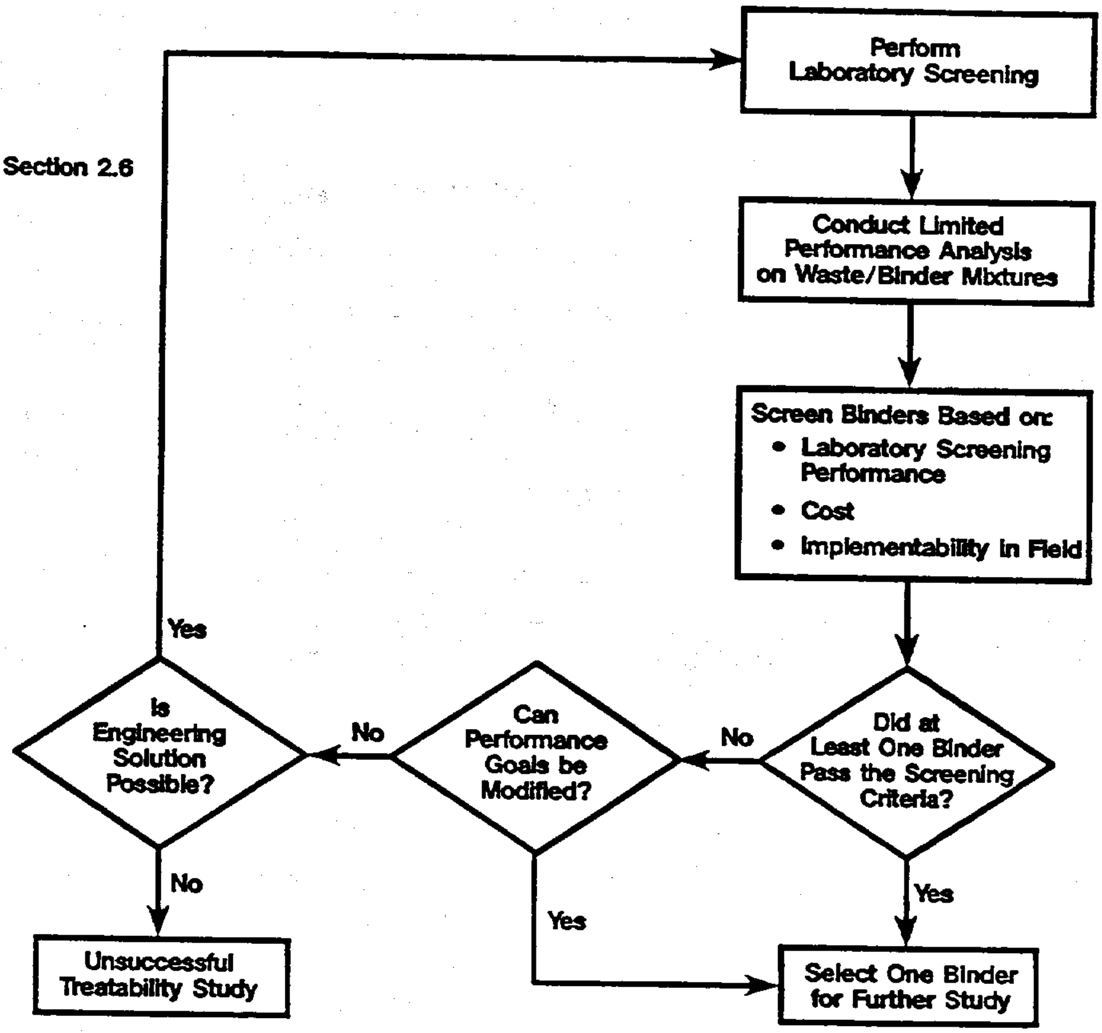

FIGURE 2-7. LABORATORY SCREENING OF WASTE/BINDER MIXTURES

1. Clearly define the experimental objectives along with the tests to be performed.

2. Define the experimental factors to be controlled, as well as the levels and combinations of these factors to be investigated.

3. Establish the method of randomization to be used.

4. Select a statistical model to describe the experiment.

5. Specify the data analysis procedures to be employed as well as the desired statistical properties.

6. Select the experimental design parameters to achieve the desired statistical properties.

2.6.2.2 Performance Testing

Bench-scale screening is performed at this stage to comparatively evaluate the candidate binding agents. As previously indicated, extensive analytical data are not needed. Depending on the performance criteria of concern, one or two simple performance tests, such as the frequently recommended TCLP and unconfined compressive strength (UCS) tests, should suffice for screening. The TCLP is recommended because of its regulatory status and because, compared to other leaching tests, it is relatively simple and inexpensive to perform. The UCS test is recommended because most disposal and reuse options for S/S-treated waste will have some level of UCS performance standards. For example, 50 psi is typical guidance per U.S. EPA (1986b). However, situations may be encountered where the use of other screening tests is justified. Testing methods are discussed in Chapter 3.

It may be appropriate at this stage to test the effectiveness of different binder/waste ratios, because an optimal ratio cannot be determined a priori. If the binder/waste ratio is not treated as a variable, some useful binder may be rejected from further consideration because it was tested at the wrong proportion(s). One test facility typically uses binder/waste ratios of 0.1, 0.3, and 0.6 based on dry weight (Barth and McCandless, 1989). These are probably appropriate for most generic binders. However, specialty binders may operate optimally at other ratios. If the binder/waste ratio is treated as a variable at this stage, then three variations will yield the necessary data for most cases. More or fewer binder/waste ratios may be needed depending on factors such as waste complexity and toxicity. However, for CERCLA remedial actions, it rarely is worthwhile to test at binder:waste ratios greater than 1.0, because of chemical costs and the disposal complications presented by the volume expansion of the waste at the higher ratios. Higher ratios may be useful if blast furnace slag or kiln dust are available or if higher water contents require higher binder addition.

Whatever performance criteria are chosen for testing, the waste should satisfy the criteria with some margin of safety because the laboratory is a more controlled environment than the field for testing. In the field, ingredient proportions and the thoroughness of mixing are more variable. Typical guidance for the extent of this margin of safety is that the performance criteria should be satisfied by at least a factor of 2. For example, TCLP-tested Pb should be ≤ 2.5 mg/L, versus the U.S. EPA threshold of 5.0 mg/L. This is technical guidance, not policy.

If screening tests fail to discriminate sufficiently among the binders (i.e., they perform similarly), then it may be appropriate to screen the binders based on other factors, such as ease of field application (implementability) or cost. Ease of application in the field refers to process complexity or sensitivity of performance to process parameters. Highly complex processes, such as numerous sequential steps and processes that are extremely sensitive to process parameters, such as exact ingredient proportions and thorough mixing, may be very difficult to implement in the field and probably should not be attempted unless preceded by a pilot- or full-scale demonstration. Health and safety considerations for workers and nearby inhabitants also affect the ease of using a particular S/S process at a particular site. Both the S/S field equipment necessary and treatment chemicals used should be conducive to safe and efficient application under actual field conditions.

A final factor affecting binder screening is cost. If all other factors (performance and implementability) are equal, then cost may be used to select a binder. The most significant cost items are usually chemicals, equipment rentals or use rates, and labor. The latter two categories of cost information are difficult to estimate at this stage. However it should be possible to develop a sense for the overall process complexity and maximum possible processing rate. Additional information pertaining to the cost of S/S treatment is provided in Section 4.10.

2.6.3 Technical Guidance

Guidance for bench-scale binder screening is summarized in Table 2-12. This information is provided to assist in planning and implementing valid bench-scale screening tests for S/S.

2.7 BENCH-SCALE PERFORMANCE TESTING/PROCESS OPTIMIZATION

2.7.1 Purpose and Objectives

At this stage in the S/S treatability study, limited treatability testing has been conducted and a promising binder has been identified. Now it is necessary to demonstrate that the binder will achieve all relevant project performance goals and to optimize the S/S process in terms of design, field implementability, and cost performance. This step in the treatability study is referred to herein as "bench-scale performance testing/process optimization" and equates to the "remedy design testing" step in U.S. EPA's guidance for performing treatability studies under CERCLA (U.S. EPA, 1989e). Bench-scale performance or remedy design testing is frequently performed soon after the Record of Decision in CERCLA projects, prior to implementing the remedy.

A descriptive performance testing protocol that will satisfy the requirements of all S/S projects cannot be specified because site-specific projects have different performance goals and because the response of individual wastes to S/S technology can be unpredictable. In the absence of extensive regulatory requirements for S/S treatment projects, acceptance criteria must be determined largely on a case-by-case basis. The approach summarized here and illustrated in Figure 2-8 advocates that the level of performance testing be set by the potential level of risk posed to human health and the environment. That is, the testing program should be based upon the guiding principles derived from the ultimate risk posed by the waste in its planned disposal or reuse environment.

Four principal factors affect risk in this context:

- Waste volume
- Type and concentration of contaminants (metals, organics, or both)

TABLE 2-12. BENCH-SCALE BINDER SCREENING GUIDANCE

1. Test the effectiveness of any pretreatment system.

2. Screen at least two to four binders at two or more binder/waste ratios.

3. Ensure there are no binder/waste incompatibilities that could pose a safety hazard (release of toxic gas, etc.).

4. Use process, waste, and binder information to determine whether to base testing on composited waste samples, worst-case samples, or both.

5. Carefully monitor, control, and record binder additions, order and sequence of additions, timing, and other procedural information.

6. Conduct several rounds of bench-scale testing to optimize binder performance.

7. The chemical compositions of the binder and binder additives should be known or chemically analyzed to ensure that these ingredients do not contain hazardous constituents or properties. Consult MSDSs at a minimum.

8. New ARARs may be developed as a result of the binder and/or binder additives (e.g., dust emissions, corrosivity [pH] limits, etc.).

9. Have the treatability study witnessed by an independent third party or regulatory agency for impartiality.

10. Simulate anticipated field conditions during curing as closely as possible (e.g., do not necessarily put the treated waste immediately into a sample jar).

11. Allow the sample to cure properly before chemical and physical analyses.

12. Calculate the percent reduction in TCLP contaminant concentration caused by stabilization both with and without the effects of waste dilution by binder ingredients.

13. Test the most critical ARARs (e.g., leaching characteristics and critical chemical/physical properties).

14. Assess air emissions if volatile organics are present.

15. Send splits of a few samples to a second laboratory for interlaboratory verification.

16. Conduct the bench-scale screening project under a proper QA/QC program, including statistical design, replication, blind controls, compliance with laboratory certification requirements, etc.

17. Calculate or measure waste volume increase from binder/water additions.

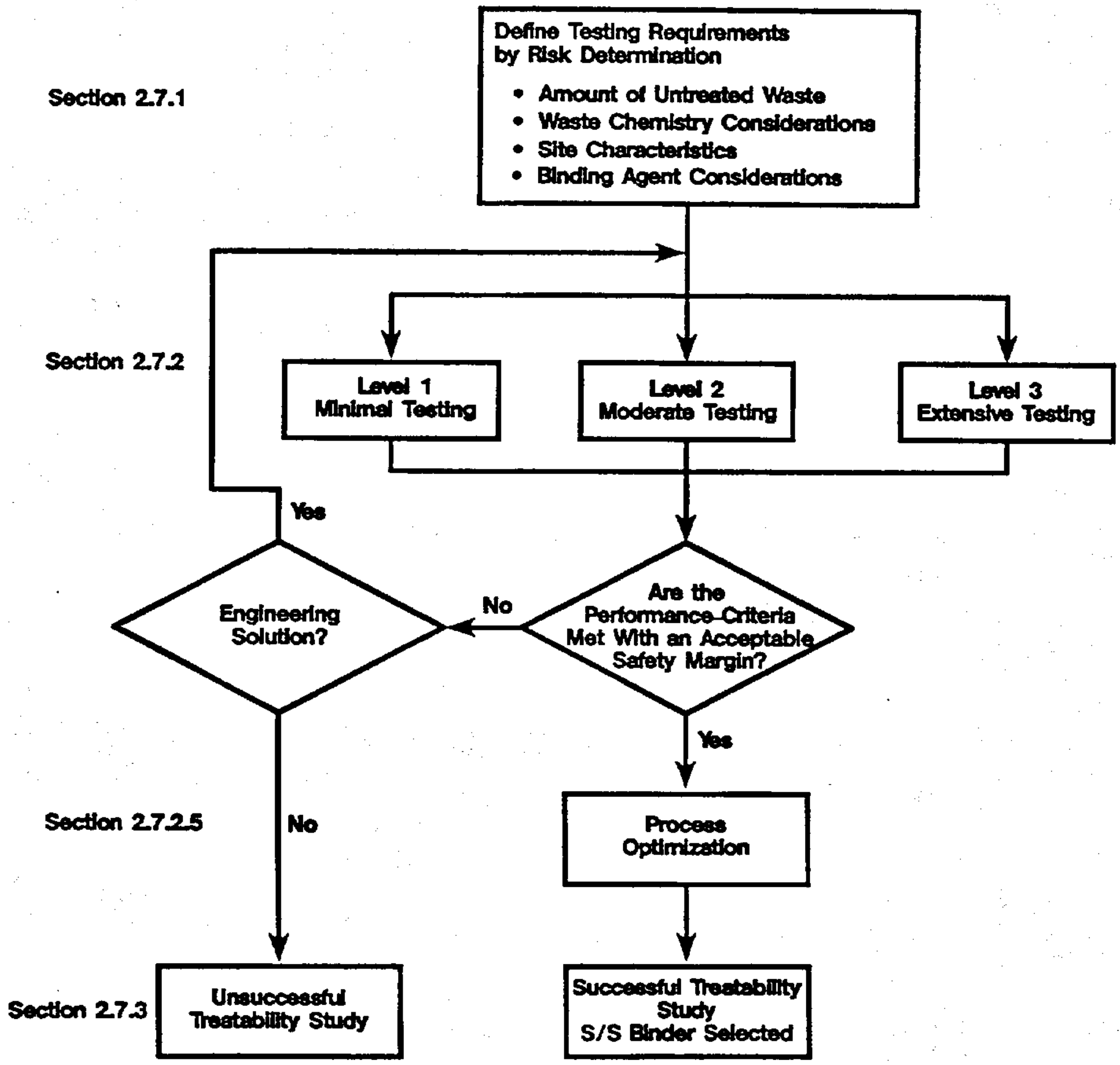

FIGURE 2-8. BENCH-SCALE PERFORMANCE TESTING OF SELECTED WASTE/BINDER MIXTURES

- Site characteristics of the planned disposal or reuse environment

- Demonstrated performance of the S/S process selected

This section provides qualitative guidance for determining the level of risk based on the above categories of factors. The level of risk then determines the general extent of recommended performance testing. More extensive testing requirements are required for projects that present greater risk in order to increase the level of confidence that the treated waste will remain stable for the long term. One type of testing requirement that is not derived from risk pertains to specific binders. Testing related to binder evaluation is discussed briefly in Section 2.7.2.3.

The goals of bench-scale performance testing and process optimization are to demonstrate that the S/S-treated waste is:

- Chemically and physically stable (i.e., no free liquids as determined by the paint filter test, low leaching rates)

- Compatible with its disposal or reuse environment (e.g., possesses adequate compressive strength, is nonbiodegradable, and has sufficiently low permeability)

- In conformance with the ARARs by an adequate margin of safety

- Cost-effective compared with other possible treatment technologies

- Demonstrated effective and readily implementable in the field

Generalized procedures and rationales for determining the level of performance testing are provided in the following sections. Please note that this approach applies mainly to projects under CERCLA remediation and RCRA placement. As indicated in Section 2.3, the testing requirements of a RCRA TSD facility are more specific and include the Paint Filter Test for free liquids, the TCLP for leachable metals, and the other three tests for hazardous waste characteristics (i.e., ignitability, corrosivity, and reactivity).

2.7.2 How Much Performance Testing?

2.7.2.1 Levels of Risk

Risk determination is probably equivocal in most cases, and exceptions to any approach will always be identified. No expert system exists yet for determining risk as it relates to S/S projects. One approach, however, is based on the principal risk factors identified in Table 2-13. This simplified approach is provided as rule-of-thumb guidance only. As indicated previously, numerous exceptions are likely to exist.

The categories of risk in Table 2-13 are (a) waste volume, (b) type and quantity of metal contaminants, (c) type and quantity of organic contaminants, (d) site (disposal or reuse) characteristics, and (e) demonstrated effectiveness of the S/S process. Each of these risk categories is subdivided into low, medium, or high risk levels. Examples of each are given in Table 2-13. The trends are straightforward. Larger volumes of waste, higher hazard contaminants, site conditions promoting possible exposure to human or ecological receptors, and undemonstrated S/S processes are all associated with higher risk and therefore higher levels of performance testing. Metals and organics are considered separately, because a waste containing both is more difficult to treat and therefore poses greater risk than a waste containing only one or the other. Table 2-13 shows where a project falls among the five risk factors and is used to determine the necessary level of performance testing, which is explained further in Section 2.7.2.2. Identifying the level of risk is a subjective determination on the part of the participants in the treatability study.

2.7.2.2 Levels of Performance Testing

Three levels of performance testing correspond to the three levels of risk from Table 2-13. Table 2-14 describes some typical testing requirements (leaching, physical, and other chemical tests) for each of the three levels. The tests to be run cannot be specified exactly, as they will depend upon the needs of the individual S/S project. For example, a freeze/thaw test may not make sense for an S/S-treated waste placed entirely below the frost line. Permeability would be of little consequence for disposal in the desert far above the groundwater table. Thus, Table 2-14 provides guidance on the overall magnitude or level of effort associated with the testing program as opposed to specific testing requirements.

TABLE 2-13. RISK FACTORS FOR EVALUATING LEVELS OF PERFORMANCE TESTING

Risk factors	Risk levels: I. Low risk	II. Medium risk	III. High risk
A. Waste volume	· <1,000 cu yd	· >1,000 to <10,000 cu yd	· >10,000 cu yd
B. Metal contaminants	· Noncarcinogenic · Low toxicity (e.g., Cr[III], Ba, Zn, Mo, Cu) · Low to moderate concentrations	· Noncarcinogenic · Moderate toxicity (e.g., Pb, Se, Sb) · Low to moderate concentrations	· Known or suspected carcinogen · High toxicity (e.g., Cr[VI], Cd, Hg, As, Be] · Very high concentrations
C. Organic contaminants	· Low total organic carbon content · Low hazardous organics · Low-interference organics	· Same general criteria as Level II metals (e.g., organic priority pollutants other than those under III, high-risk organics such as cresols, xylenes, and aldehydes)	· Same general criteria as Level III metals (e.g., PAHs, PCBs, dioxins, furans, certain pesticides, chlorophenols) · High-interference organics
D. Site characteristics	· Vadose zone disposal or depth to groundwater >25 ft · Dry climate · Low population density · Distant from drinking water source · RCRA-permitted disposal facility	· Conditions intermediate between I and III	· Saturated zone disposal or depth to groundwater <5 ft · Wet climate · High population density · Close to drinking water source · Windy conditions coupled with aboveground disposal or reuse

TABLE 2-13. RISK FACTORS FOR EVALUATING LEVELS OF PERFORMANCE TESTING (Continued)

	Risk levels		
Risk factors	I. Low risk	II. Medium risk	III. High risk
E. History of process effectiveness	· Well-established, frequently used process with generic binders and contaminants that stabilize readily	· Field-demonstrated, but not as frequently used	· Innovative or complex process for contaminants that are more difficult to stabilize (e.g., As, Cr[VI], phenol)

TABLE 2-14. LEVELS OF PERFORMANCE TESTING AND EXAMPLE TESTING REQUIREMENTS

Testing level	Example testing requirements[ab]		
	Leaching	Physical	Other chemical
I. Low	• One short-term test (e.g., 5-day ANSI/ANS/16.1)	• Minimum number of parameters needed to demonstrate compatibility with disposal or reuse environment	• As needed; pH usually required to demonstrate noncorrosiveness
II. Medium	• One short-term test (e.g., 5-day ANSI/ANS/16.1) and one medium or long-term test (e.g., MEP)	• Several physical parameters (e.g., UCS, permeability, specific gravity) • Freeze/thaw and wet/dry tests if aboveground use is planned	• As needed (e.g., pH, acid neutralization capacity)
III. High	• Several tests, including one long-term test (e.g., MEP or 90-day ANSI/ANS/16.1); geochemical and/or transport modeling may be advisable • A solvent extraction test (total waste analysis) to demonstrate the chemical stabilization of non-TCLP-list organics (see Section 4.4.3) • Nonroutine analytical procedures as required to indicate chemical bonding	• Applicable properties from Level II plus standard factor test, California bearing ratio, freeze/thaw and wet/dry tests, and others as appropriate • Biodegradation tests if pertinent to the binder	• pH, acid neutralization capacity, Eh, volatile emissions as appropriate to show chemical stability and compatibility • Bioassays as appropriate • Speciation of contaminant metals to show potential for long-term stability

[a] Assumes TCLP levels and UCS have been determined previously in laboratory screening. If the process formulation has been modified, TCLP and UCS should be rerun.
[b] These are candidate tests given as examples only.

As Table 2-14 indicates, high-risk projects require more rigorous levels of testing to establish a higher degree of confidence that the S/S-treated waste will attain and maintain the required levels of performance. For most high-risk S/S projects, this also means that the potential for long-term leaching should be assessed. For final placement close to natural waterways, the need for acute bioassay testing may also be considered. A large number and wide variety of performance tests may be conducted. Chapter 3 discusses a selection of the many available physical, leaching, chemical, biological, and microcharacterization tests. Chapter 3 may be consulted for information about the types of tests available, the information they provide, and any existing acceptance criteria.

2.7.2.3 Tests for Specific Binding Agents

Binder selection is an additional consideration in designing the performance testing program. Certain types of tests relate more to the specific properties of the binder than to the risk associated with waste chemistry and site characteristics. Examples include the following:

- When sulfide is used as a treatment chemical, pH and reactive sulfide analyses (or sulfide reactivity, the so-called "Claussen test") should be conducted to ensure that the waste meets the RCRA corrosivity (pH less than 12.5) and reactive sulfide (less than 500 mg/kg) guidelines.
- When thermoplastics or other organic binders are used, biodegradation tests may be required.

In some situations, a test method may need to be modified to accommodate a specific S/S-treated waste. For example, because the oils and bitumens in asphalts would probably lead to filter plugging, the filtration procedures may need to be modified or eliminated completely.

2.7.2.4 Acceptance Criteria

The success of the treatability study will be measured in terms of whether the tests satisfy predetermined performance objectives. Some of these criteria are regulatory limits, such as the metal thresholds that have been established for the TCLP, EP Tox, and California Waste Extraction Test (WET).

However, most criteria are not strict regulatory limits and must be determined on a case-by-case basis. For example, the target permeability and UCS criteria will vary with the site characteristics of the disposal environment. Permeability requirements will vary with the water flux through the disposal zone and the proximity to the groundwater table. The UCS criteria should be based on an engineering calculation of the load under which the waste will be placed plus a safety factor.

The approach for determining acceptance criteria generally emphasizes designing to the needs of the individual project. It is not cost-effective to design overly restrictive criteria. However, the criteria need to be adequate to ensure, with an acceptable degree of probability, that the S/S-treated waste will perform satisfactorily in the field.

If the treatability study is unsuccessful (i.e., if some performance objectives are not satisfied), then several options are available, for example:

- Revise the performance objectives within regulatory limitations (for example, exception to ARARs)
- Modify the formulations
- Investigate a completely different binder system
- Add more engineering controls to the final placement location

Most performance defects identified in treatability studies can be corrected by process or binder modifications. However, the resulting S/S treatment system may be complex or expensive. If performance is so unsatisfactory that S/S is not a viable option, then the S/S treatability study is concluded.

2.7.2.5 Process Optimization

The bench-scale treatability environment offers an excellent opportunity to fine-tune the S/S process for site-specific waste. Process optimization includes the following types of activities:

- Determining the trade-offs between reducing the binder:waste ratio and associated cost savings versus process performance

- Determining the optimal sequence of binder or additives in terms of processing rate and process performance

- Evaluating the sensitivity of the S/S process to slight variations in binder amounts, curing conditions, and/or mixing efficiency

- Evaluating the sensitivity of the S/S process to expected variations in waste properties (average vs. worst-case contaminant concentrations, variable matrix properties, etc.)

Process optimization is an important step in maximizing cost-effectiveness and determining process sensitivities.

2.7.3 Technical Guidance

Guidance for conducting bench-scale performance testing is provided in Table 2-15. The guidance provided in Section 2.6 (Table 2-12) is also applicable.

2.8 PILOT-SCALE AND FIELD DEMONSTRATIONS

2.8.1 The Need for Process Scale-Up

Bench-scale treatability testing ends when a suitable binder and binder:waste ratio is selected. The user must then determine whether a pilot test or field demonstration test of the stabilization process is necessary prior to a full-scale cleanup. A pilot test generally refers to an intermediate-scale simulation (often in the laboratory) of a full-scale operation. Field demonstration generally refers to a simulation of the full-scale operation conducted on-site with actual full-scale (or close to full-scale) equipment. A pilot or field test may be needed to build confidence in the binder selection or to gather data for design of the full-scale system. Pilot-scale studies are typically directed at resolving equipment sizing, selection, or scale-up issues. Usually in S/S technology, the field test is a dry-run of the full-scale treatment equipment under carefully monitored conditions prior to proceeding with full-scale treatment. The expense of a

TABLE 2-15. GUIDANCE FOR BENCH-SCALE PERFORMANCE TESTING

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1. The same guidelines concerning procedures for conducting bench-scale treatability tests provided under section 2.6 (Table 2-11) also apply here.

2. Performance tests are needed for all ARARs, for example:

   a. If subsurface disposal is planned, appropriate tests should be conducted (e.g., unconfined compressive strength and permeability, etc).

   b. If surface or near-surface disposal is planned, appropriate tests should be conducted (e.g., wet/dry, freeze/thaw, etc.).

   c. Long-term stability needs to be ensured. The TCLP is not sufficient evidence of long-term stability. Alternative leaching tests should be conducted that better address long-term stability (see Section 3.2) and/or the TCLP should be conducted on treated waste after different curing periods (Section 4.7).

   d. For wastes having organic contaminants with low aqueous solubilities, leaching with an organic solvent may be appropriate (see Section 4.4.3).

   e. For wastes containing organic contaminants, conduct a mass balance to account for the fractions of contaminants that are leachable, immobile, and released due to volatilization.

   f. For a suspected colloidal contaminant transport mechanism, consider substituting larger pore-size filter medium for the standard filtration medium or using centrifugation instead of filtration.

   g. Leach tests using site-specific groundwater (as opposed to generic leachate or distilled water) may be appropriate.

   h. If the binder is biodegradable, a biodegradation performance test should be conducted.

   i. If the disposal site could leach into an aquatic system, leachate bioassay may be appropriate.

   j. Note that the binders themselves may contain contaminants such as metals; these should be taken into consideration in performance testing.

3. A total contaminant analysis should generally be performed on the same subsample used for leach tests to eliminate false negatives.

4. The leaching performance data should be corrected for the effect of dilution to determine the actual extent of stabilization due to binding.

TABLE 2-15. GUIDANCE FOR BENCH-SCALE PERFORMANCE TESTING (Continued)

5. Simulate field conditions as closely as possible during curing.
6. Allow the waste to cure for an appropriate period of time before analysis.
7. The entire performance testing program should be conducted under an appropriate QA/QC program, including statistical design, replicates, analytical methods, blind controls, and other controls.
8. There should be a safety margin in the performance data relative to the numerical thresholds because the S/S process may not work as well as in the field.
9. The S/S process developed and demonstrated at this stage must be implementable in the field (i.e., not too complex).
10. The volumetric expansion of the waste during treatment must conform to the disposal space constraints.
11. The cost should be realistic for an S/S treatment option; depending on the circumstances, a realistic cost is usually less than $150/ton.
12. Splits of some proportion of the samples should be sent to a second analytical laboratory for interlaboratory comparison.
13. It is advisable for bench-scale testing to be observed by an independent third party or regulatory agency for impartiality.

pilot-scale (intermediate-scale) test is usually not warranted, except for very complex S/S projects.

The decision whether to do a pilot or field test hinges mainly on how widely a particular waste/binder system has been demonstrated in the past. Other factors such as regulatory requirements, full-scale equipment design, and cost estimation are also considered. If treatability testing shows that the waste contains common forms of contaminants that respond well to stabilization in a matrix that contains no significant amounts of interferants, and if the binder system is well-demonstrated and commonly used on these contaminants, then a pilot or field demonstration may not be necessary. If the contaminant species is complexed in the waste matrix, if the waste contains interferants, or if a not-so-well-understood binder system is being used, a pilot or field-scale demonstration is advisable to ensure the effectiveness of the process. As indicated above, a field demonstration can be conducted simply as a discrete part of the full-scale cleanup, with a pause after the demonstration to evaluate effectiveness and/or allow for regulatory review. This is a useful step for calibrating material flow rates and for determining optimal processing rates. Any deficiencies in the field equipment can be identified and corrected, and field personnel can be trained in the safe operation of the full-scale equipment. Once the S/S process has been demonstrated in the field, the cleanup can continue with the same equipment.

Safety problems can also be identified during pilot/field testing. For example, the *Handbook for Stabilization/Solidification of Hazardous Waste* (U.S. EPA, 1986c) describes how rapid addition of a reactive stabilization agent (e.g., unhydrated lime) can cause rapid volatilization of lower boiling-point organics, leading to flash fires.

A specific case history demonstrates the advisability of a field test prior to full-scale treatment. Physical conditions during full-scale cleanup may vary from those in the laboratory so as to alter or prevent the desired reactions of the stabilization process. A case in point is described by Means et al. (1991b) for a field demonstration stabilizing sand blasting grit containing copper and lead as contaminants. A laboratory-proven binder system composed of sulfide and fly ash was used during the initial demonstration. The treated waste was stored in the open on plastic sheets for curing. Samples of the cured waste showed that the waste at the top of the pile was not as well stabilized as the waste at the bottom of the pile. During further treatability testing, it was discovered that when the waste was cured in a jar, stabilization was effective. When the waste was cured on a gentle incline in the open air, simulating the field waste material, some excess stabilization reagent was observed draining off the waste material. It was concluded that environmental conditions caused by piling were preventing the reaction between the sulfide and the metal ions from reaching completion. Thus, the field system was shown to be not as effective as the bench-scale system for this stabilization project. Fortunately, the problem was identified and corrected at an early stage of field treatment.

All the factors mentioned above should be taken into consideration in determining the need for a field demonstration before full-scale cleanup. Once a decision is made to proceed with the demonstration, the steps in the flowchart of Figure 2-9 may be followed. Two to four small batches of waste

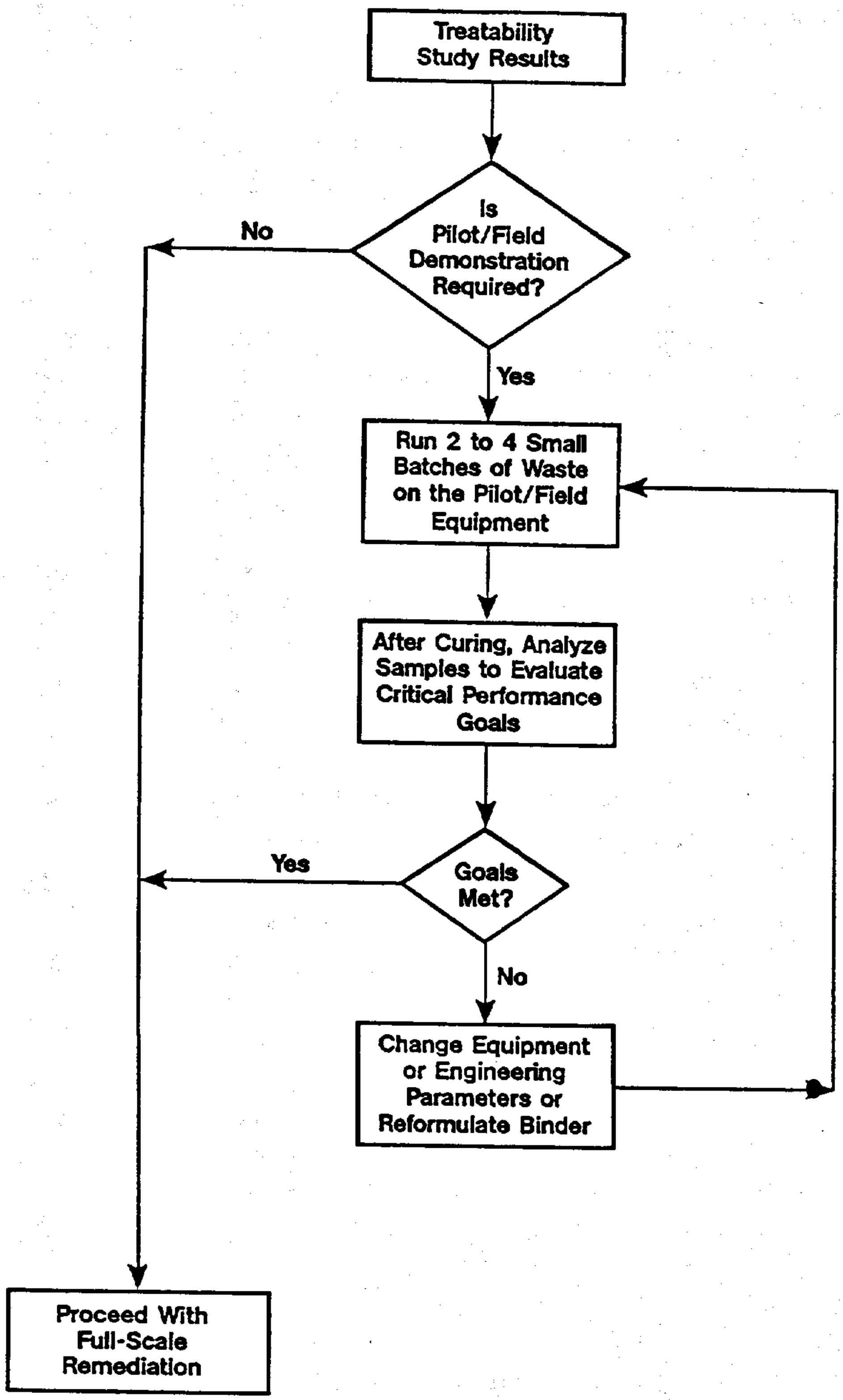

FIGURE 2-9. PILOT-SCALE TEST SCREENING

are typically run, with 1 to 15 cubic yards of untreated waste material per batch generally used depending on the size of the available equipment. Statistically significant samples are taken and analyzed by the tests described in Chapter 3 to demonstrate effectiveness. Adequate quality assurance procedures are followed during sample collection and analyses to ensure reliability.

After allowing the treated waste to cure, the samples can be analyzed and evaluated for critical performance goals as determined at an earlier stage. If the samples meet these performance objectives, the user may proceed with the full-scale cleanup. If the samples fail the performance objectives, the user has to determine whether the field-scale equipment, the binder formulation, and/or other engineering parameters (e.g., flow rates, storage environment) are at fault. Further testing may be necessary to identify the cause of the deviation between bench-scale and field-scale results.

2.8.2 Scale-Up Issues

Scale-up from a bench-scale to field demonstration or full-scale process generally focuses on the materials handling aspects of the process since the chemistry already has been addressed in the bench-scale tests. Scale-up plans should address each of the following wherever applicable:

- Waste excavation for ex situ processes
- Waste handling
- Equipment selection & sizing
- Chemical reagents (binder) storage
- Pretreatment of waste
- Presence of debris
- Materials balance
- Mixing and curing
- Stabilized waste disposal

The most common methods of stabilization are plant mixing and in situ mixing. Plant mixing involves removing the waste from its location and transferring it to a treatment plant. The waste is mixed with the stabilization agents in the fixed or mobile treatment plant. During in situ mixing, the waste remains in place, and the stabilization agents are injected or mixed with specialized augers or other equipment.

Another method, area mixing, is used mainly for treating oily sludges or semisolid wastes. In this method, a layer of waste is placed in the disposal area and covered with a layer of stabilization agents. The layers are lifted and turned over repeatedly and then dried and compacted. A top layer of clean soil is then added as a cap. Yet another method, in-drum mixing, is generally used for highly toxic wastes in drums. If there is enough headspace above the waste in the drum, stabilization agents may be added and mixed with the waste.

The U.S. EPA published several Technology Evaluation Reports on its SITE demonstrations of stabilization techniques such as plant mixing (U.S. EPA 1989h and 1989i) and in situ stabilization (U.S. EPA, 1989j). These reports contain important information on field operation and performance. The *Handbook for Stabilization* (U.S. EPA, 1986c) is also a good reference, describing operating characteristics and cost of large-scale equipment.

A discussion of some commonly used full-scale stabilization equipment follows.

2.8.2.1 Waste Excavation and Handling

Traditional earth-moving equipment (e.g., backhoes, draglines, bulldozers, front-end loaders) is used for this process. If free liquid is present on top of the waste, it may have to be pumped out and treated as a separate waste stream. The equipment operator may have to be completely enclosed or provided with breathing apparatus if air hazards are generated during excavation.

Depending on the nature of the waste and the site, the excavated waste can be transported to the treatment plant by a fixed system (conveyor or screw auger), dump truck (for soil), pump and hose (for liquids and sludges), or, if the waste is particularly hazardous, in drums. Spillage should be avoided during transport.

2.8.2.2 Stabilizing Agent Storage

For cost-effective operation, it is important that sufficient amounts of chemicals be available to avoid project shut-down for restocking. Amounts required are determined from treatability testing results, specifically the binder:waste ratio. Bins, hoppers, and silos are used for storage of dry chemicals. If liquid chemicals are being used, liquid storage tanks or drums may be necessary. Unless the waste volume is small, chemicals generally need to be replenished on a continuous basis during the project.

2.3.2.3 Pretreatment of Waste

Pretreatment may be necessary for (a) improving the material handling characteristics of the waste, (b) improving waste/binder compatibility, and (c) removing constituents that either interfere with or are not affected by S/S processing. (See Section 4.1.4). Pretreatment can sometimes also reduce the quantity of stabilization agents during mixing.

Pretreatment may include screening and/or size-reduction equipment such as crushers (to remove large rocks or debris that may clog up the mixing equipment), drying or dewatering, blending and homogenization, pH adjustment, or heating to drive off volatiles. If volatiles are being driven off, some capture mechanism for the vapors may be necessary. Oversize materials from screening may have to be treated separately or disposed of appropriately.

Pretreatment is important from a materials handling point of view, especially at sites where the waste is difficult to handle with standard earth-moving equipment. There have been instances where the entire remediation operation had to be temporarily abandoned because of problems at the pretreatment stage. Screens and crushers can easily get clogged, especially with wet, sticky, or fine materials such as clay. Use of vibratory screens or special crushers may be necessary.

2.8.2.4 Mixing and Curing

Mixing is a critical step in ensuring good S/S process performance. All precautions must be taken to ensure that the waste and binder chemicals are mixed thoroughly and allowed to cure adequately. A wide range of mixing equipment is suitable for this application. The choice of equipment depends on the type of waste/binder system and method of stabilization. In the most simple and inexpensive situation, area mixing can be done with a backhoe.

For in situ mixing, special augers and drills are used to inject the stabilization agents into the soil and to cause agitation and mixing. Backhoes can be used as in situ mixers, but the mixing is not reliable. Another in situ process is grouting, whereby fluids (usually water and cement) are injected into the ground, where they are allowed to set in place.

Plant mixing provides the maximum control on the mixing process. A range of equipment, including pug mills, extruders, ribbon blenders, sigma mixers, muller mixers, and screw conveyors is available. Standard construction-type cement or concrete mixers and transit-mix trucks have also been used. Mixing can be done as either a batch or a continuous process. Known volumes or weights of waste and chemicals can be added with reasonable accuracy into the mixer by front-end loaders or conveyors. Water or slurries can be metered and pumped in.

If continuous operation is desired, all materials must be introduced at a carefully controlled rate. This may require specialized material-handling equipment such as live-bottom feeders. Equipment such as pug mills can frequently be operated in either batch or continuous mode. Thus, it is possible to use a pug mill in batch mode during pilot or field demonstration and then change to continuous mode with several minor modifications: changing the angles on the paddles or knives on the pug-mill shaft(s), changing the level of the discharge gate, and/or changing the speed of rotation of the screws. However, when mixers are switched from batch to continuous mode, they must be recalibrated to ensure that the desired residence time and mixing are being achieved.

Mixing options also depend on the type of waste being mixed. Certain clay-type soils can become extremely sticky and adhere to the shaft and sides of the mixer, leading to poor mixing. Obtaining good mixing can also be problematic if the viscosity of the mix changes rapidly during setting. Mixer performance needs to be evaluated in order to confirm the amounts of stabilization agents needed. During bench-scale testing, the amounts of chemicals required for full-scale operation can be underestimated because less than ideal mixing efficiency was not accounted for.

The size of the mixer generally determines the maximum throughput for the entire stabilization process. Mixers vary widely in size, with achievable throughputs between 1 and 200 tons per hour. Continuous processing usually provides a greater throughput but at the possible expense of mixing efficiency. Two mixers can be used to improve mixing in high throughput continuous processes.

Curing of the waste can occur in either containers, pits, or free-standing piles. Controls should be implemented both to protect the surrounding environment from possible runoff or leaching from the curing waste and to protect the curing waste from wind and precipitation.

2.8.2.5 Stabilized Waste Disposal

If the stabilized waste is to be used as fill, the use of standard earth-moving equipment (e.g., graders, bulldozers, front-end loaders) will usually suffice. After replacement, the waste is compacted. The moisture content of the compacted material should be controlled to give the maximum density for a given material. The moisture-density relationship can be determined by the Proctor test (ASTM D698). Too much or too little moisture can be detrimental.

Stabilization generally results in a volume increase. This volume increase can be underestimated during bench-scale testing and should be re-established in the field.

Post-treatment controls (e.g., capping, slurry wall, soil cover) frequently accompany stabilization to effectively mitigate site-specific threats. Performance standards for caps are mentioned in 40 CFR 264.310 but may not always be appropriate. Final selection of capping materials and cap design depends on several factors such as climate, site hydrogeology, availability of materials, and regulatory requirements.

2.8.3 Sampling and Analysis of the Treated Waste

The guidance on sampling and analysis in Sections 2.2.1.2 and 2.2.3.3 has general applicability to the pilot or field demonstration as well. In situ projects pose special complications for verification testing. For example, drilling or coring is required and homogeneity and setting rates are more difficult to assess. Analyses must be conducted to determine compliance with the performance goals of ARARs (Section 2.3) in a statistically significant manner.