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Guide for Conducting Treatability Studies Under CERCLA: Aerobic Biodegradation Remedy Screening

Interim Guidance

EPA/540/2-91/013A
July 1991

GUIDE FOR CONDUCTING TREATABILITY STUDIES UNDER CERCLA: AEROBIC BIODEGRADATION REMEDY SCREENING

INTERIM GUIDANCE

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Risk Reduction Engineering Laboratory
Office of Research and Development
Cincinnati, Ohio 45268

and

Office of Emergency and Remedial Response
Office of Solid Waste and Emergency Response
Washington, D.C. 20460

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DISCLAIMER

The information in this document has been funded wholly or in part by the U.S. Environmental Protection Agency (EPA) under contract No. 68-C8-0061, Work Assignment No. 2-10, to Science Applications International Corporation (SAIC). It has been subjected to the Agency's peer and administrative reviews, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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 (EPA) 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 human activities and the ability of natural systems to support and nurture life. These laws direct the EPA 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 to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The primary purpose of this guide is to provide standard guidance for designing and implementing an aerobic biodegradation remedy screening treatability study in support of remedy evaluation. Additionally, it describes a three-tiered approach, that consists of 1) remedy screening, 2) remedy selection, and 3) remedy design, to aerobic biodegradation treatability testing. It also presents a guide for conducting treatability studies in a systematic and stepwise fashion for determination of the effectiveness of aerobic biodegradation in remediating a CERCLA site. The intended audience for this guide comprises Remedial Project Managers (RPMs), Potentially Responsible Parties (PRPs), contractors, and technology vendors.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

Systematically conducted, well-documented treatability studies are an important component of the remedial investigation/feasibility study (RI/FS) process and the remedial design/remedial action (RD/RA) process under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). These studies provide valuable site-specific data necessary to aid in the selection and implementation of the remedy. This manual focuses on aerobic biodegradation remedy screening treatability studies conducted in support of remedy evaluation that is conducted prior to the Record of Decision (ROD).

This manual presents a standard guide for designing and implementing an aerobic biodegradation remedy screening treatability study. The manual presents a description of and discusses the applicability and limitations of aerobic biodegradation technologies and defines the prescreening and field measurement data needed to determine if treatability testing is required. It also presents an overview of the process of conducting treatability tests and the applicability of tiered treatability testing for evaluating aerobic biodegradation technologies. The specific goals for each tier of testing are defined and performance levels are presented that should be met at the remedy screening level before additional tests are conducted at the next tier. The elements of a treatability study work plan are also defined with detailed discussions on the design and execution of the remedy screening treatability study.

The manual is not intended to serve as a substitute for communication with the experts and/or regulators nor as the sole basis for the selection of aerobic biodegradation as a particular remediation technology. In addition, this manual is designed to be used in conjunction with the Guide for Conducting Treatability Studies Under CERCLA, Interim Final.[18] The intended audience for this guide consists of Remedial Project Managers (RPMs), Potentially Responsible Parties (PRPs), contractors, and technology vendors.

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SECTION 1
INTRODUCTION

1.1 BACKGROUND

Section 121(b) of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment that "permanently and significantly reduces the volume, toxicity or mobility of the hazardous substances, pollutants, and contaminants is a principal element." Treatability studies provide data to support treatment technology selection and remedy implementation and should be performed as soon as it is evident that insufficient information is available to ensure the quality of the decision. Conducting treatability studies early in the remedial investigation/feasibility study (RI/FS) process should reduce uncertainties associated with selecting the remedy and provide a sounder basis for the Record of Decision (ROD). Regional planning should factor in the time and resources required for these studies.

Treatability studies conducted during the RI/FS phase indicate whether a given technology can meet the expected cleanup goals for the site, whereas treatability studies conducted during the remedial design/remedial action (RD/RA) phase establish the design and operating parameters for optimization of technology performance. Although the purpose and scope of these studies differ, they complement one another (i.e., information obtained in support of remedy selection may also be used to support the remedy design). [26]

This document refers to three levels or tiers of treatability studies: remedy screening, remedy selection, and remedy design.. Three tiers of treatability studies are also defined in the Guide for Conducting Treatability Studies Under CERCLA, Interim Final [18], referred to as the "generic guide" hereafter in this document. The generic guide refers to the three treatability study tiers, based largely on the scale of test equipment, as laboratory screening, bench-scale testing, and pilot-scale testing. Laboratory screening is typically used to screen potential remedial technologies and is equivalent to remedy screening. Bench-scale testing is typically used for remedy selection, but may fall short of providing enough information for remedy selection. Bench-scale studies can, in some cases, provide enough information for full-scale design. Pilot-scale studies are normally used for remedial design, but may be required for remedy selection in some cases. Because of the overlap between these tiers, and because of differences in the applicability of each tier to different technologies, the functional description of treatability study tiers (i.e., remedy screening, remedy selection, and remedy design) has been chosen for this document.

Some or all of the levels of treatability study testing may be needed on a case-by-case basis. The need for and the level of treatability testing required are managerial decisions in which the time and cost necessary to perform the testing are balanced against the risks inherent in the decision (e.g., selection of an inappropriate treatment alternative). These decisions are based on the quantity and quality of data available and on other decision factors (e.g., State and community acceptance of the remedy and experience with the technology at other sites). The use of treatability studies in remedy selection is discussed further in Section 3 of this document.

1.2 PURPOSE AND SCOPE

This guide is designed to ensure a credible approach is taken to evaluate whether aerobic biodegradation should be considered for site remediation. This guide discusses only the remedy screening level. Remedy screening studies are designed to provide a quick and relatively inexpensive indication of whether biological degradation is a potentially viable remedial technology. Remedy selection studies will also be required to determine if bioremediation is a viable treatment alternative for a site. The remedy screening evaluation should:

- Provide a preliminary indication that reductions in contaminant concentration are due to biodegradation and not abiotic processes such as photo decomposition, volatilization, or adsorption, and

- Produce the design information required for the next level of testing, should the remedy screening evaluation be successful.

The Aerobic Biological Remedy Screening Study should not be the only level of treatability study performed before final remedy selection.

1.3 INTENDED AUDIENCE

This document is intended for use by Remedial Project Managers (RPMs), Potentially Responsible Parties (PRPs), consultants, contractors, and technology vendors. Each has a different role in conducting treatability studies under CERCLA. Specific responsibilities for each can be found in the generic guide.[18]

1.4 USE OF THIS GUIDE

This guide is organized into seven sections, which reflect the basic information required to perform treatability studies during the RI/FS process. Section 1 provides background information on the role of treatability studies in the RI/FS process, describes the purpose and scope of the guide, and outlines the intended audience for the guide. Section 2 describes the different types of aerobic bioremediation processes currently available and discusses how to conduct a preliminary screening to determine if biological treatment is a potentially viable remediation technology. Section 3 provides an overview of the different levels of treatability testing and discusses how to determine the need for treatability studies. Section 4 provides an overview of the remedy screening treatability study, describes the contents of a typical work plan, and discusses the major issues that need to be considered when conducting a treatability study. Section 5 discusses the Sampling and Analysis Plan, including the Field Sampling and Quality Assurance Project Plans. Section 6 explains how to interpret the data produced from a remedy screening treatability study and how to determine if further remedy selection studies are justified. Section 7 contains the references.

This guide, along with guides being developed for other technologies, is intended to be used as a companion document to the generic guide.[18] In an effort to avoid redundancy, supporting information in other readily available guidance documents is not repeated in this document.

This document was reviewed by representatives from EPA's Office of Emergency and Remedial Response (OERR), Office of Research and Development (ORD), Office of Waste Programs Enforcement, Technology Innovation Office, and Regional offices, as well as by a number of contractors and academic personnel. The constructive comments received from this peer review process have been integrated and/or addressed throughout this guide.

As treatability study experience is gained, EPA anticipates further comment and possible future revisions to the document. For this reason, EPA encourages constructive comments from outside sources. Comments should be directed to:

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SECTION 2
TECHNOLOGY DESCRIPTION AND PRELIMINARY SCREENING

This section describes the various full-scale aerobic biodegradation technologies currently available and discusses the information necessary to screen the technology prior to commitment to a treatability test program. Subsection 2.1 describes several full-scale aerobic biodegradation systems that potentially can be used at Superfund sites. Subsection 2.2 discusses the literature and data base searches required, the technical assistance available, and the review of field data required to prescreen these technologies. Technology limitations are also reviewed in this subsection.

2.1 TECHNOLOGY DESCRIPTION

Bioremediation generally refers to the breakdown of organic compounds (contaminants) by microorganisms. In situ, solid-phase, slurry-phase, soil-heaping, and composting biological treatment techniques are available for the remediation of contaminated soils.[13][23] Aerobic biodegradation can be used as the only treatment technology at a site or along with other technologies in a treatment train. Use of aerobic biodegradation, especially in situ, has been very limited at CERCLA sites. However, the technology shows promise for degrading, immobilizing, or transforming a large number of organic compounds commonly found at CERCLA sites to environmentally acceptable compounds.

As of fiscal year 1989, biodegradation has been selected as a component of the remedy for 22 Superfund sites having groundwater, soils, sludges, or sediments contaminated with various volatile organics; phenols; creosotes; polynuclear aromatic hydrocarbons (PAHs); and benzene, toluene, ethyl benzene, and xylene (BTEX) compounds.[22]

Information on the technology applicability, the latest performance data, the status of the technology, and sources for further information is provided in a series of engineering bulletins being prepared by the EPA Risk Reduction Engineering Laboratory (RREL) in Cincinnati, Ohio.[16][17]

2.1.1 In Situ Bioremediation

In situ bioremediation involves enhancing the microbial degradation of contaminants in subsurface soil and water without excavation of the contaminated soil. The technology usually involves enhancing natural biodegradation processes by adding nutrients, oxygen (if the process is aerobic), and in some cases, microorganisms to stimulate the biodegradation of contaminants. Moisture control may be required to optimize biodegradation. If oxygen is the rate-limiting parameter, oxygen sources such as air, high-purity oxygen, or hydrogen peroxide are usually used to increase the amount of oxygen available for biodegradation. Laboratory studies indicate the addition of methane or other substrates may aid in the co-metabolic biodegradation of low molecular weight chlorinated organics. Recent evidence has shown that anaerobic processes that use nitrate as a terminal electron acceptor may be effective for the in situ treatment of benzene, toluene, xylenes, and some PAHs.[4]

In situ bioremediation is often used in conjunction with a groundwater-pumping and soil-flushing system to circulate nutrients and oxygen through a contaminated aquifer and associated soils. The process usually involves introducing aerated, nutrient-enriched water into the contaminated zone through a series of injection wells or infiltration trenches and recovering the water down gradient. Water-soluble contaminants are flushed out of the soil; less soluble contaminants remain in the soil and are biodegraded. The recovered water can then be reintroduced or disposed of on the surface (Figure 2-1). Depending on the concentration of water-soluble contaminants in the recovered water, additional treatment may be required before the water can be disposed of or recycled to the soil treatment system.

In situ bioremediation has primarily been used for the treatment of saturated soils; however, in a few instances, the technology has been used to treat unsaturated soils. The in situ bioremediation of unsaturated soils has typi-

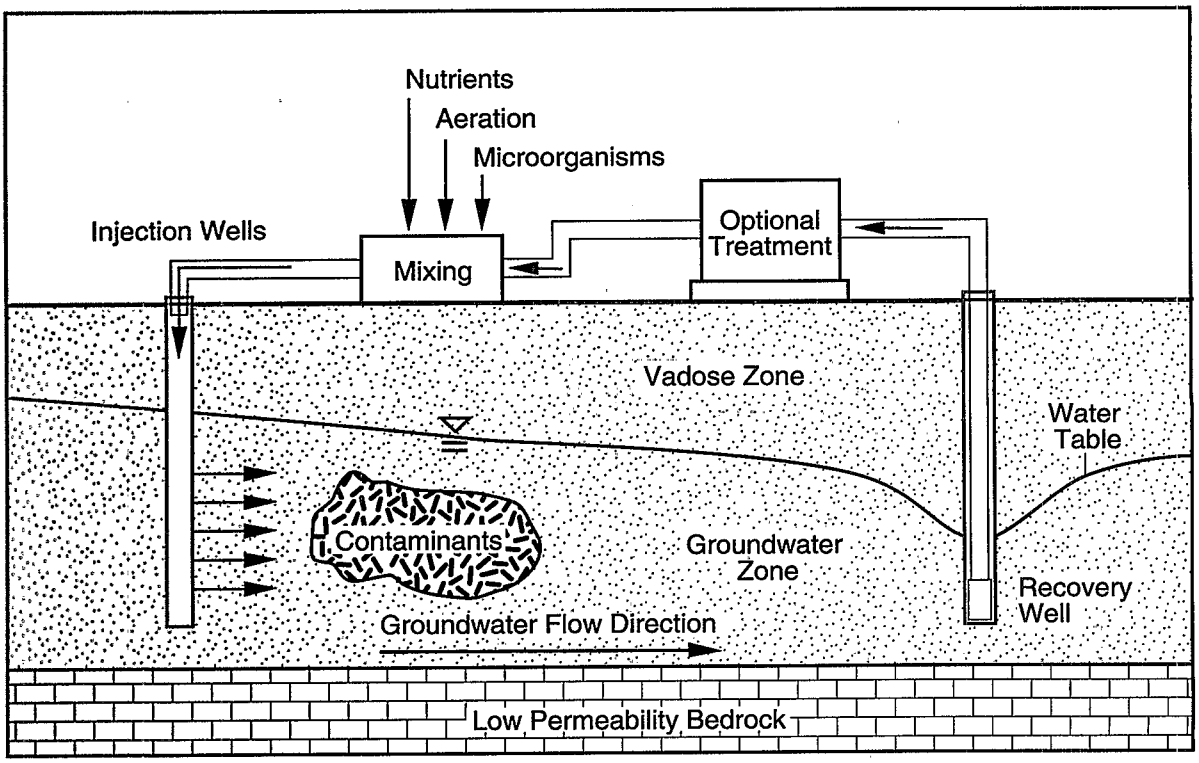


Figure 2-1. In situ bioremediation of groundwater.

cally been limited to fairly shallow depths over groundwater that is already contaminated. The treatment of unsaturated soils is difficult to control and relies on the use of percolation techniques to introduce nutrient-adjusted water and vacuum extraction techniques to enhance air exchange in the soil matrix.

In situ bioremediation treats contaminants in-place, eliminating the need for soil excavation and limiting the release of volatiles into the air. Consequently, the risks and costs associated with materials handling are reduced or eliminated. Furthermore, in situ bioremediation has the potential to clean up the source material responsible for the groundwater contamination.

2.1.2 Solid-Phase Bioremediation

Solid-phase bioremediation (sometimes referred to as land treatment) is a process that treats soils in an above-grade treatment system using conventional soil management practices to enhance microbial degradation of contaminants. Solid-phase bioremediation can be designed using shallow "tanks" to meet land-ban requirements.

Solid-phase bioremediation at CERCLA sites usually involves placing excavated soil in an above-grade soil treatment area. If required, nutrients and microorganisms are added to the soil, which is tilled at regular intervals to optimize aeration and contact between the microorganisms and the contaminants. During the operation of a solid-phase bioremediation system, pH, nutrient concentrations, and moisture content are maintained within ranges conducive to microbial activity (Figure 2-2). In some cases, the contaminated soil has to be mixed with clean soil to reduce the concentration of contaminants to levels that do not inhibit microbial activity. Solid-phase treatment systems can be modified to contain and treat soil leachate by adding underdrain and liquid treatment systems. Volatile organic compounds (VOCs) can be contained by adding an optional cover. Conventional VOC treatment can be added as part of a treatment train.

A variety of processes influence the fate of contaminants in solid-phase treatment systems. These include physical and chemical processes (such as leaching, adsorption, desorption, photodecomposition, oxidation, volatilization, and hydrolysis) and biodegradation. The physical, chemical, and biological properties of the contaminants and soil interact with site-specific variables to influence the fate of

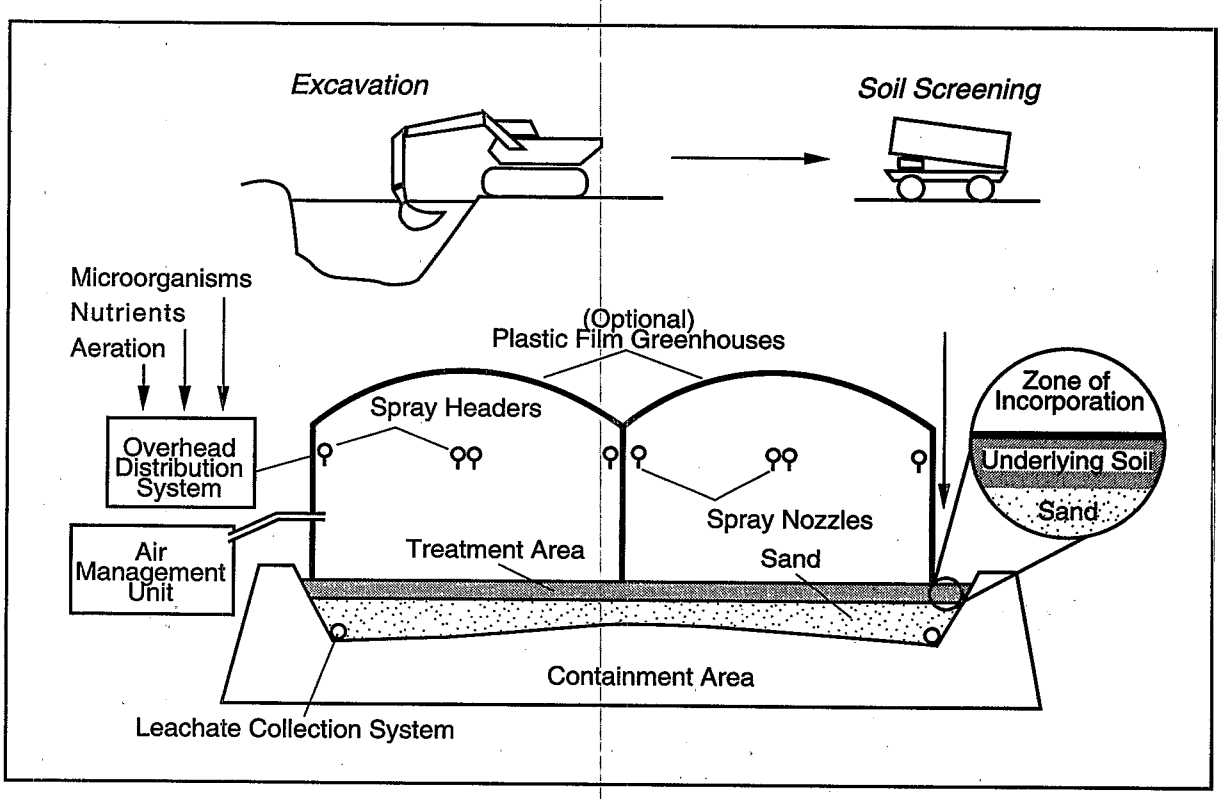


Figure 2-2. Solid-phase bioremediation.

the contaminants. The contaminants are degraded, immobilized, or transformed to environmentally acceptable components.[6]

Decomposition and immobilization of the contaminants occur within both the zone of incorporation, usually the top 15 to 30 centimeters, and the underlying layers. The zone of incorporation and the underlying soils, where additional treatment and immobilization of the contaminants occurs, are referred to as the treatment zone. The treatment zone depth may be as much as 1.5 meters. Most of the transformations, immobilization, and biodegradation occur in the zone of incorporation.

2.1.3 Slurry-Phase Bioremediation (Liquid/Solids Treatment)

In slurry-phase bioremediation, excavated contaminated soil is typically placed in an on-site, stirred-tank reactor(s) where the soil is combined with water to form a slurry. The solids content of the slurry depends on the type of soil, the type of mixing and aeration equipment available, and the rates of contaminant removal that need to be achieved. The water used in the process can be contaminated surface or ground water, thus facilitating the simultaneous treatment of contaminated soil and water. If required, nutrients and microorganisms are added to the slurry, which is then aerated and agitated to optimize contact between the microorganisms, nutrients, and oxygen so that efficient biodegradation of the contaminants can occur. The process can be operated in either a batch or a continuous mode (Figure 2-3).

As with solid-phase bioremediation, the process can be designed to contain and treat volatile organic compounds. Slurry-phase bioremediation systems can be used to treat sludges and sediments in existing lagoons and impoundments, thus eliminating the need for soil excavation (Figure 2-4). An impermeable layer should be present under the slurry-phase system to prevent contaminant migration.

2.1.4 Soil Heaping

Soil heap bioremediation involves piling contaminated soil in heaps of several meters in height. Aeration is usually provided by pulling a vacuum through the heap. Simple

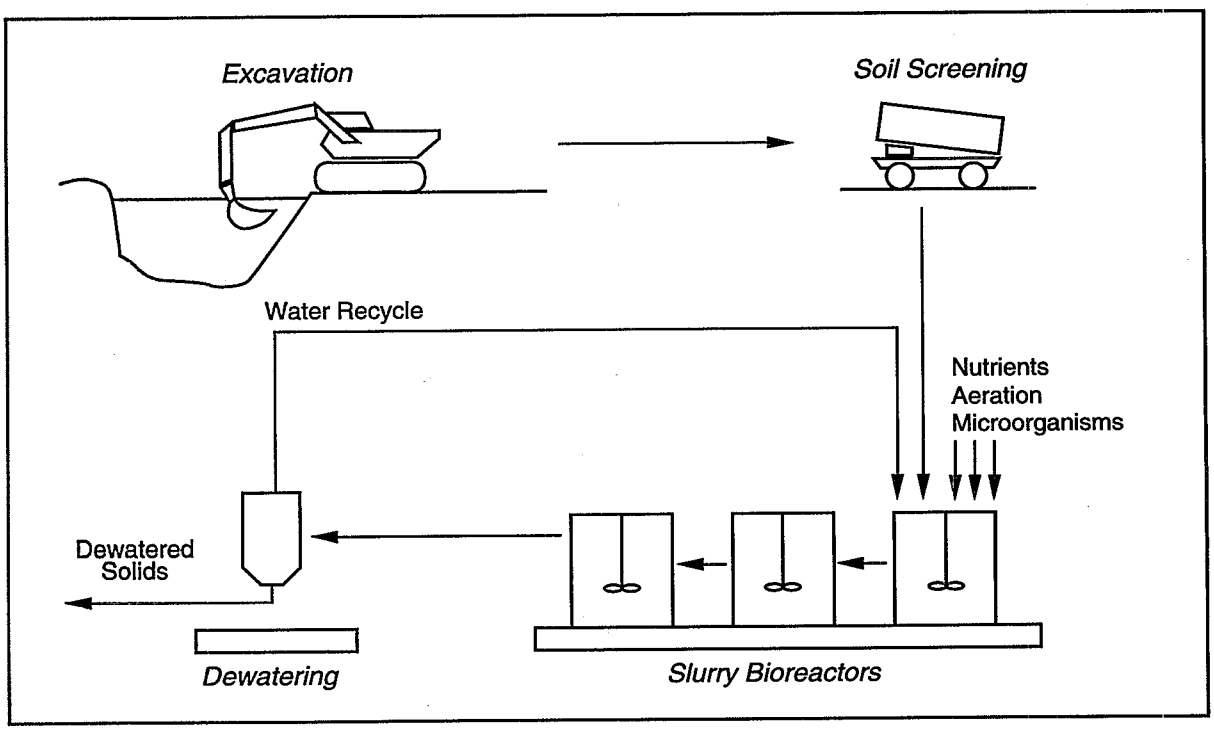


Figure 2-3. Above-ground slurry-phase bioremediation.

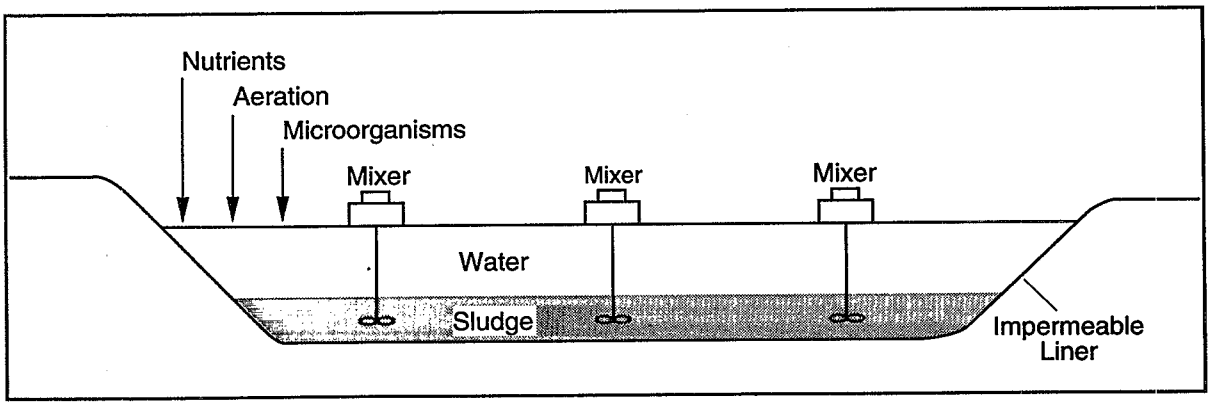


Figure 2-4. Slurry-phase bioremediation in existing lagoon.

irrigation techniques are generally used to maintain moisture content, pH and nutrient concentrations within ranges conducive to the biodegradation of contaminants. The system can be designed to control the release of volatile organic compounds by passing the exhaust from the vacuum through activated carbon (Figure 2-5).

2.1.5 Composting

Composting involves the storage of biodegradable waste with a bulking agent (e.g., chopped hay or wood chips). The structurally firm bulking agent can be biodegradable, but need not be so. Typically, two parts bulking agent are mixed with one part contaminated soil to improve the soil permeability. Adequate aeration, optimum temperature,

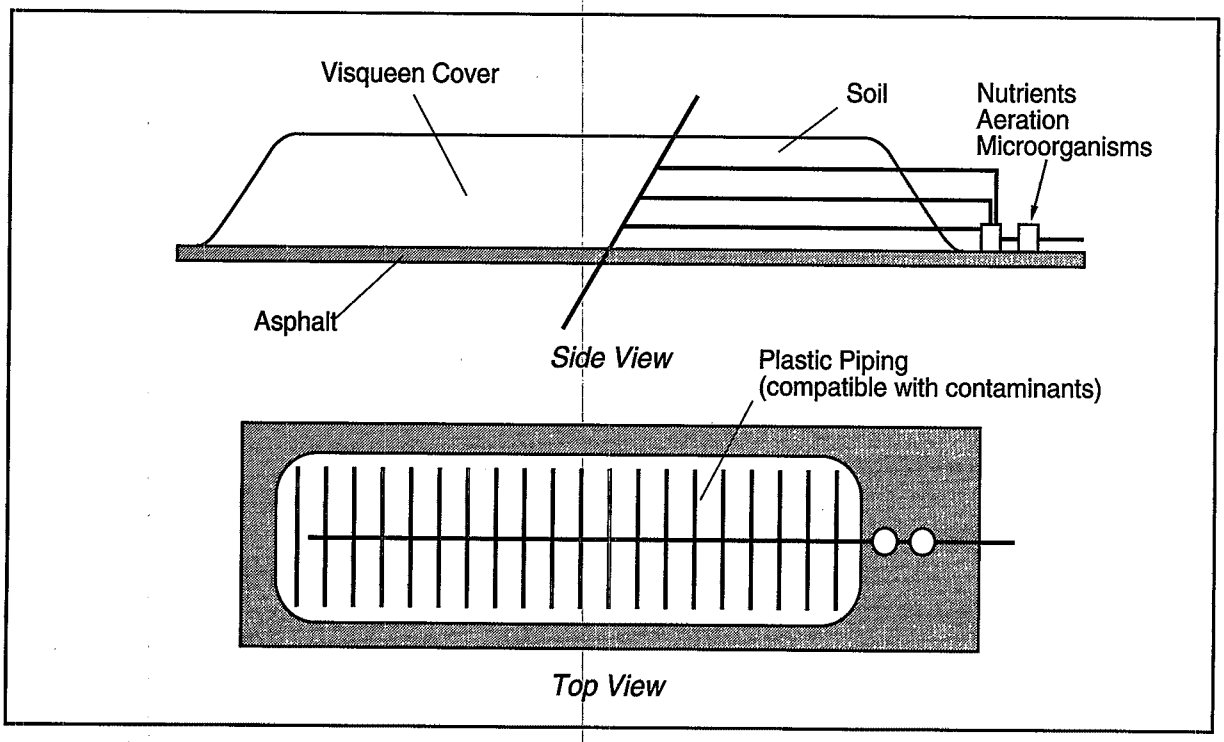


Figure 2-5. Soil heap bioremediation.

moisture and nutrient contents, and the presence of an appropriate microbial population are necessary to enhance the decomposition of organic compounds. The biodegradation process may be thermophilic. If so, microorganisms that occur naturally in the decaying organic matter biodegrade the contaminants of concern. However, the elevated temperatures associated with thermophilic biodegradation may limit the activity of indigenous and exogenous organisms.

The three basic types of composting are open windrow systems, static windrow systems, and in-vessel (reactor) systems. In the open windrow system, the compost is stacked into elongated piles (Figure 2-6). Aeration is

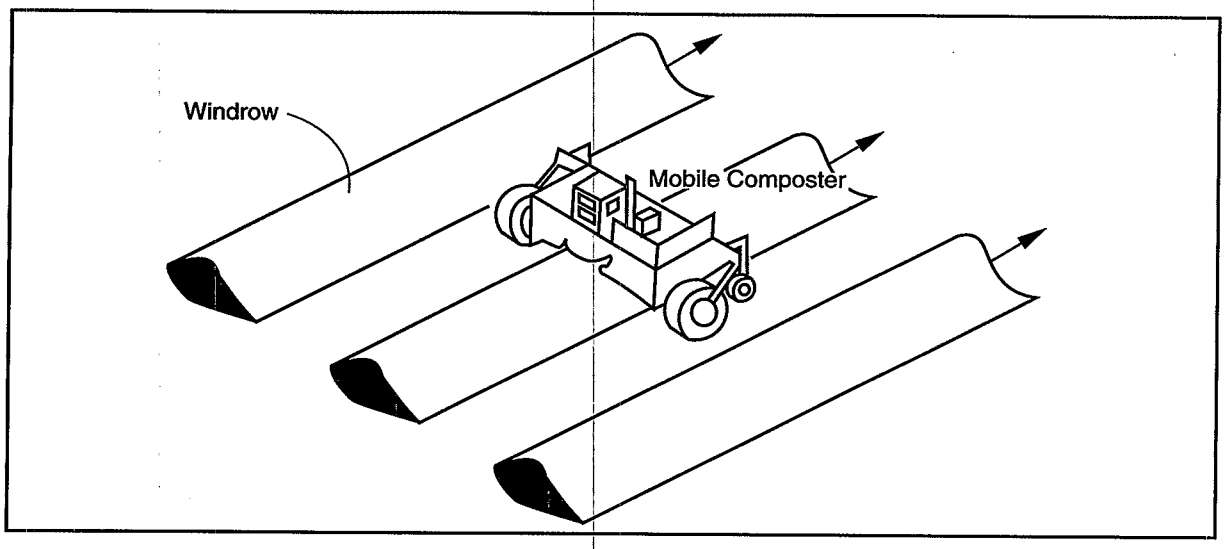


Figure 2-6. Open windrow composting.

accomplished by tearing down and rebuilding the piles. In the static windrow system piles of compost are aerated by a forced air system (e.g., the piles are built on top of a grid of perforated pipes). The in-vessel system involves placing the compost into a closed reactor. Aeration is accomplished by tumbling, stirring, and forced aeration.

2.2 PRELIMINARY SCREENING AND TECHNOLOGY LIMITATIONS

As mentioned in Section 1, the determination of the need for and the appropriate level of treatability studies required depends on the literature information available on the technology, expert technical judgment, and site-specific factors. The first two elements – the literature search and expert consultation – are critical in determining if adequate data are available or whether a treatability study is needed to provide those data. The data and information on which this decision is made should be documented.

2.2.1 Literature/Data Base Review

Several reports and electronic data bases exist that should be consulted to assist in planning and conducting treatability studies as well as to help prescreen bioremediation for use at a specific site. Existing reports include:

- Guide for Conducting Treatability Studies Under CERCLA, Interim Final. U.S. Environmental Protection Agency, Office of Research and Development and Office of Emergency and Remedial Response, Washington, D.C. EPA/540/2-89/058, December 1989.

- Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA, Interim Final. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C. EPA/540/G-89/004, October 1988.

- Superfund Treatability Clearinghouse Abstracts. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C. EPA/540/2-89/001, March 1989.

- The Superfund Innovative Technology Evaluation Program: Technology Profiles. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Research and Development, Washington, D.C. EPA/540/5-90/006, November 1990.

- Summary of Treatment Technology Effectiveness for Contaminated Soil. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C., 1989 (in press).

- Technology Screening Guide for Treatment of CERCLA Soils and Sludges. U.S. Environmental Protection Agency. EPA/540/2-88/004, 1988.

Currently, RREL in Cincinnati is expanding its Superfund Treatability Data Base. This data base will contain data from all treatability studies conducted under CERCLA. A repository for treatability study reports will be maintained at RREL in Cincinnati. The contact for this data base is Glenn Shaul at (513) 569-7408.

ORD headquarters maintains the Alternative Treatment Technology Information Center (ATTIC), a comprehensive, automated information retrieval system that integrates hazardous waste data into a unified, searchable resource. The intent of ATTIC is to provide the user community with technical data and information on available alternative treatment technologies and to serve as an initial decision support system. Since ATTIC functions as a focal point for users, it facilitates the sharing of information within the user community and creates an effective network of individuals and organizations involved in hazardous waste site remediation.

The information contained in ATTIC consists of a wide variety of data obtained from Federal and state agencies. The core of the ATTIC system is the ATTIC Data Base, which contains abstracts and executive summaries from over 1200 technical documents and reports. Information in the ATTIC Data Base has been obtained from the following sources:

- The Superfund Innovative Technology Evaluation (SITE) Program

- California Summary of Treatment Technology Demonstration Projects

- Data Collected for the Summary of Treatment Technology Effectiveness for Contaminated Soil

- North Atlantic Treaty Organization (NATO) International Data

- Innovative Technologies Program Data

- Removal Sites Technologies Data
- Resource Conservation and Recovery Act (RCRA) Delisting Actions
- USATHAMA Installation Restoration and Hazardous Waste Control Technologies
- Records of Decision (from 1988 on)
- Treatability Studies
- Superfund Treatability Data Base (also available through ATTIC).

In addition, the ATTIC system contains a number of resident data bases that have been previously developed, as well as access to on-line commercial data bases. For more information, contact the ATTIC System Operator at (301) 816-9153.

The Office of Solid Waste and Emergency Response (OSWER) maintains an Electronic Bulletin Board System (BBS) as a tool for communicating ideas and disseminating information and as a gateway for other Office of Solid Waste (OSW) electronic data bases. Currently, the BBS has eight different components, including news and mail services and conferences and publications on specific technical areas. The contact is James Cummings at (202) 382-4686.

The RREL in Edison, New Jersey, contains a Computerized On-Line Information System (COLIS), which consolidates several computerized data bases by RREL in Cincinnati and Edison. COLIS contains three files: Case Histories, Library Search, and SITE Applications Analyses Reports (AARs). The Case Histories file contains historical information obtained from corrective actions implemented at Superfund sites. The Library Search system provides access to special collections and research information on many RREL programs. The SITE AARs file provides actual cost and performance information. The contact is Pacita Tibay at (201) 906-6871.

2.2.2 Technical Assistance

The Technical Support Project (TSP) is made up of six Technical Support Centers and two Technical Support Forums. It is a joint service of OSWER, ORD, and the Regions. The TSP offers direct site-specific technical assistance to On-Scene Coordinators (OSCs) and RPMs and develops technology workshops, issue papers, and other information for Regional staff. The TSP:

- Reviews contractor work plans, evaluates remedial alternatives, reviews RI/FS, assists in selection and design of final remedy
- Offers modeling assistance and data analysis and interpretation
- Assists in developing and evaluating sampling plans
- Conducts field studies (soil gas, hydrogeology, site characterization)
- Develops technical workshops and training, issues papers on groundwater topics, and generic protocols
- Assists in performance of treatability studies.

The following support centers provide technical information and advice related to aerobic biodegradation and treatability studies:

1. **Ground-Water Fate and Transport Technical Support Center**
   Robert S. Kerr Environmental Research Laboratory (RSKERL), Ada, OK
   Contact: Don Draper
   FTS 743-2202 or (405) 332-8800

   RSKERL in Ada, Oklahoma, is EPA's center for fate and transport research, focusing its efforts on transport and fate of contaminants in the vadose and saturated zones of the subsurface, methodologies relevant to protection and restoration of groundwater quality, and evaluation of subsurface processes for the treatment of hazardous waste. The Center provides technical assistance such as evaluating remedial alternatives; reviewing RI/FS and RD/RA work plans; and providing technical information and advice.

2. **Engineering Technical Support Center**
   Risk Reduction Engineering Laboratory (RREL), Cincinnati, OH
   Contact: Ben Blaney
   FTS 648-7406 or (513) 569-7406

   The Engineering Technical Support Center (ETSC) is sponsored by OSWER but operated by RREL. The Center handles site-specific remediation engineering problems. Access to this support Center must be obtained through the EPA remedial project manager.

RREL offers expertise in contaminant source control structures; materials handling and decontamination; treatment of soils, sludges and sediments; and treatment of aqueous and organic liquids. The following are examples of the technical assistance that can be obtained through ETSC:

- Screening of treatment alternatives
- Review of the treatability aspects of RI/FS
- Review of RI/FS treatability study Work Plans and final reports
- Oversight of RI/FS treatability studies
- Evaluation of alternative remedies
- Assistance with studies of innovative technologies
- Assistance in full-scale design and start-up

2.2.3 Prescreening Characteristics

The major parameter that influences the feasibility of using biological processes is the biodegradability of the compounds of concern. Prior to conducting a remedy screening of bioremediation it is important to confirm that the compounds of concern are indeed amenable to biological treatment.

As discussed in Subsection 2.2.1, a literature search should be performed for the compounds or wastes of interest, including compounds of similar structure. The key question to be answered is whether any evidence of aerobic biodegradation of these compounds or wastes exists. The literature review should not be limited to a biodegradation technology that has been chosen for preliminary consideration. Evidence of aerobic biodegradation under conditions not likely to be applicable to a site should not be eliminated from consideration. Likewise, a literature search indicating that biodegradation is unlikely should not automatically eliminate aerobic biological technologies from consideration. On the other hand, previous studies indicating that pure chemicals will be degraded must be viewed with caution. Chemical interactions or inhibitory effects of contaminants can alter the biodegradability of chemicals in complex mixtures frequently found at Superfund sites.

The literature search should also investigate the chemical and physical properties of the contaminants. The volatility of the contaminants is one of the most important physical characteristics. Knowledge of the contaminant volatility is important in the prescreening step since highly volatile contaminants may be difficult to degrade, especially in stirred or highly aerated reactors because they volatilize before thay can be degraded.

There is no steadfast rule that specifies when to proceed with remedy screening and when to eliminate aerobic biodegradation as a treatment technology based on a preliminary screening analysis. An analysis of the existing literature coupled with the site characterization will provide the information required to make an educated decision. However, when in doubt, a remedy screening study is recommended. Several guidance documents are available to aid in determining the key contaminant and matrix characteristics which are needed to prescreen various technologies.[15][18][23] Example 1 is a hypothetical literature search provided to illustrate some of the complexities of this analysis.

Example 1.

A site is contaminated with an organic solvent. The contamination extends to a depth of 50 feet below the surface. Considering the overall extent of the zone of contamination, removal of the soil for above-ground treatment is not considered as a remediation technology for the site. However, a review of the literature reveals only two previous studies on the biodegradation of the solvent of concern.

The first study showed that greater than 95 percent of the semi-volatile solvent could be removed over a 3-week period with a slurry-phase biological treatment process utilizing naturally occurring soil microorganisms. The study made no attempt to measure losses due to volatilization. However, a 12-percent loss of solvent was measured in a control reactor where biodegradation was inhibited with mercuric chloride to account for abiotic losses (chemical degradation, sorption and volatilization). Therefore, 83 percent of the contaminant was removed by biotic processes

(biodegradation) during the study period. Even though above-ground slurry-phase treatment is not appropriate for the site of concern, the previous study did show that, under appropriate conditions, naturally occurring microorganisms can biodegrade a large percentage of the solvent.

The second study was a remedy design (pilot-scale) demonstration that showed that after 5 months the solvent could not be biodegraded in situ, even with the addition of nutrients and oxygen. This study indicates that in situ biodegradation of the solvent is not likely to occur.

At first glance, the literature review appears to rule out the use of in situ bioremediation to clean up the solvent-contaminated subsurface soil. However, caution should be used in excluding aerobic biodegradation on the basis of one study. The intent of the remedy screening treatability study is to assess the potential of a technology at a minimum cost. If there is any reason to believe aerobic biodegradation has the potential to remediate the contaminant of interest, remedy screening studies should be considered.

The first study indicated that biodegradation is potentially a viable technology. However, successful biodegradation in a slurry bioreactor is not an assurance that in situ biodegradation will occur. The second study tends to indicate that in situ bioremediation of this contaminant will not be possible. However, a simple change in pH or nutrient composition, the removal of some inhibitory substance, or the use of a different microbial population could result in successful in situ bioremediation of the solvent. In this case, the RPM decided that a quick remedy screening study was warranted to assess the feasibility of using biological treatment at the site of concern.

Examples of classes of compounds that are readily amenable to bioremediation are petroleum hydrocarbons such as gasoline and diesel fuel; wood-treating wastes such as creosote and pentachlorophenol; solvents such as acetone, ketones, and alcohols; and aromatic compounds such as benzene, toluene, xylenes, and phenols. Several documents and review articles that present detailed information on the biodegradability of compounds are listed in the reference section.[3][8][11][12][20][23] However, discretion should be exercised when using these reference materials, as microorganisms that can biodegrade compounds traditionally considered non-biodegradable are continually being discovered through ongoing research and development efforts.

2.2.4 Technology Limitations

Many factors impact the feasibility of aerobic biodegradation in addition to the inherent biodegradability as measured in the screening test. These factors should be addressed prior to the selection of aerobic biodegradation and prior to the investment of time and funds in further testing. Some of these factors are discussed in this section. A detailed discussion is beyond the scope of this document. The reader should consult references 15 through 18, and others, for more information on these factors.

The concentrations of contaminants and pH are examples of parameters that influence the feasibility of using biological treatment processes. However, it should be noted that treatment systems can be designed and engineered to accommodate wastes with high contaminant concentrations and extreme pH values. For example, diesel-contaminated soil with a pH of 2 can be treated biologically. However, a neutralization step is required to adjust the pH to within a range conducive to biological treatment (generally 6.5 to 8.5) prior to bioremediation. Likewise, if the concentrations of contaminants are high enough to inhibit microbiological activity, a dilution step can be introduced to reduce the concentrations to within ranges conducive to biological treatment. For example, solid-phase treatment systems are generally operated at a maximum of 5 to 10 percent extractable oil and grease. These concentrations of oil and grease can be achieved by mixing less contaminated soil with heavily oiled soils in above-ground processes. Metals may be leached or complexed to reduce microbial toxicity and improve the potential for contaminant treatment.

Non-uniform particle size distribution, the type of soil, and the permeability of the soil to air and water are the soil characteristics that most affect the aerobic biodegradation process, especially in situ. Organic contaminants tend to be adsorbed to fine particles such as silts and clays. Therefore, non-uniform particle size distribution can cause inconsistent degradation rates for in situ processes due to variations in biological activity associated with variable contaminant composition and concentrations. The presence of significant quantities of decaying organic matter (humus, peat, etc.) may cause high oxygen uptake rates, depleting available oxygen supplies in the soil. Materials handling and mixing in above-ground processes are affected by particle size distribution and debris present in the soil.

Low soil permeability can hinder the flow of air, moisture, and nutrients, limiting the effectiveness of in situ processes. Moisture, oxygen, and nutrient content in soils and soil pH and temperature affect in situ microbial activity. Generally, such characteristics can be controlled or modified through engineering practices.

The presence of an active microbial population with the capability to degrade the contaminants of interest is essential to the success of in situ processes. The activity and concentration of soil microbes can be stimulated by moisture, nutrient, and oxygen additions. Selected microorganisms can be added to enhance the natural population. However, the ability of these organisms to compete in situ needs to be established on a case-by-case basis. The addition of microbes and nutrients can be severely limited by low soil permeabilities. Even in relatively permeable soils, ion exchange and filtration mechanisms can limit the effectiveness of microbial and nutrient amendments.

The biodegradability of soil contaminants is affected by the solubility, volatility, and partition coefficients of the pure compounds. Interactions with the soil and other contaminants may affect these chemical characteristics. Aging of soil contaminants can lead to binding in soil pores, which can limit the availability, even of soluble compounds. Variable waste composition and concentration will affect the efficiency of aerobic biodegradation, especially in situ. The presence of elevated levels of heavy metals, pesticides, highly chlorinated organics, and some inorganic salts can inhibit microbial activity.

The importance of these factors in deciding whether to initiate or continue treatability studies can be illustrated by the following example.

Example 2.

A remedy screening test shows that a contaminant is aerobically biodegradable. However, soil sampling indicates the contaminant is located more than 25 feet deep in a soil of very low permeability. In situ biodegradation is probably not feasible due to the thickness of the low permeability soil layer and the depth of the contaminant. In this case, it may not be worth spending the funds to perform remedy selection treatability studies for in situ biological treatment processes.

SECTION 3
THE USE OF TREATABILITY STUDIES IN REMEDY EVALUATION

This section presents an overview of the use of treatability tests in confirming the selection of aerobic biodegradation as the technology remedy under CERCLA. It also provides a decision tree (Figure 3-1) that defines the tiered approach to the overall treatability study program with examples of the application of treatability studies to the RI/FS and remedy evaluation process. Subsection 3.1 presents an overview of the general process of conducting treatability tests. Subsection 3.2 defines the tiered approach to conducting treatability studies and the applicability of each tier of testing, based on the information obtained, to assess, evaluate, and confirm aerobic biodegradation technology as the selected remedy.

3.1 PROCESS OF TREATABILITY TESTING IN EVALUATING A REMEDY

Treatability studies should be performed in a systematic fashion to ensure that the data generated can support the remedy evaluation process. This section describes a general approach that should be followed by RPMs, PRPs, and contractors for all three tiers of treatability studies. This approach includes:

- Establishing data quality objectives
- Selecting a contracting mechanism
- Issuing a work assignment
- Preparing the work plan
- Preparing the Sampling and Analysis Plan
- Preparing the Health and Safety Plan
- Conducting community relations requirements
- Complying with regulatory requirements
- Executing the study
- Analyzing and interpreting the data
- Reporting the results.

These elements are described in detail in the generic guide.[18] The generic guide presents general information applicable to all treatability studies first, followed by information specific to each of the levels of treatability testing.

Treatability studies for a particular site will often entail multiple tiers of testing. Duplication of effort can be avoided by recognition of this possibility in the early planning phases of the project. The work assignment, work plan, and other supporting documents should include all anticipated activities to ensure continuity in the project as it moves from one tier to another.

There are three levels or tiers of treatability studies: remedy screening, remedy selection, and remedy design. Some or all of the levels may be needed on a case-by-case basis. The need for and the level of treatability testing required are management decisions in which the time and cost necessary to perform the testing are balanced against the risks inherent in the decision (e.g., selection of an inappropriate treatment alternative). These decisions are based on the quantity and quality of data available and on other decision factors (e.g., State and community acceptance of the remedy, new site data). The flow diagram in Figure 3-1 shows the decision points and factors to be considered in following the tiered approach to treatability studies.

Technologies generally are evaluated first at the remedy screening level and progress through the remedy selection to the remedy design level. A technology may enter, however, at whatever level is appropriate based on available data on the technology and site-specific factors. For example, a technology that has been studied extensively may not warrant remedy screening to determine whether it

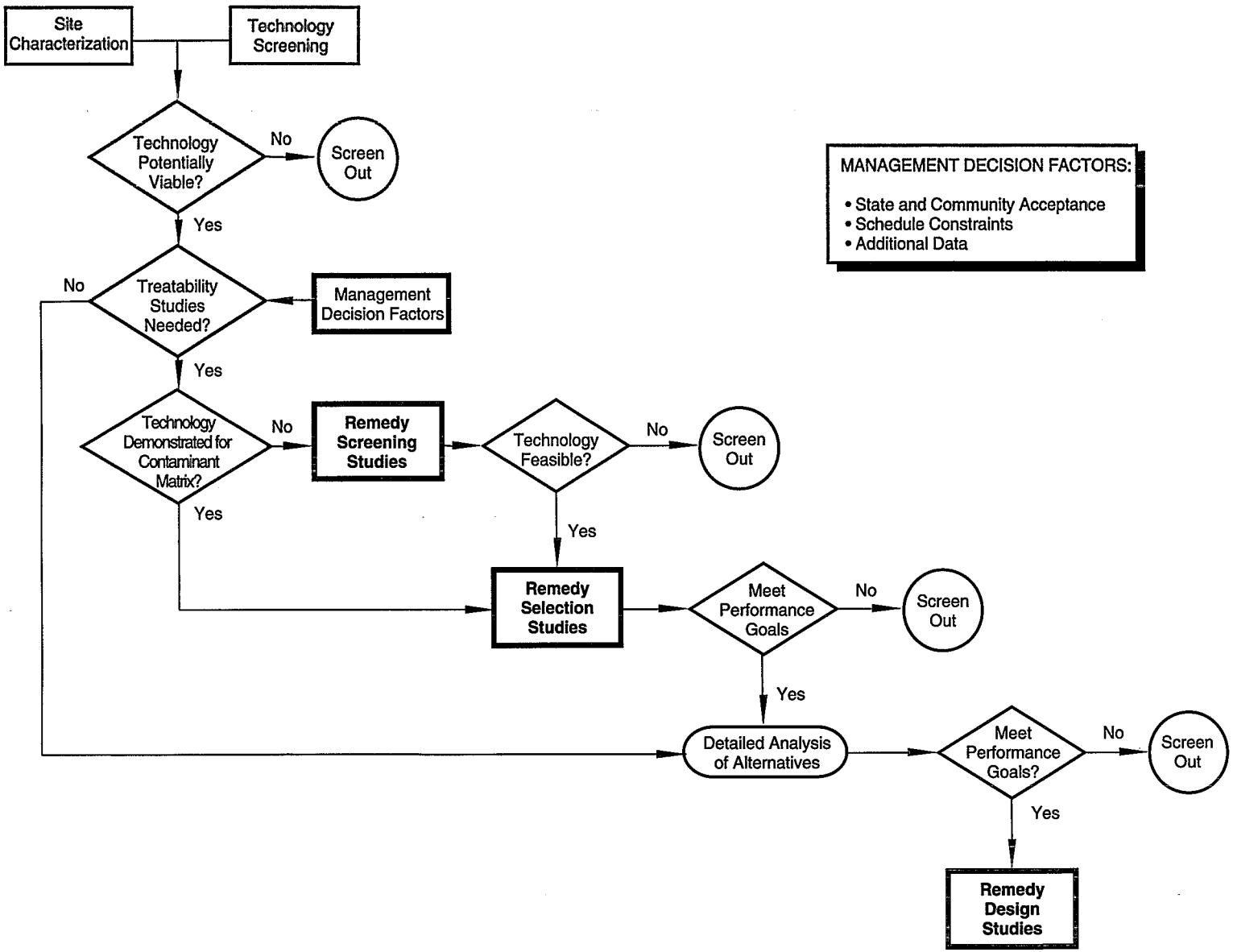


Figure 3-1. Flow diagram of the tiered approach.

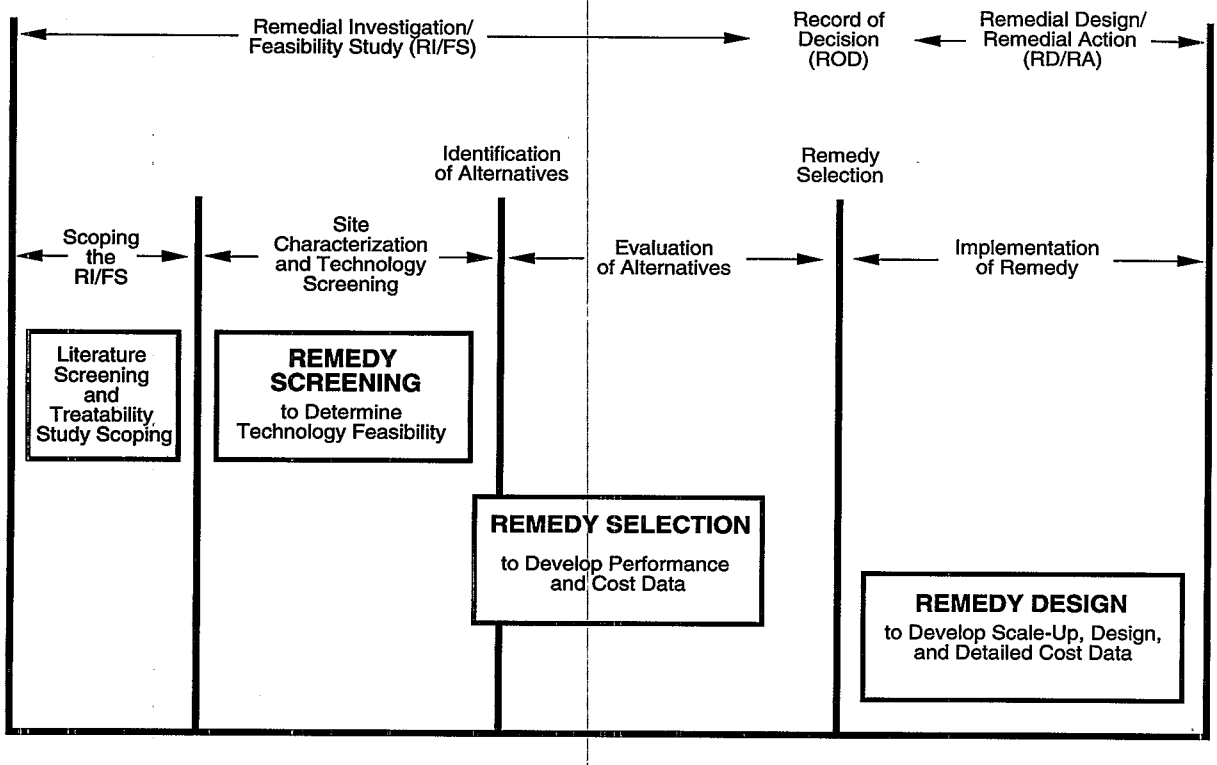


Figure 3-2. The role of treatability studies in the RI/FS and RD/RA process.

has the potential to work. Rather, it may go directly to remedy selection to verify that performance standards can be met. Figure 3-2 shows the relationship of three levels of treatability study to each other and to the RI/FS process.

3.2 APPLICATION OF TREATABILITY TESTS

Before conducting treatability studies, the objectives of each tier of testing must be established. Aerobic biodegradation treatability study objectives must be based upon the specific needs of the RI/FS. There are nine evaluation criteria specified in the EPA's RI/FS Interim Final Guidance Document (OSWER-9335:3-01); the treatability studies can provide data upon which up to seven of these criteria can be evaluated. These seven criteria are:

- Overall protection of human health and environment
- Compliance with applicable or relevant and appropriate requirements (ARARs)
- Reduction of toxicity, mobility, or volume through treatment
- Short-term effectiveness
- Implementability
- Long-term effectiveness and permanence
- Cost.

The first four of these evaluation criteria deal directly or indirectly with the degree of contaminant reduction achievable by the aerobic biodegradation process. How "clean" will the treated soil be? Will the residual contaminant levels be sufficiently low to meet the risk-based contaminant levels established to ensure that the treatment technology achieves and maintains protection of human health and the environment? What are the contaminant concentrations and physical and chemical differences between the untreated and the treated soil (e.g., has contaminant toxicity, mobility, and volume been reduced through treatment?)? The fourth criterion, short-term effectiveness, addresses the effects of the treatment technology during the construction and implemen-

tation of a remedy until the response objectives have been met.

The implementability assessment evaluates the technical and administrative feasibility of alternatives and the availability of required goods and services. The key to assessing aerobic biodegradation under these criteria is whether the contaminant is biodegradable under site-specific conditions. Additionally, the assessment evaluates whether vendors and process equipment are available to perform the remediation, if adequate space exists to perform treatment operations, and what materials handling problems might be encountered if soil must be excavated.

Long-term effectiveness assesses how effective treatment technologies are in maintaining protection of human health and the environment after response objectives have been met. Basically, the magnitude of any residual risk and the adequacy and reliability of controls must be evaluated. The residual risk factor, as applied to aerobic biodegradation, assesses the risks remaining from residual contaminant concentrations at the conclusion of remedial activities.

The final EPA evaluation criterion that can specifically be addressed during a treatability study is cost. Aerobic biodegradation is basically a process that biologically degrades organic compounds to carbon dioxide and water or to some intermediate degradation product. Remedy design treatability studies provide data to estimate the following important cost factors:

- The initial design of the full-scale unit
- The estimated capital and operating and maintenance costs
- Initial estimate of the time required to achieve target concentrations.

In some cases, remedy selection treatability studies can provide preliminary estimates of the same cost factors.

3.2.1 Remedy Screening

Remedy screening is the first level of testing. It is used to establish the validity of a technology to treat a waste. These studies are generally low cost (e.g., $10,000-$50,000) and usually require 1 week to several months to complete. They yield data that can be used as a preliminary indication of a technology's potential to meet performance goals and can identify operating standards for investigation during remedy selection testing. They generate little, if any, design or cost data and should not be used as the sole basis for selection of a remedy.

Typically, aerobic biological remedy screening studies are performed in test reactors provided with sufficient nutrients and oxygen. Generally, these studies are batch processes. These reactors may be small sacrificial batch reactors (approximately 40 ml to 1 liter in size) or larger ecosystems (1 to 10 liters) that are subsampled to monitor the progress of biodegradation. The reactors may contain saturated or unsaturated soil or slurries in water. Slurry-phase treatability tests optimize the availability of nutrients and oxygen and offer the best chance of success for remedy screening studies. Normally, pH and contaminant loading rates are adjusted to increase the chances of success. The microbial population can be indigenous to the site, from another acclimated source (i.e., wastewater treatment sludge or another area on site), selectively cultured, a proprietary mixture provided by a vendor, or any combination of the above. The bioreactors are set up for replicate sampling at several time points. The test reactors are compared to inhibited controls at each time point to determine if aerobic biological degradation occurred. The inhibited reactors are treated with sterilization agents in an effort to reduce or eliminate the biological activity in the control reactors. The mean contaminant concentration in the inhibited control replicates is compared to the mean contaminant concentration in the test reactors. The goal for a successful treatability test is a removal rate, due to biological processes, that is greater than the analytical error inherent in the test design. A reduction of the contaminant concentration over a 3- to 6-week period of 20 percent (minimum) to 50 or 60 percent (corrected for non-biological losses) would be typical of a successful treatability study. However, for some contaminants, slower degradation rates may still indicate favorable results. More information on experimental design is provided in Subsection 4.2.

Example 3 illustrates the type of information that might result from a remedy screening study and the conclusions that might be drawn from that information.

However, even if the remedy screening tests do not meet the established goals, the test results should be examined for the potential cause(s) of failure. If such parameters can be adjusted or corrected to improve the chances of success of the remedy screening studies, the RPM or contractor should consider running additional remedy screening tests.

3.2.2 Remedy Selection

Remedy selection testing is the second level of testing. It is used to identify the technology's performance on a waste-specific basis for an operable unit. These studies

Example 3.

A site contains 27,000 cubic yards of soil contaminated with chlorinated hydrocarbons. A remedy screening study is being performed to determine if bioremediation is a viable cleanup method for the soil. The objectives of the study in this case would be to determine if biological processes could reduce the average chlorinated hydrocarbon concentration by greater than 20 percent, as compared to a chemically inhibited control, in a 6-week study. The mean contaminant concentration, corrected for the abiotic control, shows a 38 percent reduction after two months. The RPM decides that aerobic biodegradation is a potentially viable technology and that remedy selection studies are warranted.

generally are of moderate cost (e.g., $50,000-$250,000) and may require several weeks to months to complete. They yield data that verify that the technology is likely to meet expected cleanup goals and can provide information in support of the detailed analysis of the alternative (i.e., seven of the nine evaluation criteria).

The remedy selection tier of testing for aerobic biodegradation normally consists of bench-scale tests which provide sufficient experimental controls such that a quantitative mass-balance can be achieved. Such studies often incorporate volatile traps. Toxicity testing of residual contaminants and intermediate degradation products is usually required. At the remedy selection level, reduction of organic contaminants to the cleanup goals, over a 1- to 3-month period, would signify the treatability test was a success. The exact removal efficiency specified as the goal for the remedy selection test is site specific.

Pilot-scale testing may be needed for remedy selection, especially for complex sites where in situ biodegradation is being considered. RREL is planning to develop additional guidance on remedy selection treatability studies for aerobic biodegradation.

3.2.3 Remedy Design

Remedy design testing is the third level of testing. It is used to provide quantitative performance, cost, and design information for remediating a site. This level of testing also can produce data required to optimize performance. These studies are of moderate to high cost (e.g., $100,000-$500,000) and may require several months or more to complete. Remedy design studies yield data that verify performance to a higher degree than the remedy selection studies and provide detailed design information. They are performed during the remedy implementation phase of a site cleanup.

Remedy design tests usually consist of bringing a mobile treatment unit onto the site or constructing a small-scale unit for non-mobile technologies. In some cases, remedy design tests may be a continuation of remedy selection tests using the same apparatus. A complete mass balance, including all non-biological pathways, should be performed at this level of testing. Typical testing periods are from 2 to 6 months. For more complex sites (e.g., sites with different types of contaminants in different areas or with different geological structures in different areas), longer testing periods may be required.

The goal of this tier of testing is to confirm the cleanup levels and treatment times specified in Subsection 4.1.1. This is achieved by operating a field unit under conditions similar to those expected in the full-scale remediation project.

Data obtained from the pilot-scale tests should be used as follows:

- Design full-scale unit
- Determine feasibility of aerobic biodegradation based on target cleanup goals
- Refine cleanup time estimates
- Refine cost predictions.

Given the lack of full-scale experience with innovative technologies, remedy design testing will generally be necessary.

SECTION 4
REMEDY SCREENING TREATABILITY STUDY WORK PLAN

Section 4 of this document is written assuming that a Remedial Project Manager is requesting treatability studies through a work assignment/work plan mechanism. Although the discussion focuses on this mechanism, it would also apply to situations where other contracting mechanisms are used.

This section focuses on specific elements of the Work Plan that require detailed discussion because they relate to the remedy screening level of aerobic biodegradation treatability studies but are not presented in other sections of the document. These elements include test goals, experimental design and procedures, equipment and materials, reports, schedule, management and staffing, and budget. These elements are described in Subsections 4.1 through 4.9. Complementing these subsections are Section 5, Sampling and Analysis Plan, which includes the Quality Assurance Project Plan, and Section 6, Treatability Data Interpretation, that address the sampling and analysis and data analysis and interpretation elements of the Work Plan. The Work Plan elements are listed in Table 4-1.

Carefully planned treatability studies are necessary to ensure that the data generated are useful for evaluating the validity or performance of a technology. The Work Plan, which is prepared by the contractor when the Work Assignment is in place, sets forth the contractor's proposed technical approach for completing the tasks outlined in the Work Assignment. It also assigns responsibilities and establishes the project schedule and costs. The Work Plan must be approved by the RPM before initiating subsequent tasks. For more information on each of these sections, refer to the generic guide.[18]

4.1 TEST GOALS

Setting goals for the treatability study is critical to the ultimate usefulness of the data generated. Goals must be defined before

Table 4-1. Suggested Organization of Aerobic Biodegradation Remedy Screening Treatability Study Work Plan

1. Project Description
2. Remedial Technology Description
3. Test Goals (see Subsection 4.1)
4. Experimental Design and Procedures (see Subsection 4.2)
5. Equipment and Materials (see Subsection 4.3)
6. Sampling and Analysis (see Subsection 4.4)
7. Data Management
8. Data Analysis and Interpretation (see Subsection 4.5)
9. Health and Safety
10. Residuals Management
11. Community Relations
12. Reports (see Subsection 4.6)
13. Schedule (see Subsection 4.7)
14. Management and Staffing (see Subsection 4.8)
15. Budget (see Subsection 4.9)

the treatability study is performed. Each tier of the treatability study needs performance goals appropriate to that tier. For example, to use remedy screening tests to answer the question, "Does aerobic biodegradation work on this contaminant?," it is necessary to define "work" (i.e., set the goal of the study). A pollutant reduction of at least 20 percent during the remedy screening tests may satisfy the test for validity of the process and indicate that further testing at the remedy selection level is appropriate to determine if the technology can meet the anticipated performance criteria of the ROD.

4.1.1 Remedy Screening Goals

The main goals of the remedy screening evaluation are to:

- Provide an indication that reductions in contaminant concentrations are due to biodegradation and not abiotic processes such as photodecomposition, volatilization, and adsorption

- Produce the design information required for the next level of testing, should the screening evaluation be successful.

Normally, the average contaminant concentration should be reduced by at least 20 percent during a 6- to 8-week study, as compared to an inhibited control, to conclude aerobic biodegradation is a potential treatment technology for the site under investigation. The 20-percent contaminant reduction is arbitrary, but is designed to maximize the chances of success at the remedy screening tier. The choice of a 6- to 8-week study is to provide a consistent endpoint for remedy screening studies. The choice of the remedy screening treatability study goals (time and contaminant reduction) will be site-specific decisions.

Example 4 is provided to demonstrate typical goals of a remedy screening study and what decision can be made when these goals are achieved.

4.2 EXPERIMENTAL DESIGN

A number of different approaches can be used to conduct the remedy screening test. These range from simple shake flask evaluations to soil pans or soil slurry reactors. The soil may be either saturated or unsaturated, depending on the goals of the study. Soil slurries will optimize mixing and will tend to maximize biological degradation. Such studies will maximize the chances of success at the remedy screening level. Unsaturated soils will often limit mixing and result in slower degradation rates. However, such systems will correlate better with field conditions in many cases and result in better extrapolation to remedy selection test systems. The object of this guidance document is not to specify a particular remedy screening method but rather to highlight those critical parameters that should be evaluated during the laboratory test.

The test should include controls to measure the impact of non-biological processes such as volatilization, sorption, and photodecomposition on the concentrations of contaminants. Inhibited controls can be established by using formaldehyde, mercuric chloride, or sodium azide to inhibit microbiological activity. However, care should be exercised when selecting a sterilizing agent. For example, sodium azide can, under certain circumstances, promote spontaneous explosive reactions. Mercuric chloride complexes certain petroleum hydrocarbons and results in artificially low hydrocarbon concentrations. Soil structure also can be modified by sterilization agents. Complete sterilization of soils can be difficult to accomplish. Incom-

Example 4

The soil of a former wood-preserving site is contaminated with pentachlorophenol (PCP) waste. The literature search indicated that PCP has been successfully biodegraded at other sites. The RPM decided a remedy screening study was needed to measure the potential for successful biodegradation at this site. A goal of 25 percent reduction of the PCP concentrations was set. The study period was set at 6 to 8 weeks. These study goals were established to maximize the chances of success for biodegradation.

A remedy screening study was performed to determine if bioremediation is a viable cleanup method for the soil. The average PCP concentration was reduced by 37 percent, over a 6-week period, after correction for the inhibited control. The RPM decided that further treatability studies were warranted and elected to have a remedy selection treatability study performed to attempt to optimize degradation.

plete mixing of sterilization agents with soils can result in pockets of surviving microbes in soil pores. In some cases, microbial populations can transform and detoxify sterilizing agents. Complete sterilization of the control is not necessary provided that biological activity is inhibited sufficiently so that a statistically significant difference between the test and control means can be determined. However, care should be taken in interpreting remedy screening study results. Substantial degradation in the control (e.g., 20-50 percent contaminant reduction, or more) can mask the occurrence of biodegradation in the test reactor. If the control reactor has the same or greater percent degradation as the test reactor, a false negative conclusion can result. Concluding that no biodegradation occurred, when in fact there was some biodegradation, can lead to elimination of this technology unnecessarily. Alternatively, closed test systems with volatile traps can be used to monitor the volatilization of compounds instead of using inhibited controls to estimate abiotic losses.[14]

A statistical experimental design should be used to conduct the treatability study in order to support decisions made from the treatability data. The various parameters of interest are included as factors in the experimental design. The treatability experiment should include monitoring the concentration of chemicals of interest over time. In general, at least three to four time periods should be studied, including the time-zero (T_0) analysis. However, if the study goals are met after a sampling period, then it is not necessary to continue sampling at additional time periods. (For example, if 70-percent reduction was achieved after 1 week, it would not be necessary to continue testing if the goal was to achieve only a 20-percent reduction.)

The test system can consist of a single large reactor or multiple small reactors. In the case of the single reactor, small subsamples are removed at various times and compared to subsamples from a second reactor in which biological activity has been inhibited. Normally, triplicate subsamples are taken at each time point. The mean contaminant concentrations in the test and control reactors are compared to see if a statistically significant change in concentration has occurred. The mean contaminant concentration in the inhibited control subsample can be subtracted from that in the test subsample to estimate the percentage the contaminant has biodegraded at each time point. In this type of system, heterogeneity within the soil system can lead to variability in contaminant concentration among the various subsamples and replicates. However, such system variability can be overcome by thorough mixing of the soil before it is distributed to the test and control systems. Examples of this type of system are large flasks, soil pans, and other large soil reactors. Care should be taken so that the system size and design do not limit the availability of oxygen and moisture and cause variability in degradation rates within the reactor.

Multiple reactors may be set up in place of a large soil system. Triplicate reactors are established for each test reactor and control group at each time point. Each reactor is filled with the same amount of soil and nutrient additives. In this case, the complete reactor contents are extracted and analyzed for each of the triplicate test and control reactors at each time point. Examples of such systems are serum bottles, slurry reactors, and aerated soil reactors. The advantage of this type of experimental apparatus is that the question of subsampling representativeness is avoided. However, the representativeness of any one reactor is questionable in this design. Thorough mixing of the soil, before it is distributed among the individual reactors, is important.

Triplicate samples provide a measure of the overall precision of the measurements made. Surrogate spikes should also be added to the matrix samples to ensure consistent analytical performance. Matrix spikes should be added to a percentage (approximately 10%) of the samples to determine overall analytical accuracy. Method blanks should be used to monitor potential contamination of samples during laboratory handling.

Respirometric measurements or other measures of biological activity can be used to predict the best times to take samples. At the beginning of the experiment, activity measurements should indicate minimal biological activity. Continued monitoring can reveal either a rapid or relatively slow onset of biological activity and indicate when samples should be taken to monitor contaminant reductions. However, respirometric measurements can indicate the loss of oxygen through chemical oxidation in addition to biodegradation.[7][10][27]

In formulating an experimental design, the total number of samples taken depends on the desired difference in concentrations that the experimenter wishes to detect, the measurement variability (the analytical coefficient of variation), and the type I and type II error probabilities. Each of these factors is discussed below.

The goal of the remedy screening scale of treatability testing is not to be able to ascertain whether the biotreatment process can meet cleanup goals but rather whether biodegradation is possible with the site-specific waste material in question. Therefore, at the remedy screening scale, it is usually not necessary to establish complete removal of the contaminant of interest. As a guide, the experiment should be designed so that a difference of 20 to 50 percent removal of the contaminant of interest can be detected between the treatment and the inhibited control.

In general, for sampling and analysis of soils and sludges, the analytical variability can be quite high (on the order of 20 to 50 percent). Therefore, a sufficient number of samples must be taken for statistically significant effects to be observed. Additional information on sample size selection is available in many statistical textbooks.[2][5][9]

The type I error probability is the chance of the experiment indicating that there is a statistically significant treatment effect when, in reality, there is not. Conversely, the type II error probability is the chance of not detecting a significant treatment effect when, in reality, the treatment was effective. Traditionally, experimental designs have been constructed so that these error probabilities are on the order of 5 percent (i.e., 95 percent confidence levels). This error probability is not appropriate for the *remedy screening scale* of treatability testing. Error rates on the order of 10 to 20 percent (i.e., 80 to 90 percent confidence levels) are more consistent with the philosophy of *remedy screening.*

It is beyond the scope of this document to go into great detail on experimental design but many good texts on the subject are available.[2][9]

An example of a simple experimental design is included in Example 5.

4.3 EQUIPMENT AND MATERIALS

The Work Plan should specify the types of equipment and materials to be used during the treatability test. For example, the size and type of glassware to be used during the test should be specified. Standard laboratory methods normally dictate the types of sampling containers that can be used with various contaminant groups. The RPM should consult such references for the appropriate containers to be used for the treatability studies.[24] Normally, glass reactors with Teflon® fittings should be used. Stainless steel also can be used with most contaminants. Care should be taken when using various plastic containers and Tygon® tubing. Such materials will adsorb many contaminants and also can leach plasticizer chemicals, such as phthalates, into the soil matrix. Typically, such analytical equipment as gas chromatograph (GC), high-pressure liquid chromatograph (HPLC), total organic carbon (TOC) analyzers, and pH meters will be required.

Example 5. Bioremediation Study

Twenty-four 20-gram samples of soil containing approximately 100 ppm phenol were added to separate 500 ml flasks along with 80 ml of water containing phosphate buffer (pH = 7.0), ammonium sulfate, and trace metals. Twelve of the resulting soil slurries were inoculated with a suspension containing approximately 10^4 phenol degrading bacteria/ml. The other 12 flasks were inoculated and then "sterilized" with mercuric chloride to form the control group. The test and inhibited control flasks were stoppered and stirred at moderate speed on stirring plates while incubating at 20°C. Three test flasks were immediately sacrificed (T_0) by adding 100 ml of methanol and shaking vigorously to extract the phenol for analysis. One ml subsamples from each flask were centrifuged at high speed in a microcentrifuge to remove soil particles. Phenol was quantified via high-pressure liquid chromatograph. At each of three subsequent time points (T_1, T_2, T_3), three additional test flasks were sacrificed and subsampled as previously described. Three inhibited control flasks were also sacrificed at each time point. The mean phenol concentration of the three test flasks was compared to the mean phenol concentration of the three control flasks at each time point to see if significant biodegradation was occurring.

4.4 SAMPLING AND ANALYSIS

The Work Plan should describe the sampling procedures to be used during field sampling and remedy screening treatability studies. Appropriate methods for preserving samples and specified holding times for those samples should be used. The procedures will be site-specific. Standard EPA and American Society for Testing and Materials (ASTM) methods are generally recommended; however, the treatability study vendor may propose modified or equivalent methods that are more suited to the specific treatment process being studied. The EPA RPM must determine the acceptability of these alternative methods with respect to the test objectives and the available method validation information provided by the vendor. The Work Plan also should note that the Sampling and Analysis Plan (SAP) will be prepared before field sampling and treatability testing begins. Section 5 provides details for the preparation of the SAP including the Field Sampling Plan (FSP) and the Quality Assurance Project Plan (QAPjP).

4.4.1 Field Sampling

A sampling plan should be developed that directs the collection of representative samples from the site for the treatability test. The sampling plan should be site-specific and describe the number, location, and volume of samples to be collected. Typically, little information is available at this point of the RI; therefore, good engineering judgment must be used. An adequate volume of soil sample should be collected from each sampling location to account for replicate treatability tests and analytical quality assurance/quality control (QA/QC) requirements.

Depending upon the goals of the remedy screening treatability study, samples representative of conditions typical of the entire site or defined areas (i.e., hot spots) within the site should be collected. The selection of soil sampling locations should be based on knowledge of the site. Information from previous soil samples, soil gas analysis using field instrumentation, and obvious odors or residues are examples of information that can be used to specify sample locations.

The method of sample collection is site-specific. For example, drill rigs or hand augers can be used to collect samples, depending on the depth of the sample required and the soil characteristics. If the target contaminants are volatile, care should be taken to minimize their loss when they are composited. Compositing is usually appropriate for soils containing non-volatile constituents; however, compositing samples on ice is a good method of minimizing the loss of volatile compounds.

4.4.2 Sampling During the Remedy Screening Treatability Study

During the remedy screening treatability study, the extent of biodegradation is assessed by removing samples from a large test reactor, or sacrificing the entire contents of smaller test systems, at predetermined time intervals. The concentrations of contaminants, at a minimum, should be determined at the beginning, at some intermediate time point, and at the end of the experiment. Therefore, a minimum of three sampling points is normally required. A useful approach is to establish enough test systems so that the remedy screening study can be extended or additional samples can be removed and archived for analysis, if required. The length of the study will be determined by the biodegradability of the contaminants. For example, treatability tests for BTEX wastes may be conducted within 3 to 4 weeks. Tests involving PAHs may take several months because microorganisms will likely attack the structurally less complicated molecules before more complex molecules. As discussed earlier, measures of microbial activity may be useful in identifying appropriate sampling times.

4.4.3 Analysis

The concentrations of some important matrix parameters are determined by using standard analytical chemistry methods (Table 4-2). These parameters should be determined before the treatability study begins. These parameters are important for the design of remedy selection and remedy design studies; they should not be used as an indication of the inappropriateness of the technology.

Table 4-2. Commonly Used Analytical Chemistry Methods for Soil Parameters

	Methods	
Analysis	Liquid/Sludge	Soil
Moisture	160.3[19]	ASTM 2216[1]
Nitrate	9200[24]/300.0[25]	—
Total Organic Carbon	9060[24]/415.1[19]	9060[24]
Total Kjeldahl Nitrogen	351.2[19]	ASTM E 778[1]
Soluble Orthophosphate	365.1[19]	—
Soluble Ammonia	350.1[19]	—
pH	9040[24]/150.1[19]	9045[24]

Contaminant concentrations should be determined at the beginning of the study and at the sample times chosen in the experimental design. Consult U.S. EPA SW-846[24] for the appropriate methods. When determining volatile and semi-volatile organics, GC or other appropriate methods (e.g., HPLC) should be used whenever possible, rather than gas chromatography/mass spectrometry (GC/MS) methods, to minimize costs. All sampling and analysis should be performed in accordance with the SAP (Section 5).

4.5 DATA ANALYSIS AND INTERPRETATION

The Work Plan should discuss the techniques to be used in analyzing and interpreting the data. The following data should be reported for each treatability test:

- Concentration of chemicals in samples at the time of sampling (field concentration) and before the samples are added to the reactors (T_0 reactor concentration)
- Amount of soil used in the reactors and a description of all modifications to the reactors
- Quantity of residual chemical(s) in each of the reactors at each sampling time
- Quantity of chemical(s) lost due to abiotic processes
- Temperature profile over the entire experiment recorded in a written log indicating type, extent, and time of any action
- Any other additions, removals, changes, manipulations, or mishaps that occur during the course of the experiment should be recorded in a written log indicating type, extent, and time of any action
- All cited analytical and microbiological procedures (recorded in a written log)
- All quality control data (e.g., recovery percentage of spikes; contaminant concentrations, if any, in experimental and analytical blanks).

Additional information on the interpretation of treatability study data is presented in Section 6 of this document.

4.6 REPORTS

The Work Plan should discuss the organization and content of interim and final reports. Once the data have been gathered, analyzed, and interpreted, they must be incorporated into a report. A suggested organization for the treatability study report is provided in Subsection 4.12 of the generic guide.[18]

If the report indicates aerobic biodegradation has potential (see Section 6 for guidance on interpretation of treatability data), the project can progress to the next level. In general, if the average reduction in contaminant concentration attributable to biodegradation exceeds 20 percent during a 6- to 8-week test period, the remedy screening is considered positive. Additional studies will be required before selecting a remedy in the ROD.

4.7 SCHEDULE

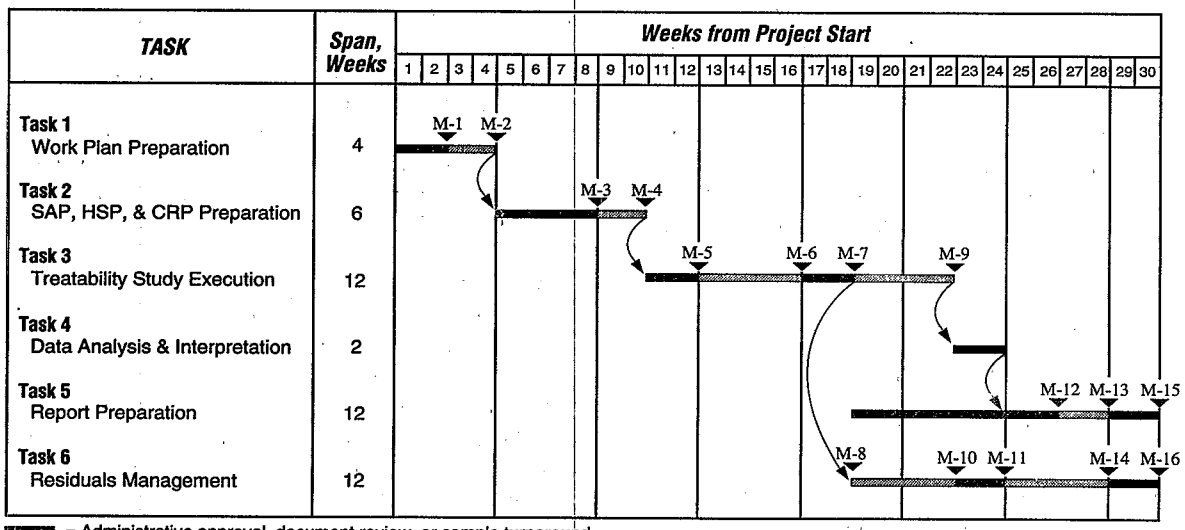
The Work Plan should discuss the schedule for completing the remedy screening treatability study. When preparing a schedule for conducting treatability studies, it is advantageous to break down the entire process into distinct tasks that are common to most studies.

Listed below are specific tasks that should always be considered when scheduling:

- Work Plan preparation
- SAP preparation
- Sample collection and disposal
- Field sample analysis
- Treatability test (including analyses)
- Data validation
- Report preparation.

The tasks that have the greatest potential for time variance are usually the Work Plan preparation and the treatability tests. The treatability test schedule is unpredictable without a firm understanding of the contaminant types and concentrations involved. For example, remedy screening treatability tests for BTEX wastes may be conducted within a couple of weeks; tests involving PAHs may take several months for the reasons discussed in Subsection 4.4.2.

The schedule itself is usually most helpful if displayed in the form of a bar chart, such as the one shown in Figure 4-1.



= Administrative approval, document review, or sample turnaround

M-1	Submit Work Plan	Wk 2
M-2	Receive Work Plan Approval	Wk 4
M-3	Submit SAP, HSP, CRP	Wk 8
M-4	Receive SAP, HSP Approvals	Wk 10
M-5	Collect Sample	Wk 12
M-6	Receive Sample Characterization Results	Wk 16
M-7	Collect Treatability Study Samples	Wk 18
M-8	Collect Project Residual Samples	Wk 18
M-9	Receive Treatability Study Analytical Results	Wk 22
M-10	Receive Project Residual Analytical Results	Wk 22
M-11	Submit Waste Disposal Approval Form	Wk 24
M-12	Submit Draft Report	Wk 26
M-13	Receive Review Comments	Wk 28
M-14	Receive Waste Disposal Approval	Wk 28
M-15	Submit Final Report; Conduct Briefing	Wk 30
M-16	Ship Wastes to TSDF	Wk 30

Figure 4-1. Example project schedule for a treatability study.

4.8 MANAGEMENT AND STAFFING

The Work Plan should discuss the management and staffing of the remedy screening treatability study and identify the personnel who will be responsible for executing the treatability study at this level. Generally, the following expertise is needed for the successful completion of the remedy screening treatability study:

- Project manager (work assignment manager)
- Chemist
- Microbiologist, environmental scientist/engineer, or bioengineer
- Lab technician
- Quality assurance manager.

Responsibility for various aspects of the project is typically shown in an organizational chart such as the one in Figure 4-2.

4.9 BUDGET

The Work Plan should discuss the budget for completion of the remedy screening treatability study. The cost of biotreatability evaluations varies tremendously. Historically, the cause of this wide variation has been significant differences in the scope of work associated with specific site characteristics. The lack of established standard procedures, to date, for performing biotreatability evaluations has led remediation firms to develop their own "standard procedures." This guide will serve as an important aid in accurately defining data that should be produced from a biotreatability remedy screening evaluation and ensuring that the data will be sufficient for deciding whether to proceed to the next phase of development of the bioremediation process.

The cost of the remedy screening phase is directly related to the method of sample collection, the number of samples collected, the type and number of chemical analyses performed on samples, and the number of replicate remedy screening tests performed. The factor which is most likely to influence the cost of the remedy screening is the ana-

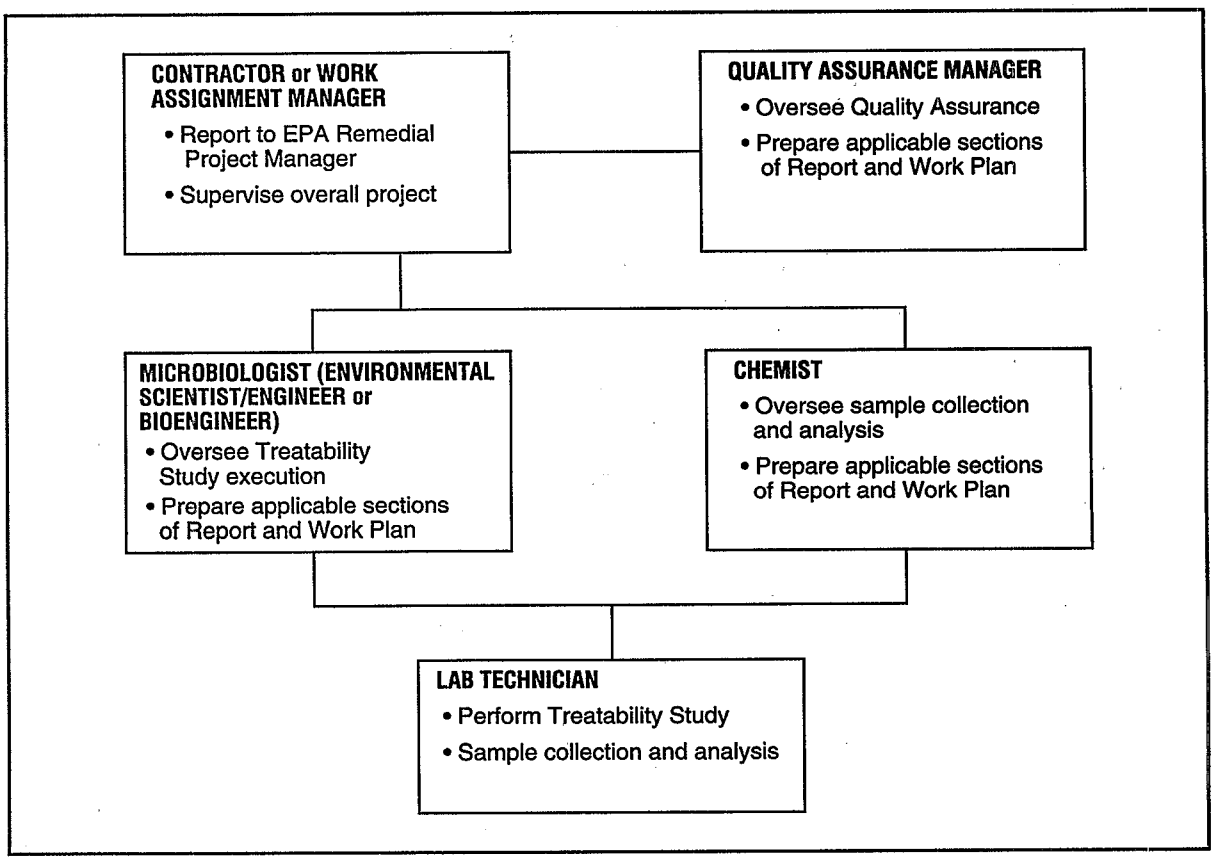


Figure 4-2. Organization chart.

lytical costs which are directly tied in with the number of replicates. One method to minimize costs is to use an inexpensive analysis of an indicator parameter and to perform a limited number of analyses for the more expensive volatile and semi-volatile priority pollutants. Use of GC rather than GC/MS methods also should help to minimize costs. Table 4-3 summarizes the major cost elements associated with remedy screening treatability tests for biodegradation of a contaminated site.

Table 4-3. Major Cost Elements Associated with Aerobic Biological Remedy Screening Treatability Studies

Cost Element	Cost Range (thousands of dollars)
Work Plan Preparation	1 - 5
SAP Preparation	1 - 5
Field Sample Collection	1 - 5
Field Sample Chemical Analysis	2 - 10
Laboratory Setup/Materials	2 - 10
Treatability Test Chemical Analysis	2 - 10
Data Presentation/Report	1 - 5
TOTAL COST RANGE	10 - 50

SECTION 5
SAMPLING AND ANALYSIS PLAN

The SAP consists of two parts — the Field Sampling Plan (FSP) and the QAPjP. This section identifies the contents of and aids in the preparation of these plans. A SAP is required for all field activities conducted during the RI/FS. The purpose of the SAP is to ensure that samples obtained for characterization and testing are representative and that the quality of the analytical data generated is known. The SAP addresses field sampling, waste characterization, and sampling and analysis of the treated wastes and residuals from the testing apparatus or treatment unit. The SAP is usually prepared after the Work Plan is approved.

5.1 FIELD SAMPLING PLAN

The FSP component of the SAP describes the sampling objectives; the type, location, and number of samples to be collected; the sample numbering system; the necessary equipment and procedures for collecting the samples; the sample chain-of-custody procedures; and the required packaging, labeling, and shipping procedures.

Field samples are taken to provide baseline contaminant concentrations and material for the treatability studies. The sampling objectives must be consistent with the treatability test objectives. Because the primary objective of remedy screening studies is to provide a first-cut evaluation of the extent to which specific chemicals are removed from the soil by biological process, the primary sampling objectives should include, in general:

- Acquisition of samples representative of conditions typical of the entire site or defined areas within the site. Because this is a first-cut evaluation, elaborate, statistically designed field sampling plans may not be required. Professional judgment regarding the sampling locations should be exercised to select sampling sites that are typical of the area (pit, lagoon, etc.) or appear above the average concentration of contaminants in the area being considered for the treatability test. This may be difficult because reliable site characterization data may not be available early in the remedial investigation.
- Acquisition of sufficient sample volumes necessary for testing, analysis, and quality assurance and quality control.

From these two primary objectives, more specific objectives should be developed. When developing the more detailed objectives, the following types of questions should be considered.

- Will samples be composited to provide more representative samples for the treatability test, or will the potential loss of target VOCs prohibit this sample collection technique?
- Are there adequate data to determine sampling locations indicative of the more contaminated areas of the site?
- Is sampling of a worst-case scenario warranted to determine if either indigenous or inoculated microorganisms are able to break down contaminants at their highest known concentrations in the field.

After the sampling objectives are clearly identified, an appropriate sampling strategy should be described. Specific items that should be briefly discussed are:

- Sampling objectives
- Calibration procedures
- Sample location selection
- Sample collection
- Sampling procedures
- Sample transportation
- Sampling equipment
- Responsible persons
- Sample media type
- Sampling strategy

- Sample location map
- Sample history recording procedures
- Sample preservation methods/holding times
- Sample custody and chain-of-custody procedures

Table 5-1 presents the suggested organization of the SAP.

TABLE 5-1. Suggested Organization of the Sampling and Analysis Plan

Field Sampling Plan
1. Site Background
2. Sampling Objectives
3. Sample Location and Sampling Frequency
4. Sample Designation
5. Sampling Equipment and Procedures
6. Sample Handling and Analysis

Quality Assurance Project Plan
1. Experimental Design
2. Quality Assurance Objectives
3. Sampling and Analytical Procedures
4. Approach to QA/QC

5.2 QUALITY ASSURANCE PROJECT PLAN

The QAPjP should be consistent with the overall objectives of the treatability study. At the remedy screening level, the QAPjP should not be overly detailed.

5.2.1 Experimental Design

Section 1 of the QAPjP must include an experimental project description that clearly defines the experimental design, the experimental sequence of events, each type of critical measurement to be made, each type of matrix (experimental setup) to be sampled, and each type of system to be monitored. This section may reference Section 4 of the Work Plan; however, all details of the experimental design not finalized in the Work Plan should be defined in this section.

The following items should be included:

- Number of samples (area) to be studied
- Identification of treatment conditions (variables) to be studied for each sample
- Type of reactors to be used for each sample
- Target compounds for each sample
- Number of replicates per condition per sampling event
- Number and time of each sampling event.

The project description should clearly define and distinguish the types of critical measurements or observations that will be made, as well as any system conditions (e.g., process controls or operating parameters) that will need to be monitored routinely. Critical measurements are those measurement, data-gathering, or data-generating activities that directly affect the technical objectives of a project. At a minimum, the determination of the target compound (identified above) in the initial soil and treated soil samples will be critical measurements.

The purpose of the remedy screening treatability study is to determine whether biological treatment is potentially applicable to the site under consideration. An example of a criterion for this determination is a 20 percent reduction in concentration of the select target compounds at the 80 percent confidence level. If a 20 percent reduction is obtained, then additional remedy selection studies would be indicated to optimize the treatment and determine the cost-effectiveness in comparison to other technologies.

5.2.2 Quality Assurance Objectives

Section 2 should list the QA objectives for each type of critical measurement and for each type of sample matrix defined in Section 1, for each of the six data quality indicators: precision, accuracy, completeness, representativeness, comparability, and, where applicable, method detection limit. See reference 21 for additional information on the preparation of a QAPjP.

5.2.3 Sampling and Analytical Procedures

The procedures used to obtain the field samples for the remedy screening treatability study are described in the FSP and need not be repeated in this section, but should be incorporated by reference.

Section 3 of the QAPjP, therefore, should contain a credible plan for subsampling the material for the remedy screening treatability study. Also, if the reactor contents are sacrificed for analysis, the methods for aliquoting the residual material in each reactor for different analytical methods must be described.

This section should also describe or reference an appropriate analytical method and a standard operating procedure for implementing the analytical method for each type of critical measurement to be made. In addition, the calibration procedures and frequency of calibration should be discussed or referenced for each analytical system, instrument, device, or technique used to obtain critical measurement data.

The methods used for analyzing the treatability study samples should be the same as those used for chemical characterization of field samples. Preference should be given to methods in "Test Methods for Evaluating Solid Waste." [24] If applicable, methods other than GC/MS methods are recommended to conserve costs.

5.2.4 Approach to QA/QC

The treatability study is designed to compare the results of a biological reactor to an inhibited control reactor over a period of time. Replicate samples (three) are taken of both experimental setups at T_0, T_1, and at least a T_2. The inhibited control is run and analyzed to account for losses of the target compounds due to any cause other than biodegradation (e.g., volatilization, adsorption).

The intended purpose of this study is to determine if the concentration of the target compounds decreases at least 20 percent in the biological reactor compared to the inhibited control at an 80 percent confidence level. Only the *relative* accuracy of the analytical measurements and the overall precision of the experiments are important.

The suggested QC approach will consist of:

- Triplicate samples of both reactor and inhibited control at each sampling time
- The analysis of surrogate spike compounds in each sample
- The extraction and analysis of a method blank with each set of samples
- The analysis of a matrix spike in approximately 10 percent of the samples.

The analysis of triplicate samples provides for the overall precision measurements that are necessary to determine whether the difference is significant at the 80 percent confidence level. The analysis of the surrogate spike will determine if the analytical method performance is consistent (relatively accurate). The matrix spike will be used to measure overall analytical accuracy. The method blank will show if laboratory contamination has had an effect on the analytical results.

Selection of appropriate surrogate compounds will depend on the target compounds identified in the soil and the analytical methods selected for the analysis.

SECTION 6
TREATABILITY DATA INTERPRETATION

This section is designed to help the RPM or contractor to interpret treatability data in screening and selecting a remedy. The information and results gathered from the remedy screening are used to determine if bioremediation is a viable treatment option and to determine if additional remedy selection and remedy design studies are needed prior to the implementation of a full-scale bioremediation process. A threshold of greater than 20 percent reduction in the concentrations of the compounds of concern, compared to the abiotic control, indicates that bioremediation is potentially a viable cleanup method and further testing is warranted. For some compounds or sites, a period of time longer than the typical 6-8 weeks may be indicative of a successful remedy screening study. An example method for interpreting the results from a remedy screening treatability study is provided below. Other valid statistical methods may be used as appropriate.

Example 6.

In a remedy screening treatability study for soil contaminated with a solvent, the average solvent concentrations in both the inhibited control and in the biologically active system were 1300 ppm at T_0. The average solvent concentration in the inhibited control was reduced to 550 ppm (T_3), a reduction of greater than 57 percent (Table 6-1). The average hydrocarbon concentration in the biologically active system was reduced to 200 ppm (T_3), a reduction of greater than 84 percent for the same time period.

TABLE 6-1. Hydrocarbon Concentration (ppm) Versus Time

SAMPLE	T_0	T_1	T_2	T_3
Inhibited Control (C_i)				
Replicate 1	1220	1090	695	575
Replicate 2	1300	854	780	580
Replicate 3	1380	1056	688	495
Mean Value	1300 ($\widehat{Ci}_0$)	1000 ($\widehat{Ci}_1$)	721 ($\widehat{Ci}_2$)	550 ($\widehat{Ci}_3$)
Concentration Change ($\widehat{Ci}_0 - \widehat{Ci}_t$) (T = 0, 1, 2, 3)	0	- 300	- 579	- 750
Bioreactor (C_b)				
Replicate 1	1327	982	550	225
Replicate 2	1320	865	674	310
Replicate 3	1253	703	666	65
Mean Value	1300 ($\widehat{Cb}_0$)	850 ($\widehat{Cb}_1$)	630 ($\widehat{Cb}_2$)	200 ($\widehat{Cb}_3$)
Concentration Decrease ($\widehat{Cb}_0 - \widehat{Cb}_t$) (T = 0, 1, 2, 3)	0	- 450	- 670	- 1100

The average contaminant concentration of the bioreactor, at each time point, is corrected by the average contaminant concentration of the inhibited control, at the same time point, to measure the biodegradation at that time point. The inhibited control accounts for contaminant losses due to volatilization, adsorption to soil particles, and chemical reactions. Some contaminant loss in the control due to biodegradation may occur since total sterilization is difficult to accomplish. However, if a statistically significant difference between the test and control means exists, then biodegradation has occurred in the test bioreactor. The difference between the two means is tested using Analysis of Variance (ANOVA) methods at the 80 percent confidence level for each of the test times. If the difference between the two means is significant at T_1, no further test measurements are required. If the difference between the two means is not significant at T_1, then the remedy screening test continues until some T_2. This process is repeated until a statistically significant difference between the two means is found or the treatability study is determined to be unsuccessful and is discontinued. In this example, a statistically significant difference between the two means occurs at T_3. The data, therefore, indicate that bioremediation is a viable treatment option and that further remedy selection studies are appropriate. The 80% confidence interval about each mean is shown in Figure 6-1 to graphically describe the variation associated with each mean.

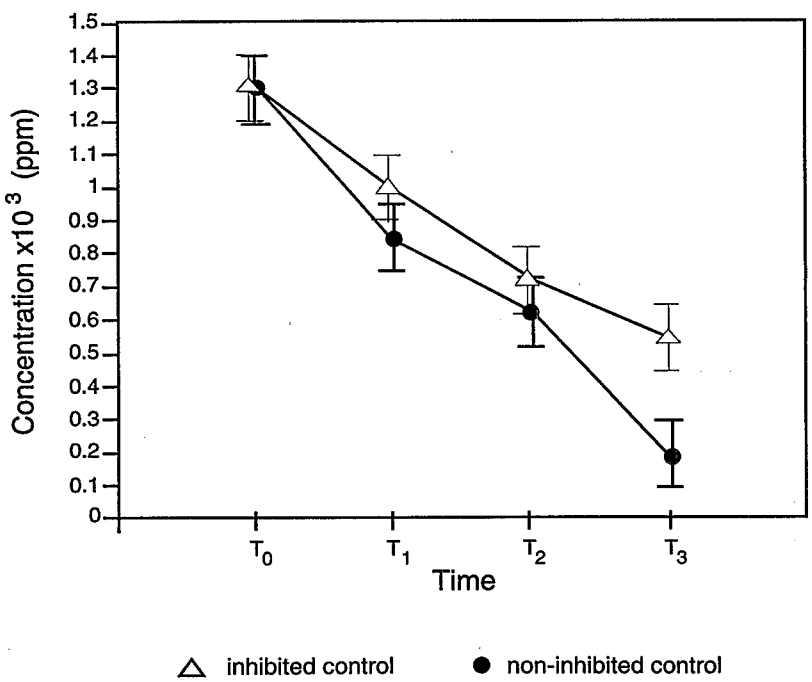


Figure 6-1. Plot of hydrocarbon concentration versus time.

If the remedy screening indicates that bioremediation is a potential cleanup option then remedy selection studies should be performed. Remedy selection testing is the second level of testing. It is used to identify the technology's performance on a contaminant-specific basis. Costs for these studies generally range from $50,000 to $250,000. They yield data that verify that the technology can meet expected clean up goals and can provide information in support of the detailed analysis of the alternative (i.e., the nine evaluation criteria).

During the remedy selection studies, microcosms designed to simulate the proposed full-scale bioremediation system are generally established. Specifically, the goals of the remedy selection microcosms are to:

- Estimate the rate at which the contaminants can be biodegraded
- Determine the impact of parameters such as nutrient addition, loading rate, and inoculation on the rate of biodegradation
- Estimate the cleanup levels achievable
- Develop design parameters for the next level of testing
- Develop preliminary cost and time estimates for full-scale bioremediation.

If required, several bioremediation processes can be evaluated simultaneously to determine which process or combination of processes is most appropriate for the cleanup of a given site. For example, if the affected materials at a site can be effectively remediated with either a solid-phase or a slurry-phase biological treatment process, both of these processes may be evaluated simultaneously. The biodegradation rates measured during the solid-phase and slurry-phase remedy selection evaluations can then be used to estimate the treatment time, equipment, and land area required by each treatment process. This procedure permits determination of which process or combination of processes can achieve most cost-effectively, the required cleanup levels in the required period of time. If sufficient design and cost information are acquired during the remedy selection tests to permit full-scale system design, further remedy design testing may be unnecessary.

Remedy design testing is the third level of testing in the RI/FS process. These studies generally range from $100,000 to $500,000. As discussed in the preceding paragraph, remedy design studies are not always required. When remedy design tests are performed, they are typically post-ROD. Therefore, if a remedy design program is conducted, it should produce the data required for final full-scale remedy design and costing. The remedy design program is usually conducted on-site and should test all equipment and processes so that accurate specifications can be made for the full-scale system.

Example 7 demonstrates the decision process to proceed from remedy screening, through remedy selection, and on to remedy design. This example is a continuation of Example 4 on page 20.

The size and scope of the remedy design program may be decided by several factors including the quantity of material available for testing, the complexity of the process, cost, time, and equipment availability. An important factor that should not be overlooked when a remedy design program is being set up is that the equipment must be sized so that realistic scale-up factors can be used for going to full-scale operation.

In conclusion, technologies generally are evaluated first at the remedy screening level and progress through the remedy selection to the remedy design level. A technology may enter, however, at whatever tier or level is appropriate based on available data on the technology and site-specific factors. For example, a technology that has been studied extensively may not warrant remedy screening to determine whether it has the potential to work. Rather, it may go directly to remedy selection testing to verify that performance standards can be met.

Example 7.

Even though the reduction in PCP concentration during the remedy screening study was sufficient to justify continuing to the remedy selection tier of treatability testing, the percentage of degradation, as compared to the control, indicated that process changes were needed at the remedy selection tier. High PCP concentrations may have been inhibiting microbial activity. The RPM decided to investigate mixing less-contaminated soil with the highly contaminated soil to lower PCP concentrations and stimulate biodegradation. Remedy selection studies, using the design modifications suggested by the remedy screening studies, resulted in an average removal of 93 percent of the PCP. Remedy design studies were performed to provide design information for a full-scale system, which was used to remediate the site successfully.

SECTION 7
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