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Guide for Conducting Treatability Studies Under CERCLA

Chemical Dehalogenation

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GUIDE FOR CONDUCTING TREATABILITY STUDIES UNDER CERCLA: CHEMICAL DEHALOGENATION

FINAL

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

and

Office of Emergency and Remedial Response
Office of Solid Waste and Emergency Response
U.S. Environmental Protection Agency
Washington, DC 20460

NOTICE

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (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 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 purpose of this guide is to provide information on conducting treatability studies involving chemical dehalogenation of soils and sludges. It describes a three-tiered approach, which consists of 1) remedy screening, 2) remedy selection, and 3) remedial design/remedial action. It also presents detailed, technology-specific information on the preparation of a Work Plan and a Sampling and Analysis Plan for chemical dehalogenation treatability studies. The intended audience for this guide comprises Remedial Project Managers, responsible parties, 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. In December 1989, the EPA published an interim final *Guide for Conducting Treatability Studies Under CERCLA*, which presents a stepwise approach or protocol for conducting treatability studies in support of remedy selection [i.e., pre-Record of Decision (ROD)] at CERCLA sites. The "generic guide" has been revised and will be issued as a final document in 1992. This guide, which presents information on treatability studies involving chemical dehalogenation of soils and sludges, is intended to supplement the information in the final generic guide.

The guide describes a three-tiered approach for conducting treatability studies, which consists of 1) remedy screening, 2) remedy selection, and 3) remedial design/remedial action. The purpose of remedy-screening studies for chemical dehalogenation technologies is to determine if the technology is chemically feasible for the contaminants/matrix of concern. If feasibility is demonstrated at the screening tier, more exhaustive testing can be performed to generate the performance and cost data necessary to support the detailed analysis and selection of the remedy. Remedial design/remedial action studies, which are performed post-ROD, provide detailed design and operating data necessary to scale up and implement the technology.

The guide also presents detailed, technology-specific information on the preparation of a Work Plan and a Sampling and Analysis Plan for chemical dehalogenation treatability studies. Elements discussed include test objectives, experimental design and procedures, equipment and materials, sampling and analysis procedures, quality assurance/quality control procedures, and data analysis and interpretation.

The intended audience for this guide comprises Remedial Project Managers, responsible parties, contractors, and technology vendors.

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ACRONYMS

APEG	Alkaline polyethylene glycolate
ARARs	Applicable or Relevant and Appropriate Requirements
ASTM	American Society for Testing and Materials
ATP	AOSTRA-Taciuk Process
BCD	Base-Catalyzed Decomposition
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CLP	Contract Laboratory Program
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DMSO	Dimethylsulfoxide
EPA	U.S. Environmental Protection Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FRC	Franklin Research Center
FSP	Field Sampling Plan
ITEP IT	Environmental Programs, Inc.
HSP	Health and Safety Plan
KOH	Potassium hydroxide
KPEG	Potassium polyethylene glycolate
LC	Lethal concentration
LDRs	Land disposal restrictions
MDL	Method detection limit
MS	Matrix spike
MSD	Matrix spike duplicate
NaOH	Sodium hydroxide
NaPEG	Sodium polyethylene glycolate
NMPC	Niagara Mohawk Power Corporation
O&M	Operation and maintenance
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated dibenzo-p-dioxin
PCDF	Polychlorinated dibenzofuran
PEG	Polyethylene glycol
QA/QC	Quality assurance/quality control
QAPjP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RD&D	Research, Development, and Demonstration
RD/RA	Remedial Design/Remedial Action
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
RP	Responsible Party
RPD	Relative percent difference
RPM	Remedial Project Manager
RSD	Relative standard deviation
SAP	Sampling and Analysis Plan
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
SOP	Standard Operating Procedure
TCDD	Tetrachlorodibenzo-p-dioxin
TMH	Triethylene glycol methyl ether
TSCA	Toxic Substances Control Act

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Charles J. Rogers
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory

Dr. Alfred Kornel
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory

Edwina Milicic
Galson Remediation Corporation

Dr. A. Bruce King
National Environmental Technology
Applications Corporation-
University of Pittsburg

Robert Hoch
SDTX Technologies, Inc.

Dr. Arthur J. Friedman
Chemical Waste Management, Inc.

A.E. (Ted) Seep, Jr.
Morrison-Knudsen Corporation

Dr. Thomas O. Tiernan
Wright State University

SECTION 1
INTRODUCTION

1.1 BACKGROUND

Under the Superfund Amendments and Reauthorization Act of 1986 (SARA), the U.S. Environmental Protection Agency (EPA) is required to select remedial actions involving treatment that "permanently and significantly reduces the volume, toxicity, or mobility of the hazardous substances, pollutants, and contaminants" [Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Section 121(b)].

Treatability studies provide valuable site-specific data necessary to support Superfund remedial actions. They serve two primary purposes: 1) to aid in the selection of the remedy, and 2) to aid in the implementation of the selected remedy. Treatability studies conducted during the remedial investigation/feasibility study (RI/FS) 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) establish the design and operating parameters necessary for both optimization of technology performance and remedy implementation. 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 remedy implementation).

Historically, treatability studies have been delayed until after the Record of Decision (ROD) has been signed. Conducting certain treatability studies early in the RI/FS should reduce the uncertainties associated with selecting the remedy, provide a sounder basis for the ROD, and possibly facilitate negotiations with responsible parties without lengthening the overall remediation schedule for the site. Because treatability studies may be expensive and time-consuming, however, the economics of cost and time should be taken into consideration during the planning of such studies in support of the various phases of the program.

In December 1989, the EPA published an interim final *Guide for Conducting Treatability Studies Under CERCLA* (hereinafter referred to as the generic guide), which presents a stepwise approach or protocol for conducting treatability studies in support of remedy selection at CERCLA sites (EPA 1989a). The generic guide is currently being revised and will be issued as a final document in 1992. Several technology-specific protocols are available, and others are being planned to supplement the information in the final generic guide.

1.2 PURPOSE AND SCOPE

This guide presents information on conducting treatability studies involving direct chemical dehalogenation of soils and sludges. For the purposes of this document, chemical dehalogenation includes those processes in which 1) a chemical reagent is applied directly to the contaminated matrix (soil or sludge), and 2) the reagent reacts with the contaminant to effect the removal of one or more halogen (chlorine, bromine, or iodine) atoms from a molecule of the contaminant. The reaction between the reagent and the contaminant may be a substitution reaction (in which the halogen atoms are replaced by other atoms or chemical groups) or an elimination reaction [in which the halogen atoms and other atoms (e.g., hydrogen) are simultaneously removed from an aliphatic compound and form a double or triple bond in the molecule]. Examples of direct chemical dehalogenation include the alkaline polyethylene glycolate (APEG) processes and base-catalyzed decomposition (BCD) processes; they do not include desorption or extraction processes followed by chemical treatment of the condensate or extraction medium. Although the examples presented herein are drawn almost exclusively from alkaline glycolate experience, this guidance document addresses the subject matter broadly enough to accommodate new processes as they are developed and proven.

1.3 INTENDED AUDIENCE

This guide is intended for use by Remedial Project Managers (RPMs), responsible parties (RPs), contractors, and technology vendors.

Remedial Project Managers are responsible for project planning and oversight at both fund-lead and enforcement sites. Their role in treatability investigations depends on the designated lead agency (Federal or State). Their activities generally include scoping the treatability study, establishing the data quality objectives, selecting a contractor, issuing a work assignment, overseeing the execution of the study, reviewing all project plans and reports, and informing and involving the public as appropriate.

Responsible parties are charged with planning and executing treatability studies under Federal or State oversight at enforcement sites.

Treatability studies are generally performed by remedial contractors or technology vendors. Their roles in treatability investigations include preparing a Work Plan and other supporting documents, complying with regulatory requirements, executing the study, analyzing and interpreting the data, and reporting the results.

1.4 USE OF THE GUIDE

1.4.1 Organization of the Guide

The guide is organized into six sections and an appendix. Section 2 presents an overview of chemical dehalogenation processes and the preliminary data required to screen the technology during the alternative development phase of the FS. Section 3 presents an overview of treatability testing in support of remedy selection and describes the applicability of the tiered approach to chemical dehalogenation treatability studies. Section 4 presents a detailed discussion of the components of a chemical dehalogenation treatability study Work Plan, and Section 5 describes the elements of a Sampling and Analysis Plan. Section 6 discusses the analysis of treatability study data and the evaluation of the technology in support of remedy selection. The appendix summarizes relevant treatability testing experience at actual sites where chemical dehalogenation has been evaluated as a potential remedial action. The reader is encouraged to consult the appropriate section(s) throughout the planning, execution, and evaluation or chemical dehalogenation treatability studies.

1.4.2 Application and Limitations of the Guide

This guide is intended to be used in conjunction with the revised, final generic guide, which presents information of general interest for all types of treatability testing. For example, the reader should refer to the generic guide for discussions on establishing treatability study objectives and complying with regulatory requirements. Information in other readily available guidance documents, such as EPA's interim final *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (EPA 1988a), is also referenced throughout the guide.

This guide focuses mainly on pre-ROD, chemical dehalogenation treatability studies performed in support of remedy selection. Detailed information on post-ROD treatability testing is presented in the final generic guide.

This document was drafted and reviewed by representatives from EPA's Office of Solid Waste and Emergency Response (OSWER), Office of Research and Development (ORD), and the Regional offices, as well as by contractors and vendors who conduct chemical dehalogenation treatability studies. Comments obtained during the peer review process have been integrated or addressed throughout this guide.

SECTION 2
TECHNOLOGY DESCRIPTION AND PRELIMINARY SCREENING

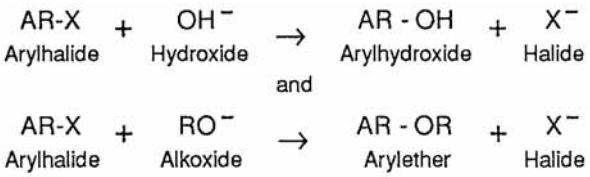
This section presents an overview of chemical dehalogenation processes for treating soils, sediments, and sludges. Subsection 2.1 includes background information on the development of the technology, a description of a full-scale system design, a discussion of the applicability and limitations of the technology, and a review of the current status of chemical dehalogenation in Superfund site remediation. Subsection 2.2 summarizes the data-collection requirements for preliminary screening of chemical dehalogenation.

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Development of the Technology

In 1978, Professor Louis Pytlewski at the Franklin Research Center (FRC) synthesized a new chemical reagent for the destruction of polychlorinated biphenyls (PCBs) (Iaconianni 1984, 1985). Since that time, a group of reagents generically referred to as "APEG" (alkali metal polyethylene glycolate) has been developed. These reagents are based on the reaction of alkali metals or their hydroxides with polyethylene glycols or their derivatives. The first reagents, which were prepared by the reaction of sodium and polyethylene glycol, are known as sodium polyethylene glycolate (NaPEG) reagents.*

Proposed mechanisms for dechlorination with NaPEG reagents involve nucleophilic substitution and oxidative dehalogenation of haloorganic compounds (Pytiewski 1979). Hydroxide and alkoxide ions displace halides of halogenated aromatics to yield phenols and aromatic ethers, respectively. The following two reactions may take place:



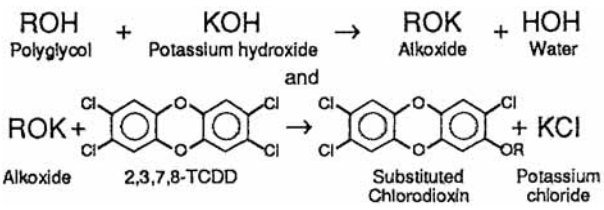
In August 1979, the EPA provided FRC with a grant to investigate the dechlorination of PCBs. Subsequent EPA grant assistance was provided to study the effects of a NaPEG reagent on PCB-contaminated soil. The results of this research are described in a Project Summary Report entitled *Dehalogenation of PCBs Using New Reagents Prepared From Sodium Polyethylene Glycolate - Application to PCB Spills and Decontaminated Soils* (Franklin Research Center 1982).

A comparison of the rates of dechlorination achieved under various conditions revealed that appreciable PCB degradation can occur even when an APEG reagent is diluted 50 percent with water (Kornel and Rogers 1985). Laboratory experiments on soils spiked with PCBs have shown, however, that water in soil greatly reduces the ability of a NaPEG reagent to dechlorinate PCBs (Iaconianni 1984, 1985). Because the use of metallic sodium can lead to dangerous side reactions if even trace amounts of water are present (Peterson 1985), FRC scientists developed a now potassium-based reagent [potassiumpolyethylene glycolate (KPEG)], which proved to be more reactive than the sodium-based NaPEG. Studies have indicated that KPEG is at least two times more reactive than NaPEG in the PCB destruction process, and it is less sensitive to water (Iaconianni 1984, 1985).

The chemistry of the KPEG technology involves reacting potassium hydroxide (KOH) with polyethylene glycol (PEG) (approximate molecular weight of 400) to form an alkoxide. The alkoxide, in turn, reacts initially with one of the chlorine atoms on an aryl ring to produce an ether and potassium chloride salt (des Rosiers 1987), as in the example for

*Since 1979, the terms "APEG," "NaPEG," and "KPEG" have been used extensively throughout the literature in a generic sense. SDTX Technologies, Inc., of Princeton, New Jersey, purchased the original Franklin patents in 1989 and now claims these terms as their exclusive service marks.

2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD):



In some KPEG reagent formulations, dimethylsulfoxide (DMSO) is added as a cosolvent to enhance reaction rate kinetics by improving rates of extraction of aryl halide wastes into the alkoxide phase (Peterson 1985).

Under mild conditions (75 to 120EC), PCBs and other inactivated chlorobenzones have reacted with PEG and KOH in less than 2 hours (Brunelle 1982, 1983). This reaction has been applied to the destruction and removal of PCBs from nonpolar media, including transformer oil.

The results of toxicological evaluations of residues resulting from KPEG treatment of Aroclor 1260 indicate that the glycol phase resulting from the treatment of Aroclor 1260 showed no evidence of oral toxicity in rats at 5000 mg/kg, produced no toxicity through dermal absorption in a mouse, and caused only mild eye irritation in a rabbit (Brunelle and Singleton 1983). Later experiments also indicated that arylpolyglycol by products from KPEG reactions are nontoxic (Rogers 1987).

In 1982, Galson Research Corporation of East Syracuse, New York, under contract to the Niagara Mohawk Power Corporation (NMPC), developed a process for the removal and destruction of PCBs in transformer oils (Woodward and King 1987). The process used a low-toxicity, low-hazard reagent to dechlorinate PCBs that were no longer soluble in the original oil. The reagent for the oil treatment process consisted of two components: a solid component (KOH) and a mixture of liquid reagent materials [PEG, DMSO, and triethylene glycol methyl ether (TMH). In 1985, the EPA and the New York Department of Environmental Control granted a mobile PCB treatment permit to NMPC to conduct a full-scale demonstration of a treatment system. By the end of 1987, the full-scale unit had treated more than 6000 gallons of transformer oil and 20,000 gallons of dioxin-contaminated waste oil under a variety of contracts.

The Vertac Chemical Corporation developed a process that promotes the successful destruction of 2,3,7,8-TCDD and other chlorinated dioxins (Howard and Sidwel1 1982). This process involves the use of anhydrous alkali metal salts of polyhydroxy alcohols to dechlorinate dioxins at atmospheric pressure. Dechlorination may also be accomplished by reacting a mixture of chlorinated dioxins, an alcohol, and a water solution of an alkali metal hydroxide. Vertac claims that 2,3,7,8-TCDD and other chlorinated dioxins are reduced to essentially zero.

APCB destruction method developed at Galson in conjunction with the EPA demonstrated that chlorinated biphenyls and dioxins could be decomposed and removed from soils (Peterson, Milicic, and Rogers 1985). A reagent consisting of a mixture of polyethylene glycol, potassium hydroxide, and dimethyl sulfoxide was used to reduce the dioxin concentrations from 2000 ppb to less than 1 ppb in a short period of time, In 1986, R. L. Peterson was granted a patent for a KPEG process for treating soils. Several other companies and research institutions have developed dechlorination processes. Among these are the Acurex process, the PPM process, and the Sunohio PC-BX process (des Rosiers 1987, Freeman and Olexsey 1986). The Acurex process, which uses a sodium reagent with a proprietary constituent, has been tested for removal of chlorinated waste from soils. This process has also reduced 2,3,7,8-TCDD in transformer oil from between 200 and 400 ppt to between 20 and 60 ppt (Metcalf and Eddy 1985).

The Sunohio PCBX process also uses a proprietary reagent to convert the PCB molecules to metal chlorides and a polyphenyl compound. This process has reduced the concentration of PCBs in transformer oils from 225 to 1 ppm. It has been used to treat PCB-contaminated material at several sites, including Maxwell Laboratories in San Diego and Chevron in El Segundo, California (Radimsky and Shah 1985).

The PPM process, which uses a proprietary sodium reagent to dechlorinate organic molecules, has reduced the PCB concentration in contaminated oil from 200 ppm to below the detection limit. As is true for all of the sodium processes, the Acurex and PPM processes cannot be used on aqueous wastes (Metcalf and Eddy 1985).

Research conducted by EPA's Industrial Environmental Research Laboratory in conjunction with Wright State University indicated that KPEG reagents can significantly reduce the levels of 2,3,7,8-TCDD in contaminated soils under certain conditions (Klee, Rogers, and Tiernan 1984). The soil samples used in these studies were obtained from a farm in Missouri where contaminated residues from a 2,4,5-trichlorophenol manufacturing operation were buried.

Chemical waste from a pentachlorophenol wood treatment facility containing parts-per-million concentrations of various polychlorinated dibenzo-p-dioxins (PCDDs) and poly-chlorinated dibenzofurans (PCDFs) was subjected to KPEG treatment in laboratory studies (Tiernan et al. 1987). The

results indicate that KPEG treatment of this waste for 45 minutes at 70EC almost completely dechlorinated ($99 percent) all of the PCDDs and PCDFs. Similar results were obtained with 15 minutes of KPEG treatment at 100EC.

Toxicological investigations of the residues from the KPEG treatment of 2,3,7,8-TCDD have indicated that they exhibit no mutagenic or toxicological effects (DeMarini and Simmons 1989).

During Galson's EPA-sponsored field implementation of the KPEG process at the Bengart and Memel site in 1986, PCBs in soil contained in 55-gallon drums were reduced to below the 50-ppm control limit set for the soil at the site (Novosad et al. 1987). The average PCB levels were reduced from 108 to 27 ppm.

In 1987-88, PEI Associates, Inc., under contract with the EPA, scaled up the KPEG process. In June 1987, PEI, in cooperation with Galson, conducted a field demonstration in Moreau, New York, to evaluate the chemical destruction of PCBs contained in a soil matrix. This pilot-scale study, which was conducted in a 40-gallon reactor, tested a KPEG reagent consisting of PEG-400, KOH, DMSO, and TMH. The percentage reduction in PCB concentration in the soil ranged from 93.9 to 99.8 (PEI Associates 1989).

Subsequent to the successful application of the 40-gallon KPEG process in Moreau, PEI developed a KPEG treatment system capable of treating PCB- and PCDD-contaminated soil in batches of 1.5 to 2 cubic yards each. This system was used to dechlorinate PCB-contarninated soil at the U.S. Navy Public Works Center on the island of Guam. Approximately 30 tons of soil with an average initial PCB concentration of 3420 ppm (Aroclor 1260) was treated. The PCB concentrations in the treated soil were reduced by more than 99.999 percent, and no individual PCB congener exceeded 2 ppm (PEI Associates 1989). The KPEG reagent used during this demonstration consisted only of PEG-400 and KOH (neither DMSO nor TMH was used).

Although the technology has been successfully demonstrated at the pilot scale, alkaline glycolate treatment of soil can be expensive because large quantities of reagents are used. The EPA and other research and private organizations are currently conducting research to develop new or improved chemical dehalogenation processes that reduce reagent cost through reagent recovery and recycling or more favorable reaction stoichiometry.

Currently under development is EPA's patented base-catalyzed decomposition (BCD) technology. The new base-catalyzed reagents have been shown to be effective for treating PCBs in soil at temperatures above 250EC and residence times above 30 minutes (Kim and Olfenbuttel 1990). Studies by the EPA on the treatment of chlorophenols, chlorinated herbicides (2,4-D, 2,4,5-T, Silvex), organochlorine pesticides (dieldrin), and polychlorinated dioxins and furans are ongoing.

A detailed engineering design of a 1-ton/hour system for BCD-treatment of PCBs in soils at the U.S. Navy Public Works Center site in Guam has been completed. The system, which was fabricated by Battelle Pacific Northwest Laboratories, consists of the following modules:

- Feed soil screening and crushing
- Reagent preparation and mixing with soil
- Rotary reactor and product conditioning
- Wet scrubber
- Scrubber water treatment

The BCD equipment is transportable and can accept continuous feed or operate as a batch process. Demonstration tests of the new system were performed in 1991.

2.1.2 Full-Scale System Design

Chemical dehalogenation treatment is largely a vendor-controlled market comprising a number of patented, proprietary processes. Firms currently offering full-scale, alkaline glycolate remediation services (direct soil treatment or as part of a treatment train) include Galson Remediation Corporation, SoilTech Inc., Chemical Waste Management Inc., and SDTX Technologies, Inc.

One example of a full-scale unit is the patented Galson APEG-PLUS™ treatment system (Galson Remediation Corporation, undated). Construction of the unit was completed in 1990. The system, which is designed to be transported on trailers, consists of the following modules:

- Reactor tanks (10 tons/batch each)
- Boiler
- Centrifuge
- Wash tank
- Reagent recovery system
- Field operations control system
- Electrical system
- Mobile laboratory

Depending on the size of the site, equipment modules can be added or subtracted as needed. Currently, the system is capable of processing 40 to 60 tons of soil per day (two reactors, two to three batches/day).

Figure 1 shows the layout for a 200 to 300 tons/day system. Contaminated soil is excavated, sized to 1/4 in., and stock-piled for treatment. Treatment proceeds in batches of approximately 10 tons each. The prepared soil is conveyed into the reactor tank, where it is slurried with the reagent and heated to the desired reaction temperature. Samples of the slurry are collected automatically for verification analysis. When the specified clean level has been achieved, the slurry is pumped to the centrifuge for separation of the soil and reagent. The clean soil is washed multiple times with water, conveyed out of the unit, and deposited back on site. The reagent, wash water, and condensate (from the reactor tank) are transferred to the reagent recovery system (evaporator), where the water is recycled to the wash tank and the reagent is refortified and recycled to the reactor tank.

A second example of a full-scale system is the SoilTech AOSTRA-Taciuk Process (ATP) unit operated by Canonie Environmental Services Corp. The SoilTech ATP unit that was operated commercially at the Wide Beach Superfund site in Brant, New York, successfully treated about 42,000 tons of PCB- contaminated clay/silt soil (Vorum 1991).

This 10-tons/hour, continuous-feed process treats soils containing between 25 and 50 ppm PCB and produces a treated product containing nondetectable levels of PCB at a 20-ppb detection limit. The unit has successfully processed soils containing up to 30,000 ppm PCB and produced similar treatment results.

Sodium hydroxide and polyethylene glycol are used as the dehalogenation reagents and the ATP unit provides the heat, retention time, and mixing conditions required for reaction to occur. The internal design of the reactor enables the process to achieve very low residual levels of PCB and organics in the treated product with minimal quantities of reagents added. A schematic flowsheet of the process is presented in Figure 2. The contaminated soil is fed into the processor by conveyor belt. It is heated in the preheat zone by indirect heat transfer from the hot, treated soil in the cooling zone. The reagents are sprayed onto the soil in this zone in an oil phase. Dehalogenation reactions occur rapidly as the soil is transported into the retort or reaction zone, where the temperature is quickly increased to about 1100EF. Any residual organic material is thermally stripped from the soil in the reaction zone. The volatilized organics are condensed. New reagents are added to the condensate and recycled to the feed end of the processor. The hot soil exits the reaction zone free of organics. As it cools, the treated product transmits its heat to the incoming feed. The retention time of the soil in the processor is less than 1 hour.

2.1.3 Applicability and Limitations of the Technology

Chemical dehalogenation technologies that use an alkaline glycolate or base-catalyzed reagent are applicable to halogenated aromatic compounds, including PCBs, PCDDs, PCDFs, chlorobenzenes, chlorinated phenols, organochlorine pesticides, halogenated herbicides, and certain halogenated ali-

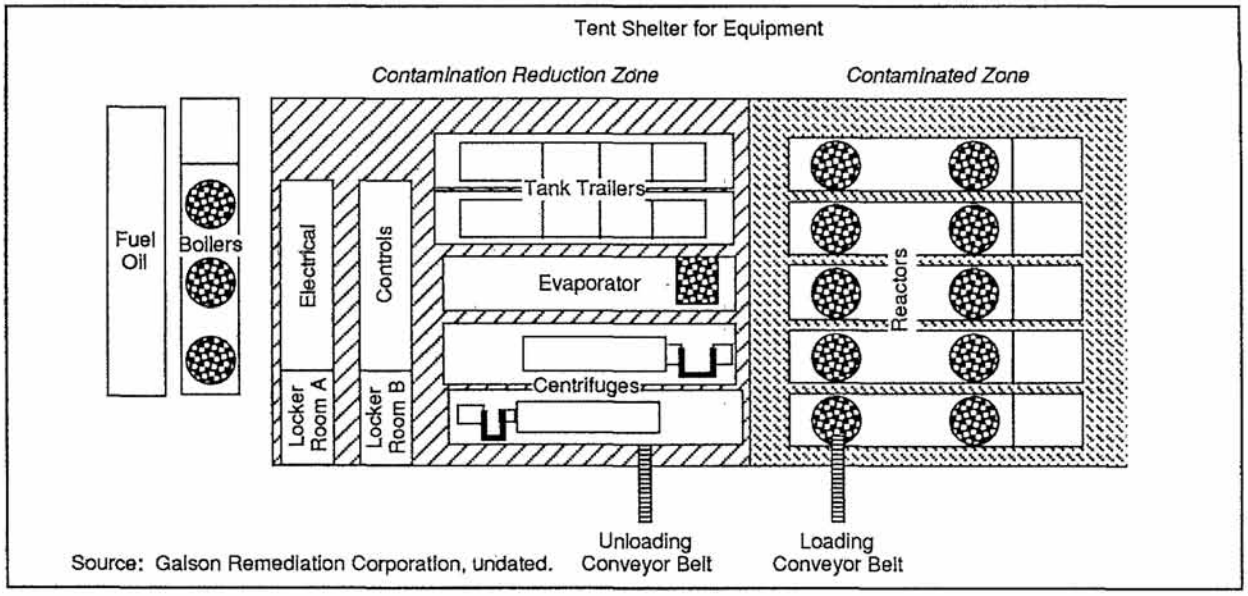
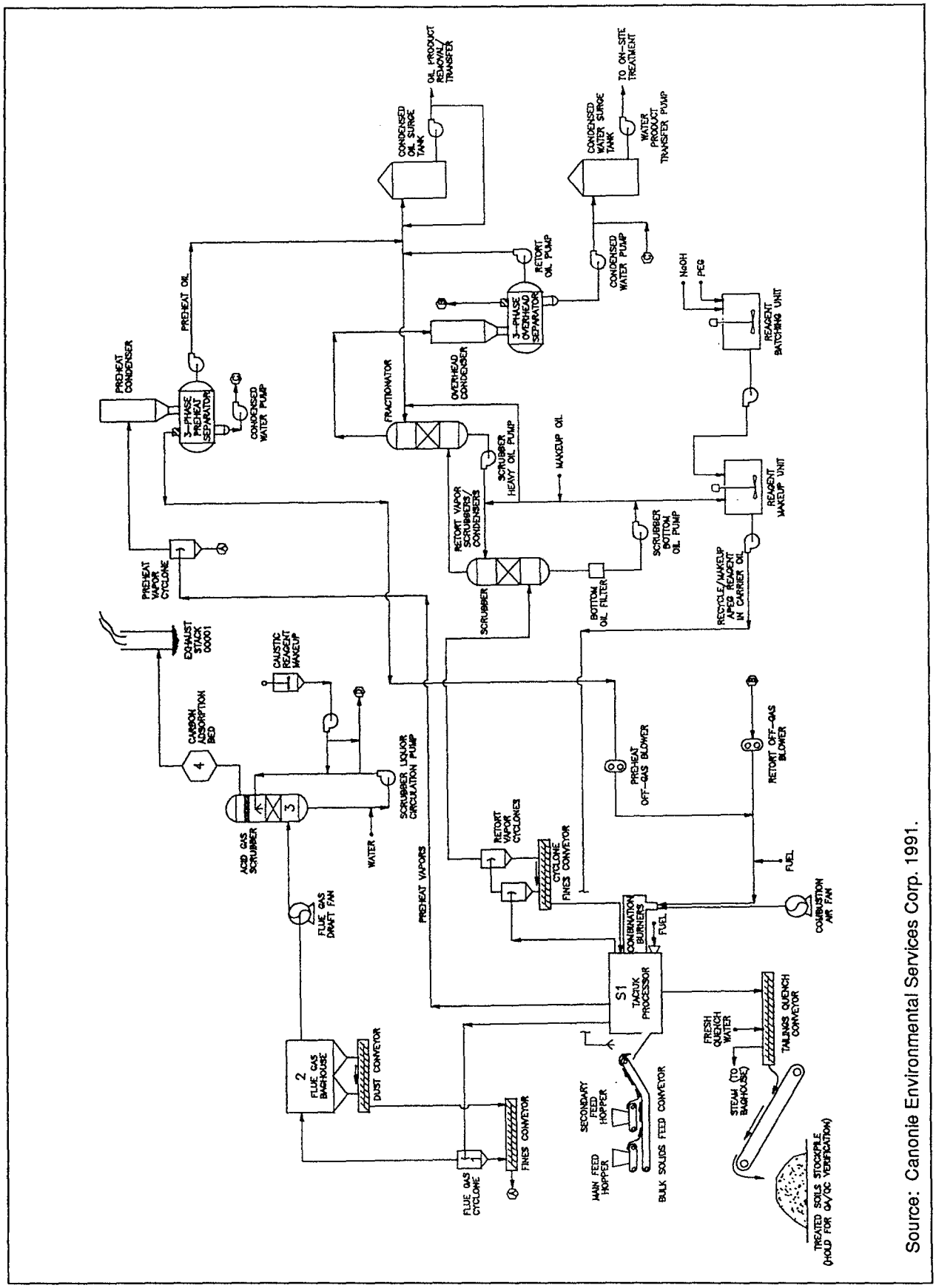


Figure 1. Galson APEG-PLUS™ full-scale chemical dehalogenation treatment system.



Source: Canonie Environmental Services Corp. 1991.

Figure 2. SoilTech AOSTRA-Taciuk Process flowsheet.

phatics (e.g., ethylene dibromide, carbon tetrachloride, chloroform, and dichloromethane). If other volatile organic, semivolatile organic, or metal contaminants are present, chemical dehalogenation can be used in conjunction with other technologies, such as low-temperature thermal desorption, solvent extraction, or biodegradation, as part of a treatment train. Chemical dehalogenation technologies are applicable to soils, sludges, and sediments; however, energy requirements will be higher for treatment of high-moisture-content wastes. Soil type (clay content) does not preclude treatment.

Chemical dchalogenation effectiveness depends on thorough mixing of the contaminants and treatment reagents, which requires that the waste matrix be excavated; in situ applications of the technology are not likely to be effective. For each site, the reagent formulation and optimum process conditions (temperature and reaction time) must be determined through treatability testing. Treated soils and residuals from chemical dehalogenation treatment may require posttreatment (e.g., neutralization) prior to their final disposition. To date, reaction byproducts in the treated soil have not been well characterized. As with all chemical treatment processes, safety hazards (chemical exposure, fire/explosion) are also a concern.

2.1.4 Status of Superfund Site Remediation Involving Chemical Dehalogenation

To date, chemical dehalogenation has been selected in the ROD for cleanup of contaminated soils at four Superfund sites. Wide Beach Development, Brant, Now York (Region II, August 1985); Re-Solve, Inc., North Dartmouth, Massachusetts (Region I, July 1987); Sol Lynn/Industrial Transformers, Houston, Texas (Region VI, March 1988); and Myers Property, Hunterdon County, New Jersey (Region II, September 1990). The current status of each of these sites is described in this subsection.

The Wide Beach Development site is a 55-acre residential community consisting of 60 homes in Brant, New York. Oil contaminated with PCBs was spread on the roadways for dust control between 1968 and 1978. Soil in the roadways, adjacent drainage ditches, driveways, and front yards is contaminated with PCBs in concentrations of up to 1000 ppm. Approximately 30,000 cubic yards of contaminated soil exists on site. Bench- and pilot-scale treatability studies of a proprietary chemical dehalogenation process were conducted on Wide Beach soils during the summer of 1988. A second proprietary process was demonstrated on site in September 1990. The site is currently in remedial action with full-scale treatment of soil to a PCB level below 2 ppm.

The Re-Solve, Inc., site is a former waste chemical reclamation facility. This 6-acre site lies between a residential area and a wetland in North Dartmouth, Massachusetts. Between 1974 and 1980, Re-Solve, Inc., collected and disposed of hazardous wastes. During this period, the site became contaminated with chlorinated and nonchlorinated solvents and PCBs. Chemical dehalogenation was selected in the ROD to treat the 22,500 cubic yards of PCB-contaminated soil and 3000 cubic yards of contaminated wetland sediment. In 1987, laboratory-scale treatability studies of a proprietary chemical dehalogenation process were conducted on Re-Solve soil. Since that time, the remedy has been changed to thermal extraction of the hydrocarbons from the soil/sediment followed by chemical dehalogenation of the condensate. Pilot-scale treatability studies of this proprietary process are currently being planned.

Sol Lynn/Industrial Transformers is a ¾-acre site located in a light industrial area of Houston, Texas. This site was operated as an electrical transformer salvage and recycling facility between 1971 and 1978, and as a chemical recycling and supply company through 1980. During these operations, workers spilled PCB-contaminated transformer oil and trichloroethylene wastes on the soil. Between 1000 and 2500 cubic yards of soil is contaminated with PCBs in concentrations up to 5000 ppm. After the remedy was selected, a proprietary solvent extraction process using chemical dehalogenation to treat the condensate was tested in a series of pilot studies. This process was rejected because of safety concerns. A direct chemical dehalogenation process is currently being tested and shows promise for full-scale treatment. If implemented on site, this proprietary design will treat the PCBs in the soil to below 25 ppm.

The 7-acre Myers Property site is a former pesticide and industrial chemical manufacturing facility in Hunterdon County, New Jersey. From 1928 to 1959, improper handling of hazardous substances resulted in the onsite contamination of soil, sediment, debris, and groundwater with volatile organics, PCBs, dioxin, and the pesticide DDT (dichlorodiphenyltrichloroethane). The selected remedial action for the site includes the excavation and chemical dehalogenation of 48,700 cubic yards of DDT-contaminated soil and sediment. In 1989, an innovative dehalogenation technology was investigated at the laboratory scale. A bench-scale treatability study or a proprietary alkaline glycolate-based process was also conducted.

2.2 TECHNOLOGY PRESCREENING AND TREATABILITY STUDY SCOPING

Prescreening is an important first step in the identification of potentially applicable treatment technologies and the

need for treatability testing. Because of the strict time schedules and budget constraints placed on the completion of an RI/FS, it is crucial for the planning and scoping of treatability studies to begin as early as possible. As discussed in Subsection 3.1, these efforts should be initiated during the RI/FS scoping.

Technology prescreening and treatability study scoping will include searching the chemical dehalogenation literature and treatability data bases, consulting with dehalogenation experts and vendors, and determining data needs. Technology experts are available within EPA to assist project managers with technology prescreening and treatability study scoping. In-house consultation services available to EPA project managers are discussed in the final generic guide.

Potentially applicable technologies are prescreened based on three factors: effectiveness, implementability, and cost. Table 1 presents the site and technology data that are required to prescreen the chemical dehalogenation process.

The effectiveness evaluation focuses on 1) the potential to treat the estimated volume of contaminated media and to achieve the remediation goals identified in the remedial action objectives, 2) the potential impacts on human health and the environment during construction and implementation, and 3) the documented performance for treating similar contaminants and matrices. Information needed to evaluate the effectiveness of chemical dehalogenation includes the contaminated media type and volume, the contaminant type and concentration, and the past performance of the process on similar waste contaminants and matrices.

Implementability addresses both the technical and administrative aspects of implementing a technology. When prescreening chemical dehalogenation, commercial availability and past performance can provide an indication of its technical implementability. Applicable administrative factors will include the ability to obtain necessary permits; the availability of adequate treatment, storage, and disposal capacity and services; and the availability of mobile equipment. Accessibility of the site to large, tractor-trailer-based treatment units and adequate onsite space for their deployment are also factors of implementability.

Cost plays a limited role in the prescreening of technologies. The cost analysis is made on the basis of engineering judgment and past treatment operations. This evaluation is crude, and its results alone will not be adequate to eliminate innovative options such as chemical dehalogenation from further consideration.

Table 1. Data-collection Requirements for Prescreening Chemical Dehalogenation

Required data	Prescreening criteria
Effectiveness	
Contaminated media type	Applicable to soils, sludges, and sediments.
Volume of contaminated media	Cost-effective for volumes greater than 1000m^3.
Contaminant type	Applicable to halogenated aromatics and aliphatics (PCBs, PCDDs/PCDFs, chlorobenzenes, chlorinated phenols, organochlorine pesticides, halogenated herbicides).
Contaminant concentration	Applicable to concentrations of parts per million or greater.
Past performance on similar wastes	Demonstrated applicability for waste contaminants and matrices should be available in the literature.
Implementability	
Availability of process	Should be a commercially available process.
Administrative	Necessary permitting requirements should be achievable; necessary treatment, storage, and disposal services should be available; equipment should be readily available.
Accessibility of site	Site should have adequate accessways and space to set up large trailer-based equipment and staging areas for excavated soil.
Cost	
Relative capital and O&M costs	Cost estimates, based on engineering judgment and historical costs, should be comparable to other options.

SECTION 3
USE OF TREATABILITY TESTS IN REMEDY SELECTION AND IMPLEMENTATION

The selection of remedial actions involves several risk-management decisions. Uncertainties with respect to performance, reliability, and cost of treatment alternatives underscore the need for well-planned, well-conducted, and well-documented treatability studies. The final generic guide provides a framework for planning, conducting, and evaluating treatability studies in support of remedy selection and implementation. The following subsections give a brief overview of this process and describe the applicability of treatability tests to chemical dehalogenation technologies.

3.1 THE PROCESS OF PRE-ROD TREATABILITY TESTING IN SELECTING A REMEDY

As discussed in the RI/FS guidance (EPA 1988a), site characterization and treatability investigations are two of the main components of the RI/FS process. As site and technology information is collected and reviewed, additional data needs for evaluating alternatives are identified. Pre-ROD treatability studies may be required to fill some of these data gaps.

In the absence of data in the available technical literature or treatability data bases, treatability studies can provide the critical performance and cost information needed to evaluate and select treatment alternatives. The RI/FS guidance specifies nine evaluation criteria for use in the detailed analysis of alternatives. Treatability studies can generally provide data to address seven criteria:

1) Overall protection of human health and the environment

2) Compliance with applicable or relevant and appropriate requirements (ARARS)

3) Implementability

4) Reduction of toxicity, mobility, or volume through treatment

5) Short-term effectiveness

6) Cost

7) Long-term effectiveness

State and Community acceptance, the other two criteria affecting the evaluation and selection of the remedial alternative, can influence the decision to conduct treatability studies on a particular technology.

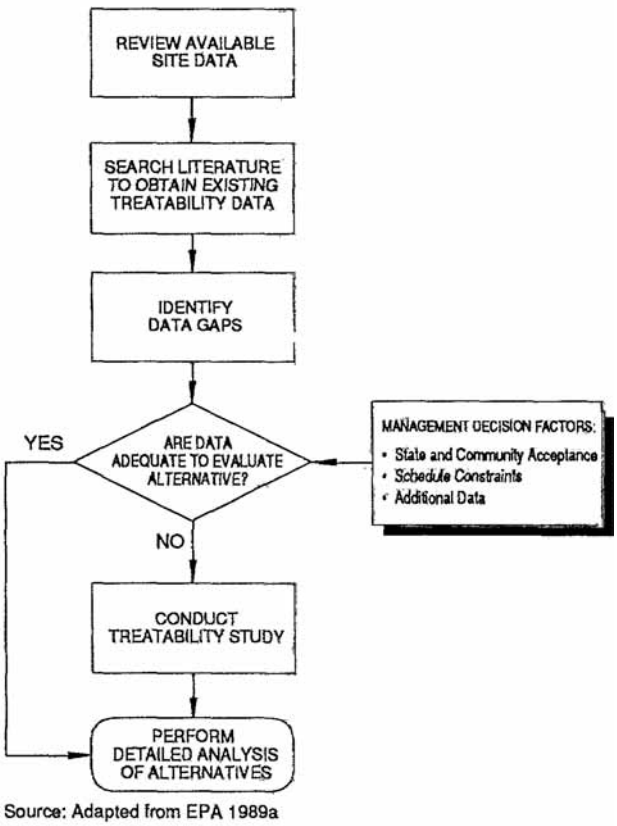
The general decision tree presented in Figure 3 illustrates when treatability studies are needed to support the evaluation and selection of an alternative. After the existing site data have been reviewed, a literature survey is conducted to obtain any existing treatability data for the alternative and the contaminants and matrices of concern. The data are then evaluated in terms of the seven RI/FS criteria to identify any data gaps.

The need to conduct a treatability study on any alternative is a management decision. In addition to the technical considerations, certain nontechnical factors must also be considered:

- State and community acceptance of the alternative
- Time constraints on the completion of the RI/FS and the ROD
- New site, waste, or technology data that may have an impact on the technology's performance

If the existing data are adequate for an evaluation of the alternative for remedy selection, no treatability studies are required. Otherwise, treatability studies should be performed to generate the data necessary to conduct a detailed analysis of the alternative.

Generally, treatability testing of alternative technologies can begin during the initial phases of site characterization, as shown in Figure 4. Treatability studies must be scoped and initiated as early as possible (i.e., during the scoping phase) to keep the RI/FS on schedule and within budget.



Source: Adapted from EPA 1989a

Figure 3. Decision tree showing when treatability studies are needed to support the evaluation and selection of an alternative.

The need for pre-ROD treatability testing is a risk-management decision in which the costs and time required to conduct treatability studies are weighed against the risks inherent in the selection of a treatment alternative. As a general rule, treatability testing should continue until sufficient information has been collected to support both the full development and evaluation of all treatment alternatives and the remedial design of the selected alternative. Treatability studies can significantly reduce the overall risks and uncertainties associated with the selection and application of a technology, but they cannot guarantee that the chosen alternative will be completely successful. As more studies are completed and new knowledge is gained about innovative alternatives, however, success rates should improve.

The flow diagram in Figure 4 traces the stepwise data reviews and management decisions that occur in the tiered approach to treatability testing. As discussed in Subsection 2.2, site characterization/technology screening is the first step in this approach. Technologies that are determined to be potentially applicable for treatment of the site's waste (based on effectiveness, implementability, and cost) are retained as alternatives, all others are screened out. The decision to conduct a treatability study on any of the retained alternatives is based on the availability of technology-specific treatability information and on input from management. If sufficient information exists to evaluate a particular alternative against the nine evaluation criteria in the detailed analysis of alternatives, a treatability study is not required.

If significant questions remain about the feasibility of the technology for the site, a remedy-screening treatability study should be performed. If the technology has already been shown to be effective in treating the contaminants/matrix of concern, the remedy-screening tier may be by-passed in favor of a remedy-selection treatability study. If the remedy-selection study indicates that the technology can meet the performance goals, a detailed analysis of the alternative should be performed.

Post-ROD remedial design/remedial action (RD/RA) treatability studies of the selected alternative will generally be necessary to support the implementation of the remedy.

The final generic guide presents a protocol for conducting all phases of a treatability investigation. This protocol is designed to assist in planning and performing systematic, scientifically sound treatability studies. The generic guide includes discussions on:

- Establishing data quality objectives
- Identifying sources for treatability studies
- Issuing the Work Assignment
- Preparing the Work Plan
- Preparing the Sampling and Analysis Plan
- Preparing the Health and Safety Plan
- Conducting community relations activities
- Complying with regulatory requirements
- Executing the treatability study
- Analyzing and interpreting the data
- Reporting the results

Although the protocol is generally applicable to treatability investigations of any technology and at any tier of testing, some of the steps in the protocol possess certain technology-specific elements that merit additional discussion. One of

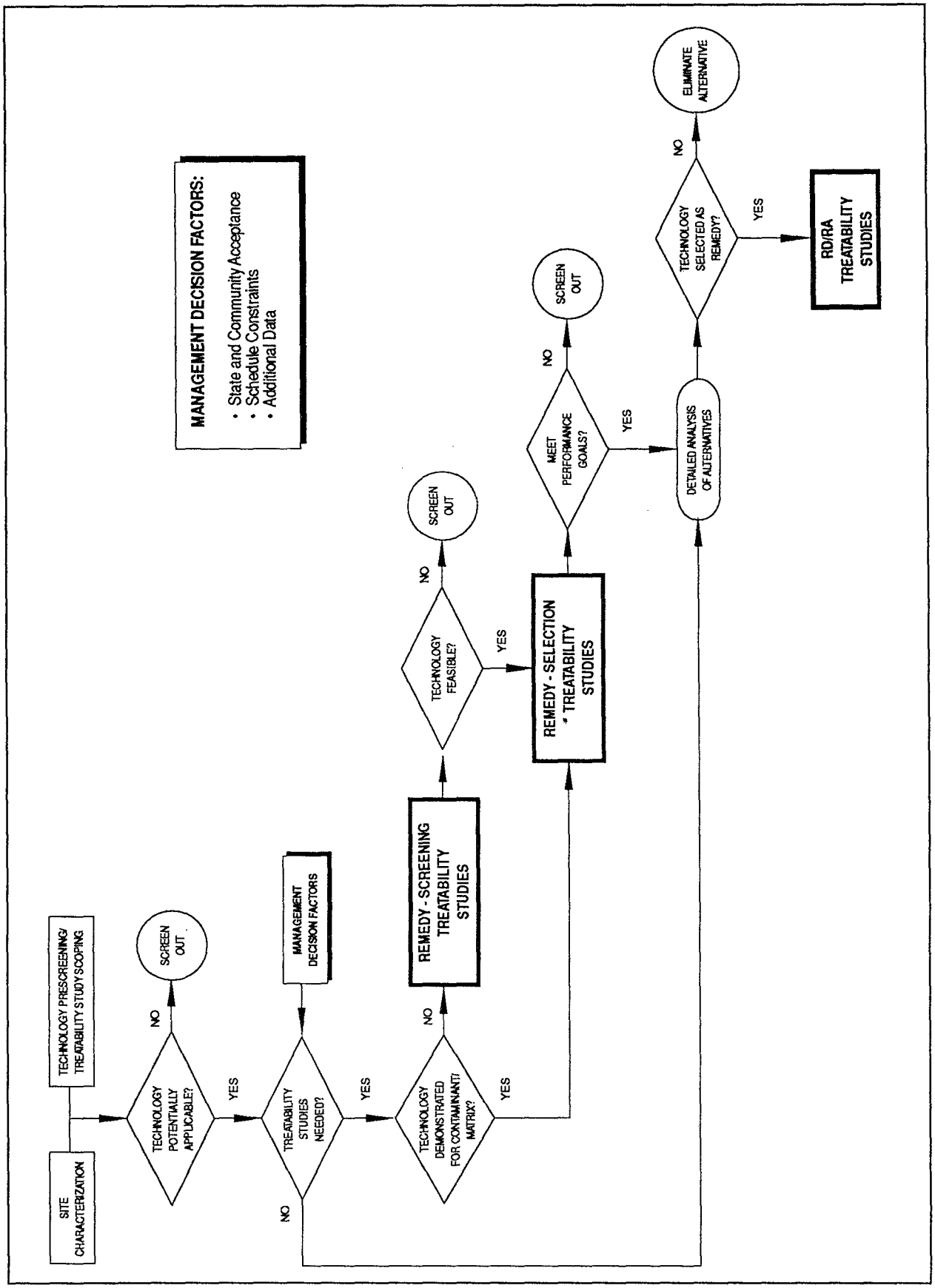


Figure 4. Flow diagram of the tiered approach.

these steps, preparing the Work Plan, is discussed in Section 4 of this document with regard to chemical dehalogenation treatability studies. Preparing the Sampling and Analysis Plan is discussed in Section 5, and Section 6 addresses analysis and interpretation of data from chemical dehalogenation tests. Steps in the protocol that are applicable to all technology investigations—such as issuing the work assignment and reporting the study results—are not discussed in this document because they are addressed in detail in the final generic guide.

3.2 APPLICABILITY OF TREATABILITY TESTING TO CHEMICAL DEHALOGENATION

Figure 5 presents the three tiers of treatability testing (remedy screening, remedy selection, and remedial design/remedial action) and their relationship to the RI/FS and RD/RA processes. The three tiers are described here.

1) Remedy Screening—Small-scale studies performed in the laboratory that provide gross performance data for feasibility evaluation. Remedy-screening studies are characterized by the following:

   - Relatively low cost
   - Short amounts of time to perform
   - Less stringent quality assurance/quality control (QA/QC)

2) Remedy Selection—Small-scale studies performed in the laboratory or field that provide detailed performance and cost data for remedy selection. Remedy-selection studies are characterized by the following:

   - Moderate cost
   - Moderate amounts of time to perform
   - Stringent QA/QC

3) Remedial Design/Remedial Action—Post-ROD, pilot-scale studies performed in the field that provide scale-up and design optimization data. Remedial design/remedial action studies are characterized by the following:

   - High cost
   - Long amounts of time to perform
   - Moderately stringent QA/QC

The three-tiered approach to treatability testing is designed to be flexible to meet site- and technology-specific needs. Some technologies, including chemical dehalogenation, may not be investigated at all three tiers. The applicability of the tiered approach to chemical dehalogenation treatability studies is outlined in Table 2 and is discussed in this subsection. Information on performing chemical dehalogenation treatability tests is presented in Section 4.

3.2.1 Literature Survey

The decision to perform a chemical dehalogenation treatability study is based on the available site characterization data, input from management, and the results of a literature survey. Although the literature survey is not a tier of testing, it is included in Table 2 because it is a necessary preliminary step that aids in treatability study scoping.

The purpose of the literature survey is twofold. First, it should identify potentially applicable processes that have been adequately demonstrated and that are commercially available. Second, it should obtain all existing treatability data that are relevant to the site's waste matrix and contaminants of concern. The treatability data on chemical dehalogenation processes available as of this writing are summarized in the appendix of this document.

The objective of the literature survey is to determine specific treatability data requirements. If a particular chemical dehalogenation process has already been demonstrated to be effective for treating the contaminants/matrix of interest, a remedy-screening study may not be required. Alternatively, if little or no data exist in the literature for the contaminants/matrix to be treated, a screening study will be required to address this data need.

3.2.2 Remedy-Screening Treatability Studies

Remedy screening is the first step in the tiered approach. Its purpose is to determine the potential feasibility of chemical dehalogenation as a treatment alternative for the contaminants/matrix of interest. A chemical dehalogenation process is potentially feasible if it can be shown that the chemical reactions occurring between the dehalogenation reagents and the contaminants have the potential to dehalogenate the waste adequately.

The need to perform screening studies of chemical dehalogenation processes is contaminant- and matrix-specific. For example, the feasibility of several proprietary processes for the treatment of PCBs and dioxins in various soil types has been established and is well documented in the literature. Therefore, screening studies of these processes will generally not be

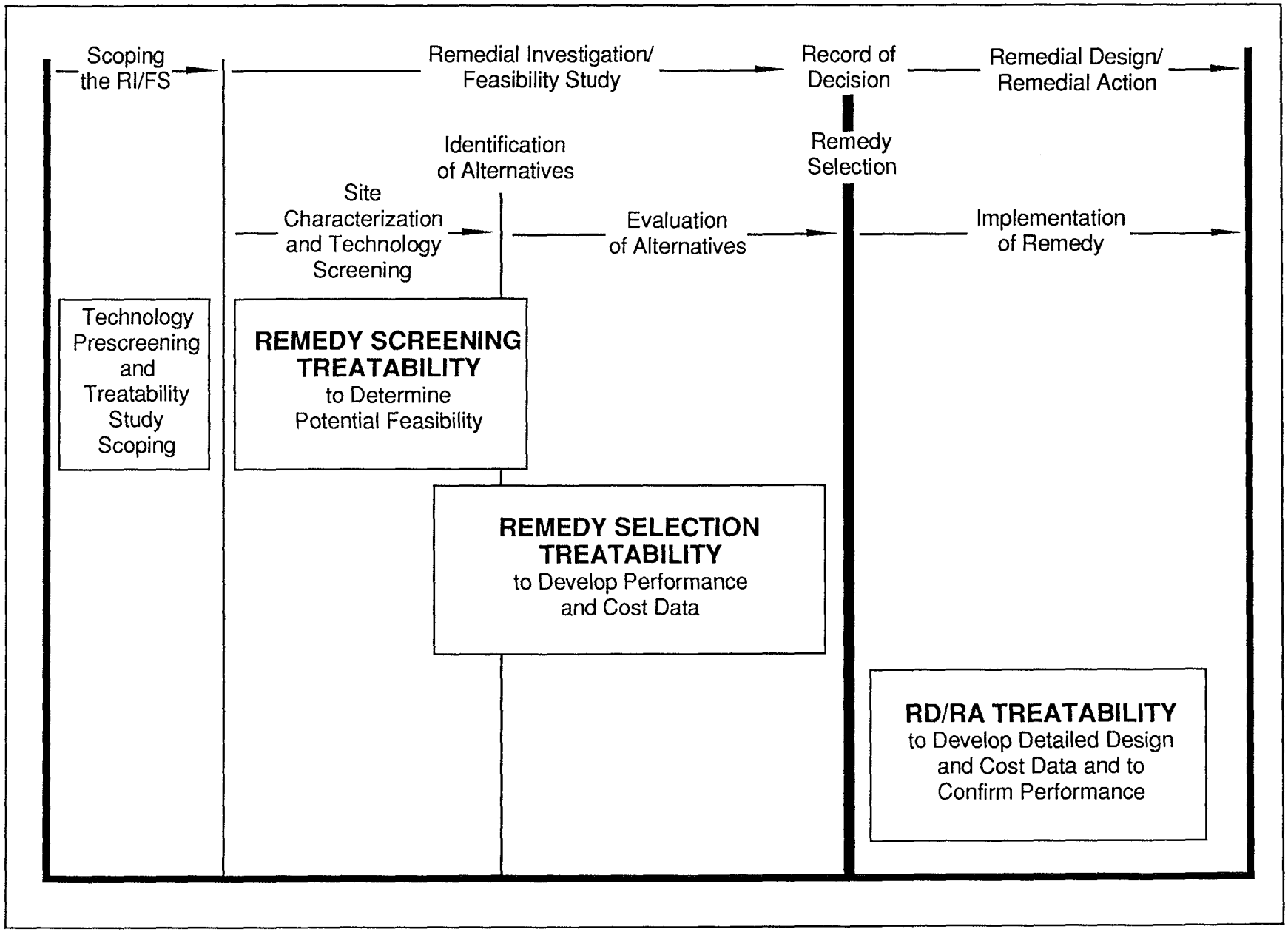


Figure 5. The role of treatability studies in the RI/FS and RD/RA process.

Table 2. Applicability of Tiered Approach to Chemical Dehalogenation Treatability Studies

	Literature survey	Remedy screening	Remedy selection	ROD	RD/RA
Purpose	• Identify potentially applicable processes • Obtain existing treatability data	• Determine process feasibility for contaminants/matrix	• Generate performance and cost data for the detailed analysis of alternatives		• Generate scale-up, design, and cost data for implementation of selected remedy
Objective	• Determine treatability data needs	• Achieve >90% reduction in target contaminant concentrations	• Meet site cleanup criteria for target contaminants		• Optimize process
Parameters investigated	Not applicable	• "Severe" conditions	• Temperature • Reaction time • Reagent formulation/loading • Other process specific parameters • Sample type		• Feed rates • Mixing rates • Heating rates • Other equipment specific parameters
Data generated	Not applicable	• Concentration of target contaminants before and after treatment	• Effects of process parameters on target contaminant concentrations • Characteristics of product and residuals • Capital/O&M cost estimates		• Materials-handling characteristics • Reagent recovery/ recycling efficiency • Energy/chemical usage • Treatment train performance • Residuals treatment performance

required when PCBs or dioxins are the contaminants of concern. When the treatment of other halogenated organics, such as chlorinated phenols or halogenated aliphatics, or other matrices, such as sediment are involved, however, screening studies may be required, particularly given the proprietary nature of chemical dehalogenation reagents.

Typically, remedy-screening treatability studies are conducted at the bench scale under "severe" conditions, based on available data and knowledge of the reaction chemistry. These conditions may include a substantial excess of reagent, high reaction temperature, and extended treatment duration. The concentrations of the target (or indicator) contaminants in the soil are measured before and after treatment to determine the efficiency of the dehalogenation process. Generally, this is the only measure of performance obtained at the screening tier.

The suggested performance goal for remedy-screening treatability studies is a 90 percent or greater reduction in the concentrations of the target contaminants. (Alternatively, site cleanup criteria can be used if they have been determined at this early stage in the RI/FS process.) If this goal is achieved, the process is considered a feasible alternative and is retained for further evaluation. If greater than 90 percent reduction in the target contaminant concentrations cannot be achieved under the severe conditions of screening treatability studies, the technology should be screened out.

A preliminary cost estimate for treatment of the contaminants/matrix of interest by chemical dehalogenation also may be developed at this tier for the purpose of screening different processes.

3.2.3 Remedy-Selection Treatability Studies

Remedy selection is the second step in the tiered approach. A remedy-selection treatability study is designed to verify whether a chemical dehalogenation process can meet the site cleanup criteria and at what cost. The purpose of this tier is to generate the critical performance and cost data necessary for remedy evaluation in the FS.

After the feasibility of dehalogenation has been demonstrated, either through screening studies or a literature review, various process or operating parameters are investigated at the remedy-selection tier. As in screening studies,

tests are normally conducted at the bench scale and the concentrations of the target contaminants in the soil are measured before and after treatment to determine the efficiency of the dehalogenation process. At this tier, however, operating parameters such as treatment temperature, reaction time, and reagent formulation/loading are examined for their effects on target contaminant concentrations. The choice of parameters to be investigated should be based largely on the contractor's or vendor's experience and engineering judgment and on the available funding. Alternatively, several samples of the waste representing the range of site conditions likely to be encountered may be subjected to testing under a more limited scope. In either case, a remedy-selection study should provide the RPM with enough information to ensure that the performance objectives can be reliably met.

Performance goals for remedy-selection treatability studies should correspond to the anticipated remedial action objectives (cleanup criteria) for the site. If the dehalogenation process can achieve these cleanup criteria, it should be retained as an alternative for detailed analysis in the FS. The development of treatability study performance objectives is described in more detail in Subsection 4.1 of this document.

Data from remedy-selection treatability studies can be used to characterize the product and residuals from dehalogenation treatment. Depending on the requirements of posttreatment testing, multiple bench tests or a modest pilot-scale run may be necessary to generate the requisite sample volume, particularly if the process is part of a treatment train.

Data generated at this treatability tier can also be used to estimate the costs of full-scale implementation of the alternative, as required in the detailed analysis. Subsection 6.1 of this document includes a detailed discussion on the use of treatability study data in the preparation of this cost estimate, which should have an accuracy of +50 percent to -30 percent.

3.2.4 Remedial Design/Remedial Action Treatability Studies

Remedial design/remedial action is the final step in the tiered approach. These studies are conducted after the remedy has been selected and the ROD has been signed. The need for an RD/RA chemical dehalogenation treatability study may be identified by the RPM, the PRP, the vendor, or the remedial designer. The designer should carefully review the available site-, technology-, and waste-specific treatability data before deciding whether an RD/RA treatability study is needed.

In the implementation of a remedy, RD/RA treatability studies can be used 1) to select among multiple chemical dehalogenation processes and prequalify vendors or these processes, 2) to select the most appropriate of the remedies prescribed in a Contingency ROD, or 3) to support Agency-prepared detailed design specifications for dehalogenation systems and treatment trains.

Vendor/Process Prequalification

A single remedy is usually selected in the ROD. This remedy is often identified as a technology class or family (e.g., chemical dehalogenation) rather than a specific process. Selection of a treatment class affords flexibility during the remedial design to procure the most cost-effective vendor and process.

One method of selecting an appropriate chemical dehalogenation process is to use RD/RA treatability study results to "prequalify" a pool of vendors. In these studies, all interested parties are provided with a standard sample of waste. Each vendor uses that sample to design and perform a treatability study and reports the treatment results to the lead agency. Based on these results, the lead agency determines which vendors are qualified to bid on the RA. Generally, the vendor should achieve results equivalent to the cleanup criteria defined in the ROD to be considered for prequalification.

Contingency RODs

In some situations additional flexibility in the ROD may be required to ensure implementation of the most appropriate technology for a site. When this occurs, the selected remedy may be accompanied by a proven contingency remedy in a Contingency ROD.

Although treatability studies of chemical dehalogenation will be conducted during the RI/FS to support remedy selection, sufficient testing to address all of the significant uncertainties associated with the implementation of this technology may not be feasible. This situation, however, should not cause dehalogenation to be screened out during the detailed analysis of alternatives in the FS. If, based on performance potential, dehalogenation appears to provide the best balance of trade offs from among the options considered, CERCLA Section 121 (b)(2) provides support for selecting the technology in the ROD despite the uncertainties.

Implementation of a chemical dehalogenation remedy, however, may be contingent upon the results of RD/RA treatability testing. When dehalogenation is selected and its performance is to be verified through additional treatability testing, a proven treatment technology may also be included in the ROD as a contingency remedy. In the event the RD/RA treatability study results indicate that dehalogenation cannot achieve the cleanup goals at the site, the contingency remedy is implemented.

Detailed Design Specifications

To support the remedial action bid package, the lead agency may choose to develop detailed design specifications. If technical data available from the RI/FS are insufficient for designing the chemical dehalogenation remedy, an RD/RA treatability study may be necessary. Post-ROD treatability studies can provide the detailed cost and performance data required to optimize the chemical dehalogenation process and to design a full-scale treatment system. Conducted at the pilot-scale, these studies typically generate the following types of data:

- Materials-handling characteristics
- Reagent recovery/recycling efficiency
- Energy/chemical usage
- Treatment train performance
- Residuals treatment performance

The parameters investigated at the RD/RA tier may include feed rates (continuous processes), number of treatment cycles (batch processes), mixing rates, heating rates, and other equipment-specific parameters. The objective of these studies is to optimize the process in terms of both performance and cost.

If an RD/RA treatability study is required to support the detailed design specifications, the designer will be responsible for planning the study and defining the performance goals and objectives.

Post-ROD RD/RA treatability studies can also be performed to support the design of treatment trains. Although all parts of a treatment train may be effective at treating die wastes, matrices, and residuals of concern, issues such as unit sizing, materials handling, and systems integration also must be addressed. Treatability studies of one unit's operations can assist in identifying characteristics of the treated material that may specifically need to be considered in the design of the rest of the train.

3.2.5 Case Study: Tiered Approach Applied to a CERCLA Treatability Study

The following case study illustrates how the tiered approach can be applied to a treatability investigation at a CERCLA site. In this example, chemical dehalogenation has been identified as a potential remedial alternative. Treatability data gaps are identified in the literature survey. The feasibility of a commercially available process is investigated in the remedy-screening study. In the remedy-selection study, performance and cost data and information on the toxicity of the treated product are collected for use in the detailed analysis of alternatives.

CASE STUDY: TIERED APPROACH APPLIED TO A CERCLA TREATABILITY STUDY

Background

The soil at a Superfund site was contaminated with the insecticide DDT (dichlorodiphenyltrichloroethane) and its metabolites DDD (dichlorodiphenyldichloroethane) and DDE (dichlorodiphenyldichloroethylene). One of the site's remedial action objectives was to reduce the concentrations of DDT, DDD, and DDE in the soil to below 10 ppm. Remedial technologies and process options were screened based on their ability to meet this remedial objective. Alternatives for treatment of the soil were then developed and screened based on their effectiveness, implementability, and cost. Three remedial action alternatives--incineration, soils washing, and chemical dehalogenation--were retained for further consideration during the detailed analysis. Chemical dehalogenation was classified as an innovative technology.

Literature Survey

A literature survey was conducted on each of the three alternatives to identify processes within each technology type that are commercially available and to collect treatability data on these processes. The literature survey produced a sufficient amount of performance data on the incineration of DDT for an immediate detailed analysis of this alternative against the nine RI/FS evaluation criteria.

The literature survey on soils washing identified a commercially available process that had been investigated as part of the Superfund Innovative Technology Evaluation (SITE) Program. Based on these SITE data, this process was determined to be sufficiently well demonstrated for detailed analysis.

The chemical dehalogenation literature survey identified data on the treatment of PCBs in soil; however, no process had yet been investigated for its ability to treat DDT contamination. Without these data, chemical dehalogenation could not be evaluated against the reduction of toxicity, mobility, and volume criterion. Data on its cost, long-term effectiveness and permanence, and compliance with ARARs were also found to be

CASE STUDY (continued)

insufficient for evaluation of chemical dehalogenation as an alternative. Consequently, a two-tiered treatability study was performed to address these data needs.

Remedy-Screening Treatability Study

The chemical dehalogenation literature survey identified a proprietary alkaline polyethylene glycol (APEG) process that uses potassium hydroxide (KOH) and the cosolvent/catalyst dimethylsulfoxide (DMSO). The vendor of this process was contracted to perform a remedy-screening treatability study to determine the feasibility of using this process to treat the DDT-contaminated Superfund site soil.

Contaminant concentrations in the untreated soil ranged from 100 ppm DDE to 8000 ppm DDT. The performance goal of this study was to achieve concentrations of less than 10 ppm each for DDT, DDD, and DDE in the treated soil, contaminant levels that corresponded to the site's remedial action objective.

A particle-size distribution analysis of the soil indicated that normal agitation and centrifugation procedures would be adequate. The amount of KOH required for treatment was determined by analyzing the KOH absorption capacity of the soil.

In a bench-scale reactor, 1 kg of soil was mixed with 1 kg of reagent. Preparation of the reagent, which was based on the vendor's past treatability experience, consisted of 167 g polyethylene glycol, 167 g triethyleneglycol methyl ether, 334 g DMSO, and 332 g 45-percent KOH. The reaction was conducted at 150EC.

Monitoring samples were collected from the reactor at 1-hour intervals and analyzed for DDT, DDE, and DDD. The reaction was stopped when the concentration of each of these contaminants was lowered to below 10 ppm. This level of dehalogenation was achieved in 3 hours.

At the conclusion of the reaction, the reagent and soil fractions were separated by centrifugation. The soil was then rinsed with water. All exit fractions (treated and washed soil, recovered reagent, soil wash-water, and condensate) were analyzed for DDT and its metabolites in accordance with Contract Laboratory Program (CLP)-based methods.

The CLP-based analyses indicated nondetectable levels of DDT, DDE, and DDD in the treated soil and in all exit fractions. Mass-balance calculations indicated that 59 g of KOH was consumed during treatment. Based on original contaminant concentrations, the maximum amount of KOH that could be consumed in dehalogenation reactions was 5 g. The remaining KOH was believed to have been consumed in side reactions with the soil.

Remedy-Selection Treatability Study

Based on the favorable results of the remedy-screening study, the APEG process was determined to be feasible for reducing the total mass of toxic halogenated contaminants in the site's soil. Data on cost, long-term effectiveness and permanence, and compliance with ARARs, however, were still needed for an evaluation of chemical dehalogenation as an alternative. Therefore, a remedy-selection study was performed.
Several test objectives were established before testing was initiated. As the RI progressed, the site's cleanup criteria were set at 1 ppm for DDT and its metabolites. These criteria translated into equivalent performance goals for the remedy-selection testing. Another test objective was to generate a cost estimate that could be used in the detailed analysis. This cost estimate would be refined by designing the treatability study to evaluate reagent loading, formulation, and recovery. A third test objective was to assess the toxicity, mutagenicity, and bioaccumulative nature of the reaction products.

The bench-scale equipment and methodology used were unchanged from those for the remedy screening. In the first test run, reagent loading was reduced by 40 weight percent to 600 g reagent for treatment of 1000 g soil. In the second test, the reagent formulation was investigated by replacing KOH with sodium hydroxide (NaOH) at the reduced loading. The reactions were conducted at 150C.

Monitoring samples were collected from the reactor at 1-hour intervals and analyzed for DDT, DDE, and DDD. The reactions were allowed to continue until the contaminant concentrations were lowered to 1 ppm or less or until the rate of reduction reached zero.

Based on the screening samples, treatment with the lower reagent loading was still effective. Contaminant concentrations were reduced to less than 1 ppm after 5 hours of treatment with the smaller quantity of KOH

CASE STUDY (continued)

in the reagent. When KOH was replaced by NaOH in the reagent formulation, however, the 1 ppm performance goal could not be achieved after treatment for 14 hours. Reagent recovery analysis showed that half as much NaOH (compared with KOH) was consumed by side reactions with the soil. A reduction in reagent cost may therefore be achieved by replacing some of the KOH with NaOH.

Because the APEG system had not been previously used to treat DDT-contaminated soil, the reaction products were assayed to determine whether they were toxic, mutagenic, or bioaccumulative. Testing included assessments of:

- Acute oral toxicity
- Acute aquatic toxicity
- Mutagenicity
- Earthworm survival

All tests and bioassays except the earthworm survival test were conducted by using a synthesized reaction product prepared without soil. Each of the pesticide concentrations in the reaction product was less than 2 ppm.

The reaction product was administered to guinea pigs to evaluate its acute oral toxicity. The sample was lethal at a dose of 2500 mg/kg. Test animals suffered ataxia, tremors, and convulsions before death, which suggests that the reaction product is neurotoxic.

Acute aquatic toxicity was evaluated with fathead minnows exposed to a lethal concentration for 50 percent (LC_{50}) of the test animals. Results of the LC_{50} range finder test demonstrated an LC_{50} of 1200 ppm for fathead minnows. The LC_{50} of DDT itself is 19 ppb, much lower than that measured for the reaction product.
The reaction product was subjected to the Ames test to determine if it had mutagenic potential. At doses of 5.0 and 1.0 mg/plate, the product was toxic to the *Salmonella* bacteria. At doses of 0.5, 0.05, and 0.005 mg/plate, the product was nontoxic and nonmutagenic.

The EPA Earthworm Survival Test was conducted to evaluate the acute toxicity potential of the treated soil to soil-dwelling organisms. A sample of treated soil was washed with water an additional four times to reduce the soil conductivity to 900 mmho. The earthworms burrowed into the soil without any visible signs of distress; however, the site soil produced 100 percent mortality within 24 hours. Because earthworms can typically live in pesticide-contaminated soil for several days, the rapid mortality was attributed to the residual DMSO in the soil.

In the detailed analysis of alternatives, major treatment cost factors for chemical dehalogenation were identified as total soil volume, reaction time, and soil moisture content. Treatment cost estimates ranged from approximately \$325 to \$400 per yd^3 of soil. The final cost estimate, including excavation, mobilization/ demobilization, analyses, and long-term site monitoring, was developed with an accuracy of +50/-30 percent.

Applicable or relevant and appropriate requirements (ARARs) at the site that directly concerned chemical dehalogenation included a location-specific ARAR to protect a sensitive wetland area adjacent to the site. The bioassessment data generated during the treatability study were used to evaluate compliance with this requirement.

SECTION 4
TREATABILITY STUDY WORK PLAN

Carefully planned treatability studies are necessary to ensure that the resulting data are useful for evaluating the feasibility, performance, and cost 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. Table 3 presents the suggested organization of a treatability study Work Plan.

Table 3. Suggested Organization of Treatability Study Work Plan

1.	*	Project description
2.	*	Remedial technology description
3.		Test objectives
4.		Experimental design and procedures
5.		Equipment and materials
6.		Sampling and analysis
7.	*	Data management
8.		Data analysis and interpretation
9.		Health and Safety
10.		Residuals management
11.	*	Community relations
12.	*	Reports
13.		Schedule
14.		Management and staffing
15.		Budget

Source: EPA 1989a.

Elements of a Work Plan that are standard for all technologies are starred in the table and described in general terms here. Further information on these items can be found in the final generic guide. The remaining elements are discussed in greater detail in the subsections that follow.

Project Description.

The project description provides background information on the site and summarizes existing waste characterization data (matrix type and characteristics, contaminant concentration and distribution). The project description also specifies the type of study to be conducted--remedy screening, remedy selection, or RD/RA. For treatability studies involving multiple tiers of testing, it states how the need for subsequent levels of testing will be determined from the results of the previous tier.

Remedial Technology Description.

This section briefly describes the chemical dehalogenation process to be tested. A flow diagram can be included that shows the input stream, the output stream, and any residual streams generated as a result of the treatment process. For treatability studies involving treatment trains, the remedial technology description should address all the unit operations the system comprises. A description of the anticipated pre- and post treatment requirements may also be included here.

Data Management.

Treatability studies must be well documented, particularly if the findings are likely to be challenged by a responsible party, the State, or the community. This section describes the procedures for recording observations and raw data in the field or laboratory, including the use of bound notebooks, data collection sheets, and photographs. If proprietary processes are involved, this section also describes how confidential information will be handled.

Community Relations.

A Community Relations Plan is required for all remedial response actions under CERCLA. This section describes the community relations activities that will be performed in conjunction with the treatability study. These activities may

include, but are not limited to, preparing fact sheets and news releases, conducting workshops or community meetings, and maintaining an up-to-date information repository.

Reports

Complete and accurate reporting of chemical dehalogenation treatability study test results is critical, as decisions about treatment alternatives will be based, in part, on the outcome of these studies. Besides assisting in the selection of the remedy, the reporting of treatability studies will increase the existing body of scientific knowledge regarding the applications and limitations of this treatment process.

As an aid in the selection of remedies and the planning of future treatability studies, the Office of Emergency and Remedial Response requires that a copy of all treatability study reports be submitted to the Agency's RREL Treatability Data Base Repository, which is being developed by the Office of Research and Development (EPA 1989b). Submitting treatability study reports organized in the manner suggested in the final generic guide will increase the usability of this repository and assist in maintaining and updating the data base.

4.1 TEST OBJECTIVES

The Work Plan outlines the treatability study test objectives and describes how they will be used in evaluating chemical dehalogenation for selection at a site. Test objectives consist of meeting quantitative performance goals or making a qualitative engineering assessment of the process. Well-reasoned test objectives will ensure that the treatability study provides meaningful, scientifically sound data for remedy evaluation and selection.

Test objectives for remedy-screening treatability studies of chemical dehalogenation focus on the degree of reduction in toxicity achieved as a determinant of feasibility. As shown earlier in Table 2, a performance goal of greater than 90 percent reduction in the target contaminant concentrations should be achieved at this tier. If this test objective is met, chemical dehalogenation is considered a feasible alternative and is retained for remedy-selection testing.

At the remedy-selection tier, the treatability study test objectives should correspond to the site's final remediation goals. These numerical values establish the minimum acceptable amount or concentration of a contaminant that may remain on site or be discharged to the environment. Preliminary remediation goals are set by the lead agency based on chemical-specific health-based applicable or relevant and appropriate requirements (ARARs) and assumptions about reasonable maximum land-use and standard exposure pathways. Ideally, final remediation goals or "cleanup criteria" will be determined for a site early in the RI/FS process, before any remedy-selection treatability studies are conducted. At sites where this is not the case, test objectives must be developed.

Like remediation goals, remedy-selection test objectives should be based on ARARs. Potential ARARs for the remediation of soil contaminated by halogenated organics include the Resource Conservation and Recovery Act (RCRA) land disposal restrictions (LDRs) and the Toxic Substances Control Act (TSCA) regulations for PCBs. Where wastewater that is generated and released as a residual of chemical dehalogenation treatment may carry halogenated organics to ground or surface water, the Clean Water Act may provide potential ARARs. Guidance on potential ARARs is available in CERCLA *Compliance with Other Laws Manual: Interim Final* (EPA 1988b) and *CERCLA Compliance with Other Laws Manual: Part II* (EPA 1989c).

The LDRs promulgated under 40 CFR Part 268 of RCRA restrict the land disposal of certain industrial wastes containing spent solvents, dioxins, California List wastes, and the First Third, Second Third, and Third Third listed wastes. These restrictions also apply to soils contaminated with these wastes, including soil generated from removal and remedial actions at Superfund sites, corrective actions and closures at RCRA-regulated disposal sites, and private party cleanups. Guidance on LDRs is available in a series of Superfund Fact Sheets including the following:

- *Superfund LDR Guide #1: Overview of RCRA Land Disposal Restrictions* (EPA 1989d)
- *Superfund LDR Guide #2: Complying With the California List Restrictions Under Land Disposal Restrictions* (EPA 1989c)
- *Superfund LDR Guide #3: Treatment Standards and Minimum Technology Requirements Under Land Disposal Restrictions* (EPA 1989f)
- *Superfund LDR Guide #4: Complying With the Hammer Restrictions Under Land Disposal Restrictions* (EPA 1989g)
- *Superfund LDR Guide #5: Determining When Land Disposal Restrictions Are Applicable to CERCLA Response Actions* (EPA 1989h)
- *Superfund LDR Guide #6A (2nd Edition): Obtaining a Soil and Debris Treatability Variance for Remedial Actions* (EPA 1990a)

- *Superfund LDR Guide #6B: Obtaining a Soil and Debris Treatability Variance for Removal Actions* (EPA 1990b)

- *Superfund LDR Guide #7: Determining When Land Disposal Restrictions Are Relevant and Appropriate to CERCLA Response Actions* (EPA 1989i)

- *Superfund LDR Guide #8: Compliance with Third Third Requirements under the LDRs* (EPA 1990c)

Treatment standards for RCRA-restricted wastes are promulgated under 40 CFR Part 268 Subpart D. The Agency recognizes that it is generally more difficult to treat contaminated soil than corresponding industrial wastes. Consequently, EPA plans to establish concentration-based treatment standards specifically for contaminated soil and debris. The regulated list of constituents will include dioxins/furans, PCBs, and their precursors, among others.

As described in *Guidance on Remedial Actions for Superfund Sites with PCB Contamination* (hereinafter referred to as the PCB guidance) (EPA 1990d), there are three primary options for treatment of nonliquid PCBs at concentrations of 50 ppm or greater that are compliant with TSCA ARARs (40 CFR 761.60-761.79):

1) Incineration

2) Treatment equivalent to incineration

3) Disposal in a chemical waste landfill

Under 40 CFR 716.60(e), chemical dehalogenation can be used to treat PCB-contaminated material with no long-term management of residuals if treatment achieves a level of performance equivalent to incineration. As described in the PCB guidance, equivalence can be verified by demonstrating that the solid treatment residuals contain less than or equal to 2 ppm PCBs. If chemical dehalogenation cannot achieve this level of performance, but does result in substantial reductions (i.e., 90-99 percent), treatment plus long-term management in a chemical waste (TSCA-approved) landfill may be acceptable.

The PCB guidance recommends cleanup levels of 1 ppm PCBs for PCB-contaminated Superfund sites where land use is residential. Assuming no soil cover or management controls, this cleanup level equates to approximately a 10^{-5} excess cancer risk. In areas where land use is industrial, the PCB guidance recommends a range of 10 to 25 ppm PCBs for cleanup levels. These levels approximate a 10^{-4} excess cancer risk (assuming exposure equivalent to that in residential areas). Remedial alternatives should reduce PCB concentrations to these site-specific levels or limit exposure to concentrations above these levels.

The cleanup levels recommended in the PCB guidance can be used to set performance goals for chemical dehalogenation treatability studies at the remedy-selection tier. Chemical dehalogenation need not achieve 1 ppm PCB at a residential site to be successful. As part of an alternative, chemical dehalogenation should achieve a level of treatment that will allow the entire remedy to be protective of human health and the environment. For example, a test objective of 10 ppm PCBs may be appropriate for a residential site if chemical dehalogenation is part of a treatment train and the alternative includes long-term management controls that will reduce exposure to 1 ppm PCBs.

By achieving performance goals based on cleanup criteria, the remedy-selection treatability study provides data needed to conduct evaluations of 1) the long-term effectiveness and permanence of chemical dehalogenation, and 2) the reduction in toxicity, mobility, and volume of the contaminants. As discussed earlier, these evaluations take place during the detailed analysis of the alternatives phase of the FS. Achieving the clean levels also allows chemical dehalogenation to be selected as a remedial action with reasonable certainty that the site response objectives can be achieved.

The long-term risks posed to biota by the disposal of treated product on site may also require investigation at the remedy selection tier. Bioassays of treated product require large volumes of material. Generally, such quantities are not available from bench-scale studies. A pilot-scale test, however, could generate sufficient product for biotoxicity testing. If pre-ROD pilot tests are to be performed at a site, a test objective stipulating a reduction in toxicity to test organisms should be set to provide bioassay data for the assessment of long-term effectiveness and permanence in the detailed analysis of alternatives.

4.2 EXPERIMENTAL DESIGN AND PROCEDURES

The Work Plan should clearly outline the experimental design and procedures to be used for each tier of treatability testing planned.

4.2.1 Remedy-Screening Treatability Studies

Remedy screening of chemical dehalogenation is intended to determine if the technology is feasible for a given waste stream. Screening studies are applicable if little or no data exist with respect to the performance of the technology for

the contaminant/matrix of interest. To reduce the risks of falsely screening out the technology at this early stage, the treatment should be carried out under "severe conditions"; i.e., the reaction should proceed with the use of excess reagent at a high temperature for an extended period of time. The particular reaction conditions used should be based on the process vendor's knowledge of the equipment and reaction chemistry. A single test run should be performed, and only limited QA/QC is required.

At the screening tier, the experimental procedures should not be complex. Only pre- and posttreatment samples will be collected. Physical and chemical analysis will be limited. The vendor or testing facility should supply their standard operating procedures (SOP) for these sampling and analysis events as part of the treatability study Work Plan.

4.2.2 Remedy-Selection Treatability Studies

If chemical dehalogenation is determined to be potentially feasible at the remedy-screening tier, the effect of varying operating parameters on treatment performance can be investigated at the remedy-selection tier. Parameters that can be evaluated at this tier include reagent formulation and loading, temperature, reaction time, and other process-specific parameters. Duplicate or triplicate test runs should be performed, and a stringent level of QA/QC is required.

A remedy-selection treatability study must be designed to generate sufficient quantities of treated product and treatment residuals for characterization and posttreatment testing. Treated product may have many uses in a remedy-selection study. In addition to being analyzed for target contaminants and reaction byproducts, treated product will be required for additional investigations, such as biotoxicity testing, bulk density determination, mechanical testing (i.e., durability, permeability, unconfined compressive strength), and nutrient analysis. To design an appropriate treatability study, these posttreatment tests must be chosen in advance. If the dehalogenation process is part of a treatment train, the amount of treated material needed to investigate other train components must also be determined before the chemical dehalogenation study is designed. Experimental design, options for generating this additional product include, but are not limited to, multiple batch, bench-scale (1 to 10 liters) tests performed in a "lock-step" procedure; a single batch, pilot-scale (50 to 100 liters) test; or a combination of both.

Treatment residuals should also be characterized at this tier, to the extent practical. Full-scale chemical dehalogenation treatment may generate several residual streams, including spent reagent and wash waters, condensate (aqueous and organic fractions), and process off-gases. In a remedy-selection treatability study, these streams can be sampled and analyzed for target contaminants and selected reaction byproducts. The experimental design and procedures of the treatability study should allow for investigations of these residuals.

To establish that the target contaminants were dehalogenated and not simply removed from the waste and transferred to the residuals, a material balance should also be performed. This analysis requires careful measurement of the mass and volume of all materials that enter and exit the treatability study apparatus. These data, combined with the contaminant concentrations in the raw soil, treated product, and treatment residuals, will facilitate this determination.

Investigations of reagent recovery, residuals treatment, and soil pre- and posttreatment also may be initiated at the remedy-selection tier; however, because of the quantity of materials required, such investigations may be delayed until post-ROD RD/RA testing.

At the remedy-selection tier, the experimental procedures should model the expected field operations, particularly with regard to the residual streams that will be generated. The vendor or testing facility should supply their SOP as part of the treatability study Work Plan. This SOP should be sufficiently detailed to permit the RPM to evaluate the adequacy of the proposed technical approach.

4.3 EQUIPMENT AND MATERIALS

In addition to the experimental design and procedures, the Work Plan should clearly specify the equipment and materials to be used during each tier of testing. Remedy screening treatability Studies normally are performed in a batch system with off-the-shelf laboratory glassware and bench-scale equipment. A typical bench-scale reactor consists of a reaction flask, a stirrer, a heating mantel, and a condensate collection system. Figure 6 shows a typical chemical dehalogenation bench-scale reactor. Remedy-selection studies will be performed with larger bench- or, occasionally, pilot-scale equipment. These systems may include ancillary equipment such as a feed preparation and delivery system, a steam plant, a reactant delivery system, and a soil/reagent separation system. Figure 7 shows the details of an example pilot-scale reactor.

The Work Plan also should specify the reagent formulation(s) to be tested, many of which are proprietary. The alkaline glycolate reagents generally contain an alkaline metal hydroxide (e.g., NaOH or KOH), an alcohol or glycol (e.g., polyethylene glycol), and an optional cosolvent or catalyst (e.g., dimethylsulfoxide).

4.4 SAMPLING AND ANALYSIS

This subsection describes the factors associated with sampling and analysis that affect the development of the Work Plan for chemical dehalogenation treatability studies. Examples of these factors are the number and types of samples and analyses required, sample preparation procedures, and the number of replicates and blanks. These factors will affect the project schedule and budget requirements that must be determined in the development of the Work Plan. Issues related to the development of a Sampling and Analysis Plan (SAP) are discussed in Section 5.

4.4.1 General Considerations

During the development of the Work Plan, available data fromthe RI on the physical and chemical properties of the matrix should be reviewed and evaluated with respect to completeness and adequacy. Data of interest include the following:

- Target halogenated organic contaminants and concentration ranges.
- Spatial distribution of target contaminants (e.g., location of "hot" zones).
- Presence of contaminants at levels that limit the use of a testing or disposal facility (e.g., few facilities can accept wastes containing dioxins or PCBs above certain concentrations).
- Presence of other contaminants (e.g., certain organic solvents) that may interfere with the extraction and analysis of target contaminants.
- Presence of reactive species (e.g., elemental forms of certain metals) that may be affected by the dehalogenation reagents.
- Soil type.
- Moisture content (soils) or solids content (sludges, sediments).
- Particle-size distribution.

These data should be evaluated along with the treatability test objectives for the development of an approach for collection, preparation, and analysis of samples for treatability testing. If the available data are insufficient, the Work Plan may need to include either an initial site sampling

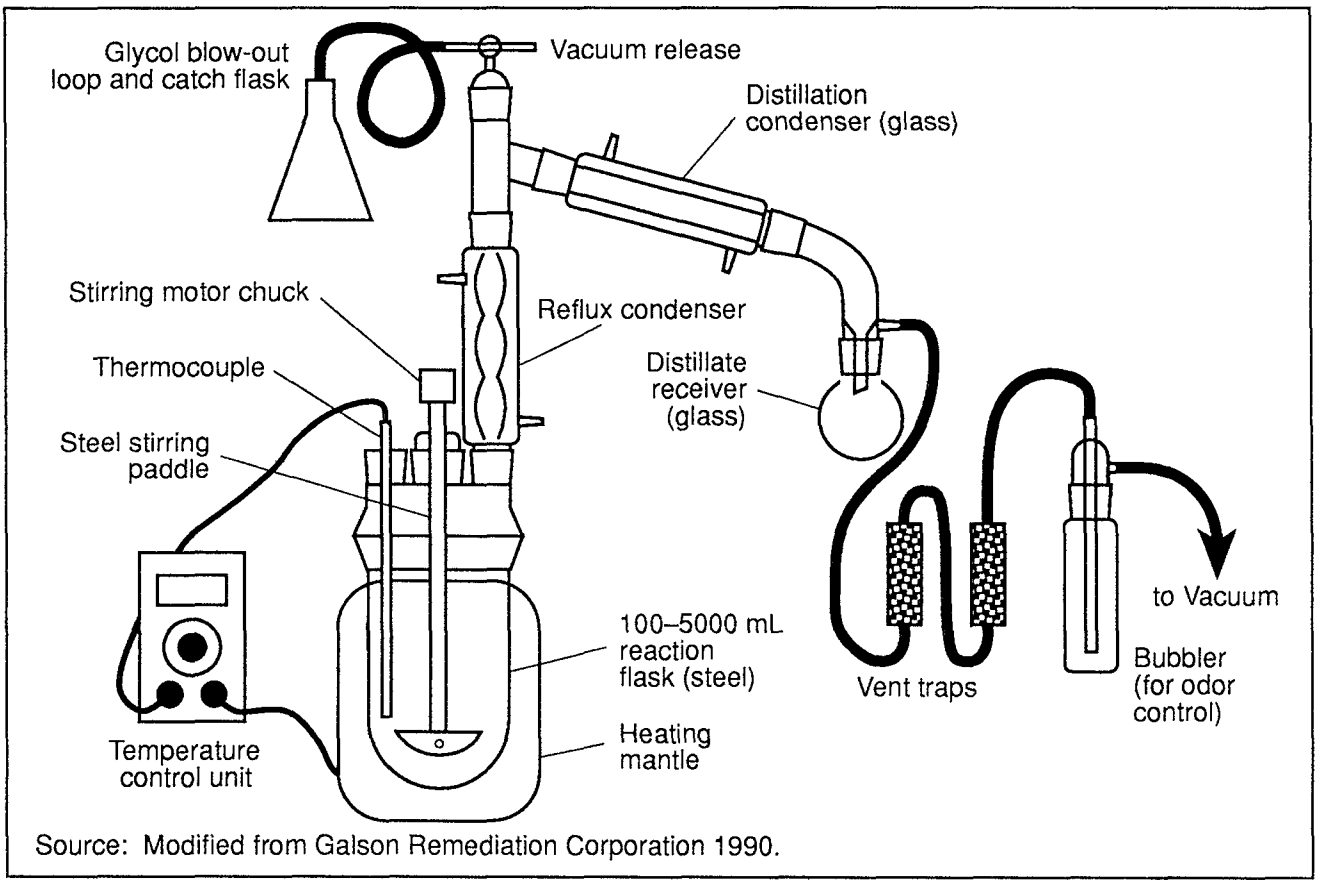


Figure 6. Example chemical dehalogenation bench-scale reactor.

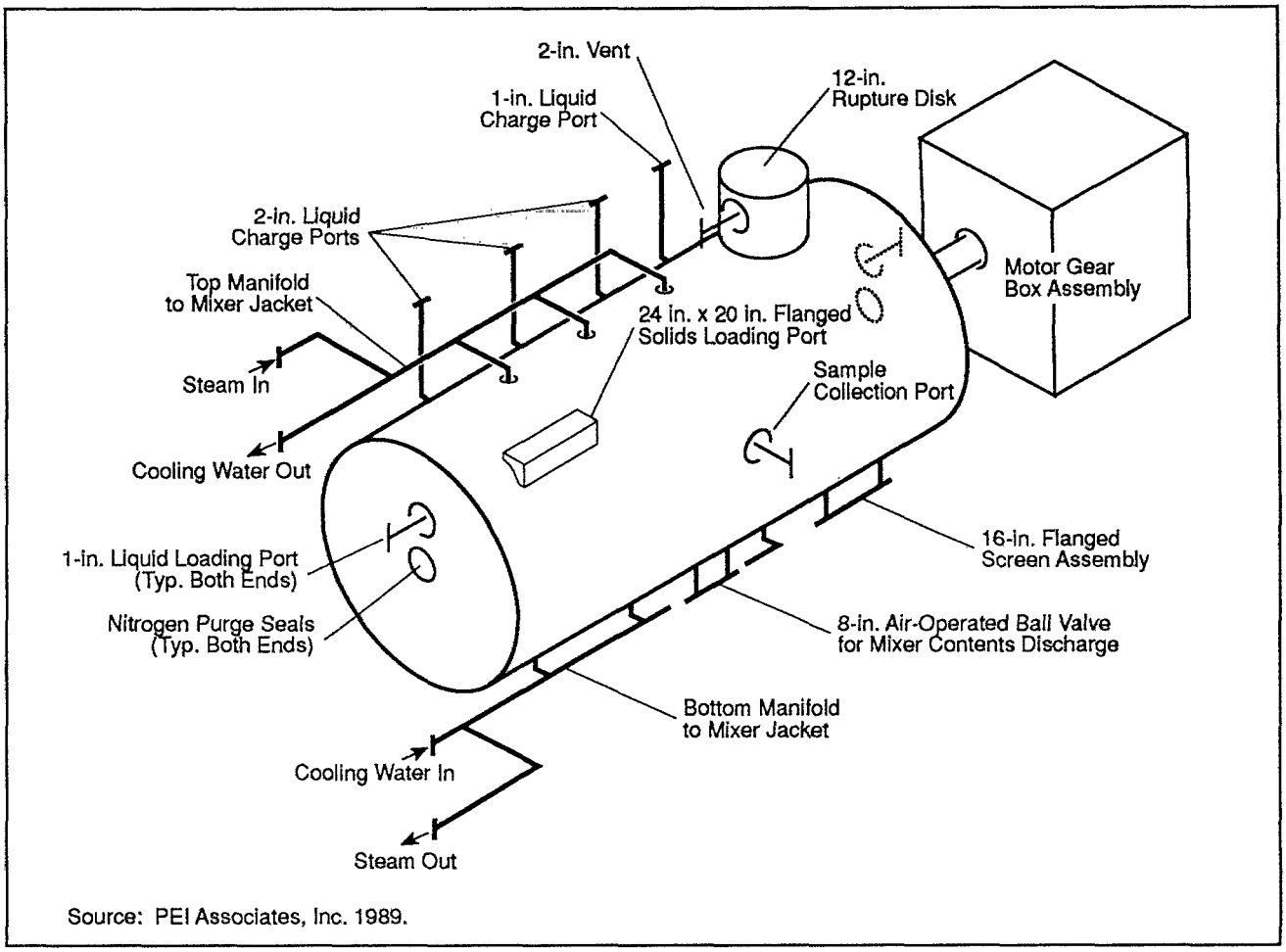


Figure 7. Example chemical dehalogenation pilot-scale reactor.

visit to collect the necessary waste characterization data or the use of a field analytical screening method to prescreen soil and to select appropriate sample locations for the treatability studies.

4.4.2 Field Sampling and Sample Preparation

The objectives of treatability testing influence the type or sample to be collected (i.e., "average-case" or "worst-case" sample). For remedy-screening studies involving wastes that have not previously been tested, soils with average concentrations of the target contaminants should be sampled. For remedy-selection studies involving wastes that have been extensively tested, samples representing worst-case soil concentrations or conditions should be selected. Grab samples from the hot zones will yield samples representative of worst-case conditions. For studies involving multiple, widely different matrices, samples of each type should be collected and tested separately. If results from the treatability testing of different treatment technologies are to be directly compared, the same type of sample must be used in each test.

In most cases, soil samples collected in the field will require some preparation prior to treatability testing of chemical dehalogenation processes. At a minimum, sample preparation will usually involve sample screening to remove oversize material and debris and sample homogenization for greater analytical precision and comparability. Studies conducted at the pilot scale also may involve crushing of oversize soil particles that do not pass through the screens. The need for additional pretreatment is largely equipment specific and should be based on the vendor's recommendations. Depending on the tier of treatability testing and the field conditions, these sample preparation activities may take place in the field or in the laboratory.

The amount of sample collected should be based on the quantities needed for each test run and for pre- and posttreatment analyses as well as the number of test runs and replicate analyses to be performed. Bench-scale test-, at the remedy-

screening tier generally require small sample volumes (<1 L per test run). The increased number of test runs and the extent of pre- and posttreatment analyses for bench-scale, remedy-selection testing will require that a greater total waste sample volume be collected. Pilot-scale tests conducted in support of remedy selection will require much larger sample volumes (> 100 L per batch). If the dehalogenation process is part of a treatment train, the volume of treated product and treatment residuals needed for later testing also will impact the total volume of waste to be collected. An excess amount of waste sample should always be collected in the event additional test runs and analyses should be required during the course of the study and to account for losses during sample preparation and for other contingencies.

4.4.3 Waste Characterization

Table 4 summarizes the waste characterization analyses that should be considered in developing The Work Plan. The types of analyses usually performed are similar for both remedy-screening and remedy-selection treatability studies. Standard EPA and the American Society for Testing and Materials (ASTM) methods are generally recommended; however, the treatability study vendor may propose modified or equivalent methods for noncritical measurements. 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.

Various chemical tests may be used to establish the baseline concentration of the target halogenated organic contaminants and other contaminants of interest. In the case of chemical dehalogenation treatment, the target contaminants may be PCBs, dioxins/furans, pesticides/herbicides, halogenated benzenes and phenols, or halogenated aliphatics. For remedy-screening studies, only one analysis for the target contaminants expected to be present in the untreated waste may be necessary. For remedy-selection studies, however, two or three replicate analyses may be required to establish the homogeneity of the waste and to determine statistical confidence levels for the target contaminant concentrations.

Additional compounds of interest at the remedy-selection tier may include selected possible halogenated byproducts from the degradation of the target contaminants. For example, if pentachlorophenol is the target contaminant present, analysis for trichlorophenols (e.g., 2,4,5-trichlorophenol) and dichlorophenols (e.g., 2,4-dichlorophenol) may be appropriate to establish a pretreatment baseline concentration for these potential degradation byproducts. The selection of other halogenated organic compounds should be based on the likely chemical reactions and relative toxicity of the

Table 4. Waste Characterization Analyses

Parameter	Remedy screening	Remedy selection	Description of test[a]	Use of data
Target halogenated organic contaminants	X	X	Gas chromatography Gas chromatography/mass spectrometry	Establish baseline for determining target contaminant reduction and treatment effectiveness.
Other halogenated organic compounds		X	Gas chromatography Gas chromatography/Mass spectrometry	Establish baseline for investigating formation of specific reaction byproducts.
Other chemical parameters Volatile oraganics		X	Gas chromatography	Establish baseline for investigating contaminant losses. Identify health and safety hazards.
Metals		X	Atomic absorption spectroscopy Inductively coupled plasma spectroscopy	Establish baseline for investigating contaminant losses. Identify health and safety hazards.
pH/base absorption capacity	X	X	Electrometric Titration Proprietary methods	Determine reagent formulation/loading
Moisture content	X	X	Oven dry	Determine reagent formulation/loading
Particle-size distribution	X	X	Sieving Hydrometer	Determine experimental apparatus.
Biotoxicity		X	Algae Macroinvertebrates Fathead minnow larvae Seed germination Earthworm Microtox™ Ames	Establish baseline for comparing biotoxicity of waste before and after treatment.

[a] Test methods may be EPA, ASTM, or equivalent.

byproducts. Compounds that could interfere with the chemical dehalogenation process or those that affect treatment or handling of residual fractions from the process also may be of interest at the remedy-selection tier. For example, volatile organic compounds may be tested as a basis for calculating volatile losses during treatment. Occasionally, the potential presence of highly toxic or carcinogenic compounds may warrant additional analytical testing.

Soil moisture content and pH or buffering (base absorption) capacity are used to formulate the chemical dehalogenation reagent at the remedy-screening and remedy-selection tiers. High-moisture-content soils may require greater quantities of reagent because of the dilution effects of the soil water. Acidic soils or soils with a high buffering capacity will require excess base to compensate for base-consuming reactions with the soil. Particle-size analysis of the soil is used to determine the experimental apparatus needed for mixing and soil/reagent separation. For example, sandy soils with low clay content may be separated by vacuum filtration, whereas soils with significant fines content may require centrifugation.

As with other treatability studies, additional characterization tests may be required by the laboratory or testing facility to maintain compliance with their operating permit. Waste characterization tests may also be required for disposal of unused samples.

Bioassays of the untreated waste may be required to establish baseline biotoxicity data if replacement of the treated product on site is being evaluated as a disposal option. These methods are described later in Subsection 5.1.7.

4.4.4 Treated Product and Residuals Sampling and Analysis

Table 5 summarizes the analyses of the treated soil and other fractions resulting from the treatment process (i.e., used reagent solution, rinse water, condensate, and absorbent traps) that should be considered in developing the Work Plan. Generally, posttreatment sampling and analysis at the remedy-screening tier will be limited to the target halogenated organic contaminants in the treated product. At the remedy-selection tier, the treatment residuals also should be analyzed. Standard EPA and ASTM methods are generally recommended; however, the treatability study vendor may propose modified or equivalent methods subject to acceptance by the EPA RPM.

Target halogenated organic contaminants and other compounds of interest include those discussed in Subsection 4.4.3. Posttreatment analytes at the remedy-selection tier also may include selected potential halogenated byproducts. Because the analytical results at the remedy-selection tier will be used to evaluate the technology's ability to meet the

Table 5. Treated Product and Treatment Residuals Analysis

Parameter	Remedy screening	Remedy selection	Description of test[a]	Use of data
Target halogenated organic contaminants	X	X	Gas chromatography Gas chromatography/mass spectrometry	Determine target contaminant reduction and treatment effectiveness.
Other halogenated organic compounds		X	Gas chromatography Gas chromatography/mass spectrometry	Investigate formation of specific reaction byproducts.
Other chemical parameters Volatile oraganics		X	Gas chromatography	Evaluate posttreatment and disposal options. Investigate contaminant losses due to treatment.
Metals		X	Atomic absorption spectroscopy Inductively coupled plasma spectroscopy	Evaluate posttreatment and disposal options. Investigate containment losses due to treatment.
pH	X	X	Electrometric Titration	Evaluate posttreatment and disposal options.
Physical and mechanical parameters		X[b]	Permeability Pore volume Unconfined compressive strength	Evaluate suitability of treated product for onsite disposal.
Biotoxicity		X[b]	Algae Macroinvertebrates Fathead minnow larvae Seed germination Earthworm Microtox™ Ames	Evaluate biotoxicity of treated product. Determine reduction in biotoxicity of waste. Evaluate suitability of treated product for onsite disposal.

[a] Test methods may be EPA, ASTM, or equivalent.
[b] Treated product or treated product extract only.

cleanup goals for the site, two or three analyses may be required to determine statistical confidence levels for the target contaminant concentrations in the treated product. Analysis for target and other contaminants of interest in the treatment residuals also may be necessary at the selection tier to demonstrate dehalogenation of the target contaminants rather than physical removal.

This determination would require a careful accounting of the mass of all materials that enter and exit the system. The material balance, combined with the concentrations of target contaminants in all exit fractions, can then be used to refine the estimate of actual dehalogenation efficiency of the process.

In addition to chemical tests, physical and toxicological tests also may be conducted on treated product or treatment residuals at the remedy-selection tier to evaluate posttreatment and disposal options. If treated product is to be placed back into the original excavation (i.e., not in an onsite disposal cell), determination of its mechanical properties, pH, and nutrient levels and the leachability of remaining contaminants may be required. It is important to note that mechanical test methods may require significant quantities of soils (e.g., 20 kg); therefore, the vendor may have to perform multiple test runs to generate sufficient quantities of material for analysis. Bioassays also may be necessary for evaluation of the toxic or mutagenic effects of chemical dehalogenation residuals on biota. Applicable tests include freshwater algae, daphnid, and minnow assays of product extracts and seed germination and earthworm tests of treated product. These tests are described in Subsection 5.1.7.

If treated product is to be placed in an onsite disposal cell or transported for disposal at an offsite RCRA facility, it may be subject to RCRA land disposal restrictions. Depending on their ultimate disposition, residual fractions may be subject to additional testing requirements under TSCA, RCRA, the Clean Water Act, and the Clean Air Act.

4.5 DATA ANALYSIS AND INTERPRETATION

Data from remedy-screening and remedy-selection treatability studies will be used to evaluate chemical dehalogenation during the detailed analysis of alternatives. Analysis and interpretation of the treatability study data must relate back to the test objectives discussed in Subsection 4.1. Careful consideration should be given to the uses of the data during the development of this section of the Work Plan. A detailed discussion on the interpretation and use of chemical dehalogenation treatability data is provided in Section 6.

4.5.1 Remedy-Screening Treatability Studies

Remedy screening of chemical dehalogenation generally involves testing a small sample of the waste to determine whether the process is feasible. If the feasibility of the process is demonstrated, the effects of varying operating parameters on treatment performance can be investigated at the remedy-selection tier. A reduction of more than 90 percent in the concentration of the target contaminant at the screening tier generally indicates that chemical dehalogenation is feasible and should be retained for further analysis.

For remedy-screening treatability studies, the concentration of the target contaminants before and after treatment should be tabulated, as shown in Figure 8. The reaction conditions used also should be reported, along with recommendations for the parameters to be investigated in subsequent treatability studies.

Parameter	Before treatment, ppb	After treatment, ppb
Pesticides/herbicides		
4,4'-DDE	15.7	<0.047
4,4'-DDT	86.7	<0.016
DDD	23.7	<0.016
Furans		
TCDF	8.03	<1.71
PeCDF	22.9	<1.46
HxCDF	8.77	<3.69

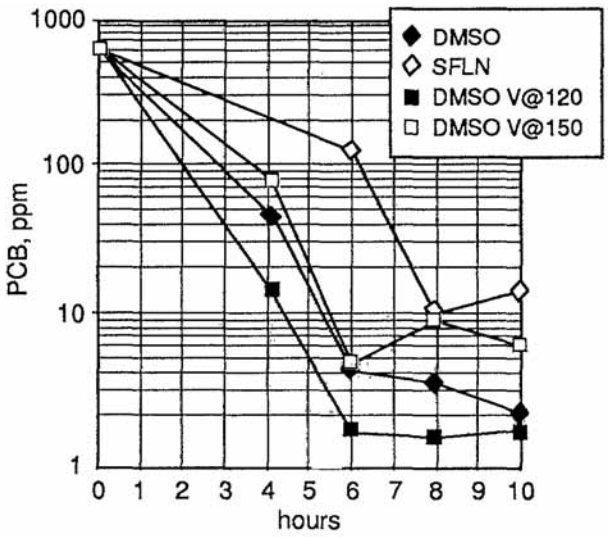
Figure 8. Example tabulation of results from a remedy-screening treatability study.

4.5.2 Remedy-Selection Treatability Studies

Remedy-selection treatability studies of chemical dehalogenation generally follow either a positive remedy-screening test or a determination that the technology is likely to be feasible for the waste based on preexisting knowledge of the waste and the treatment technology. Remedy-selection studies examine the effects of varying operating parameters on treatment performance. Parameters that can be investigated at this tier include reagent formulation and loading, temperature, reaction time, and other process- specific parameters.

As an aid to the decision maker in the analysis and interpretation of data from chemical dehalogenation tests, the con-

centration of the target contaminants may be plotted versus changes in the critical process parameters, as shown in Figure 9. Alternative methods of presenting the data may be proposed by the technology vendor, depending on the experimental design and the procedures followed. A material balance that accounts for all of the solids and liquids entering and exiting the system also can be used to ensure that the contaminants have been chemically altered, not simply physically removed. These data can be summarized in a tabular format, as shown in Figure 10.



Source: Galson Research Corporation 1988.

Figure 9. Example graphical presentation of results from a remedy-selection treatability study.

	g in	g out	g change	Recovery, %
Soil	300.0	149.6	-150.4	50
Samples		23.5	23.5	
Reagent	300.0	176.0	-124.0	59
Wash 1	300.0	336.9	36.9	112
Wash 2	300.0	363.3	63.3	121
Distillate		53.8	53.8	
"Solids"	300.0	173.1	-126.9	58
"Liquids"	900.0	930.0	30.0	103
Total	1200.0	1103.1	-96.9	92

Source: Galson Research Corporation 1988.

Figure 10. Example tabulation of material balance data from a remedy-selection treatability study.

4.6 HEALTH AND SAFETY

A project-specific Health and Safety Plan (HSP) is required for all chemical dehalogenation treatability studies conducted on site or at an offsite laboratory or testing facility permitted under RCRA. This requirement includes research, development, and demonstration (RD&D) facilities, but it does not apply to facilities that are conditionally exempt from Subtitle C regulation by the treatability study exemption [40 CFR 261.4(e) and (f) or equivalent State regulations].

The vendor or testing facility should supply the HSP with the treatability study Work Plan. The HSP describes the work to be performed in the field and in the laboratory, identifies the possible physical and chemical hazards associated with each phase of field and laboratory operations, and prescribes the appropriate protective measures necessary to minimize worker exposure. The preparation of an HSP is discussed in the final generic guide. Hazards specific to chemical dehalogenation treatability studies are discussed in the following subsections.

4.6.1 Chemical Hazards

Chemical hazards are associated with both the treatment process and the waste. Caustics used in the process and acids used for neutralization will pose inhalation and skin absorption hazards. If cosolvents such as DMSO are used, they can enhance the absorption of chemicals into the skin. Waste contaminants such as PCBs, PCDDs/PCDFs, and pesticides will pose additional chemical hazards. Polychlorinated biphenyls are recognized as potential carcinogens, and PCDDs/ PCDFs are considered carcinogenic, acnogenic, teratogenic, and embryotoxic. The HSP should identify the appropriate skin and respiratory protection for the chemical hazards to which workers may be exposed

.

4.6.2 Physical Hazards

Fire and explosion hazards exist whenever heat is associated with a chemical treatment process. Explosive quantities of hydrogen gas may be generated when wastes containing certain metals in their elemental form (e.g., aluminum and zinc) are mixed with alkaline treatment reagents such as potassium hydroxide. Treatment of certain chlorinated aliphatics at high concentrations may produce compounds that are potentially explosive (e.g., chloroacetylenes) or pose a fire hazard. The use of DMSO or similar reagents may lead to the formation of highly flammable volatile organics (e.g., methyl sulfide). The HSP should stipulate the precautions for preventing fires and explosions (e.g., laboratory hoods, equipment vents/releases, and nitrogen purge systems).

4.7 PERMITS

Treatability studies of chemical dehalogenation technologies are subject to certain regulatory requirements under Federal environmental laws. The treatability study Work Plan should describe how the laboratory or testing facility will comply with all applicable requirements (e.g., storage or quantity limitations). The final generic guide describes the permitting and operating requirements under CERCLA and RCRA.

Under TSCA, laboratories or testing facilities that handle PCB-containing materials must obtain a Research and Development Permit. (For fixed laboratories, this permit can be obtained from the appropriate EPA Regional Office. For mobile laboratories, it can be obtained from the EPA Office of Toxic Substances, Chemical Regulation Branch.) Storage of PCB-containing materials for purposes of treatability testing is limited to no longer than 1 year.

4.8 RESIDUALS MANAGEMENT

Residuals generated as a result of treatability testing must be managed in an environmentally sound manner. Early recognition of the types and quantities of residuals that will be generated, the impacts that managing these residuals will have on the project schedule and costs, and the roles and responsibilities of the various parties involved is important for their proper disposal.

The Work Plan should include estimates of both the types and quantities of residuals expected to be generated during chemical dehalogenation treatability testing. These estimates should be based on knowledge of the treatment technology and the experimental design. Project residuals may include the following:

- Unused waste not subjected to testing
- Treated waste
- Treatment residuals (e.g., spent reagent, condensate)
- Laboratory samples and sample extracts
- Used containers or other expendables
- Contaminated protective clothing and debris

The Work Plan should describe whether treatability study residuals will be returned to the site; investigated on or offsite as part of a treatment train; or shipped to a permitted treatment, storage, or disposal facility (i.e., RCRA Subtitle C facility for hazardous wastes, RCRA Subtitle D facility for solid wastes, or TSCA or RCRA facility for PCB-containing wastes). The final generic guide discusses the management of residuals regulated under RCRA as well as applicable Department of Transportation regulations.

4.9 SCHEDULE

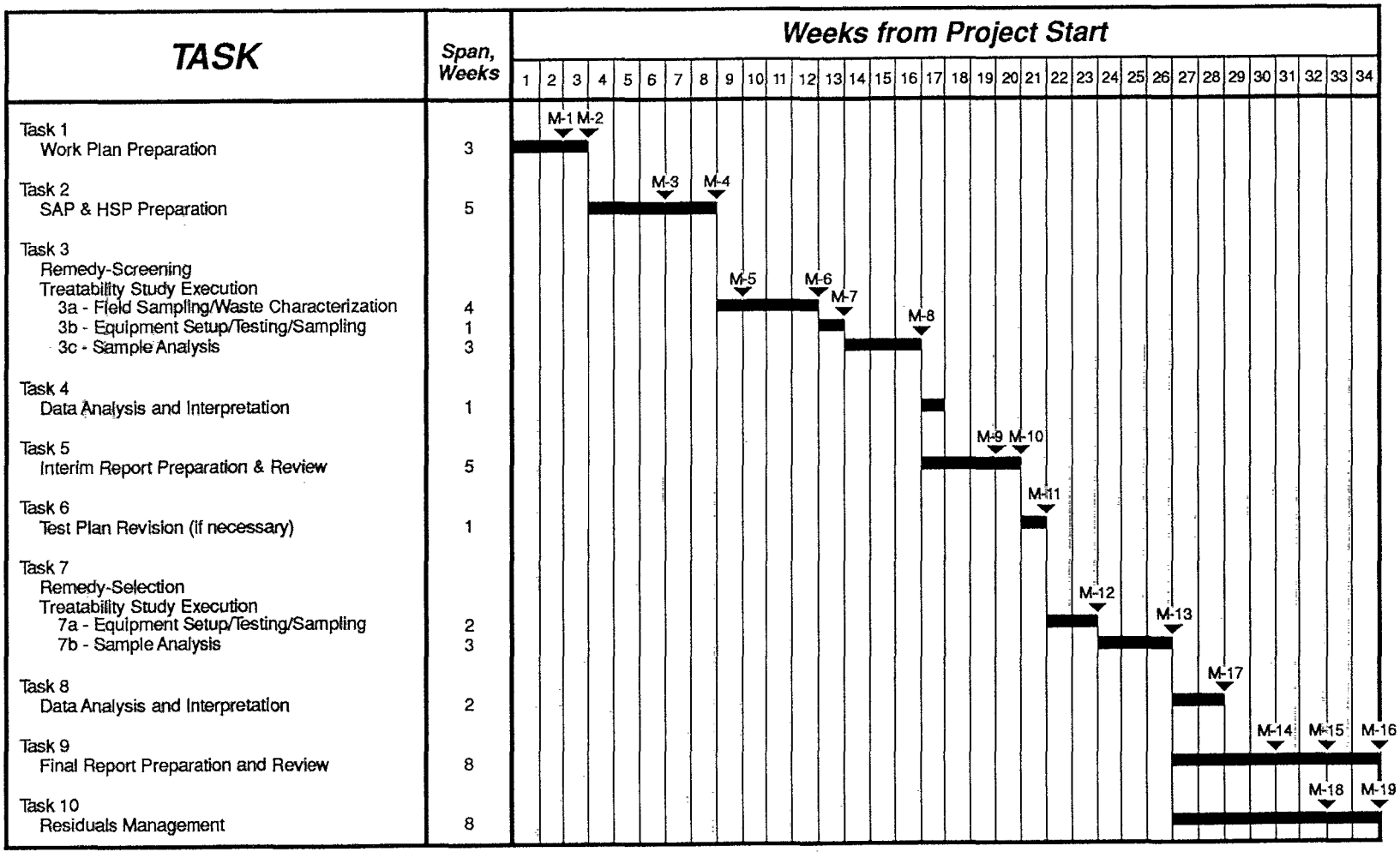
The Work Plan should contain a schedule indicating the planned starting and ending dates for the tasks outlined in the Work Assignment. The duration of a chemical dehalogenation treatability study will vary with the level of testing being conducted. Remedy-screening studies can usually be performed within a few weeks. Remedy-selection studies, however, may require several months. In addition to the time required for actual testing, the schedule must allow time for obtaining approval of the various plans; securing any necessary environmental, testing, or transportation permits; shipping analytical samples and receiving results; seeking review and comment on the project's deliverables; and disposing of the project's residuals.

The schedule may be displayed as a bar chart such as that shown in Figure 11. In this example, both remedy-screening and remedy-selection treatability studies are planned. Performance of the selection studies is contingent upon the results of the screening studies, which are presented in the Interim Report. In this particular schedule, the actual treatability tests (Subtasks 3b and 7b) will require only 1 to 2 weeks to perform. The entire two-tiered study, however, spans a period of 8 months.

4.10 MANAGEMENT AND STAFFING

This section of the Work Plan identifies key management and technical personnel and defines specific project roles and responsibilities. The line of authority is usually presented in an organization chart such as that shown in Figure 12. The RPM is responsible for project planning and oversight. At Federal- and State-lead sites, the remedial contractor directs the treatability study and is responsible for the execution of the project tasks. At private-lead sites, the responsible party performs this function. The treatability study may be subcontracted in whole or in part to a vendor or testing facility with expertise in chemical dehalogenation.

In addition to the Work Assignment Manager, the contractor should assign a Quality Assurance Officer and a Health and Safety Officer. Individual task leaders also should be assigned; these may include chemists, engineers, and toxicologists. Other support staff may include technicians, a sample custodian, and a disposal coordinator.



The Subcontractor Manager may be responsible for one or more tasks and should report directly to the Work Assignment Manager. Project personnel will often perform multiple roles in a treatability study, and some individuals may serve as multiple-task leaders.

4.11 BUDGET

The treatability study budget presents the projected costs for completing the chemical dehalogenation treatability study as described in the Work Plan. Elements of a budget include labor, administrative costs, and fees; equipment and reagents; site preparation (e.g., building a concrete pad) and utilities; permitting and regulatory fees; unit mobilization; on-scene health and safety requirements; sample transportation and analysis; emissions and effluent monitoring and treatment; unit decontamination and demobilization; and residuals transportation and disposal. Figure 13 shows the applicability of the various cost elements to the three tiers of testing. The final generic guide, which provides a description of potential treatability study cost elements, should be referred to prior to preparation of the Work Plan budget.

The size of the budget will generally reflect the complexity of the treatability study. Consequently, the number of operating parameters chosen for investigation at the remedy selection tier and the approach used to obtain these measurements will often depend on the available funding. For example, for some chemical dehalogenation processes it may be less costly to obtain data on contaminant reduction versus reaction time at the completion of a test run rather than periodically throughout the test. The technology vendor should be consulted to obtain this kind of information during the planning of the treatability study.

Analytical costs can have a significant impact on the project's overall budget. Sufficient funding must be allotted for the amount of analytical work projected, the chemical and physical parameters to be analyzed, and the required turn-around time. Specialty analyses, such as for dioxins and furans, can quickly increase the analytical costs. Dioxin/furan analyses generally cost about $1000 per sample.

A 34-week remedy-screening/remedy-selection treatability study, such as the one presented in Figure 11, may be performed at a cost of between $50,000 and $ 100,000.

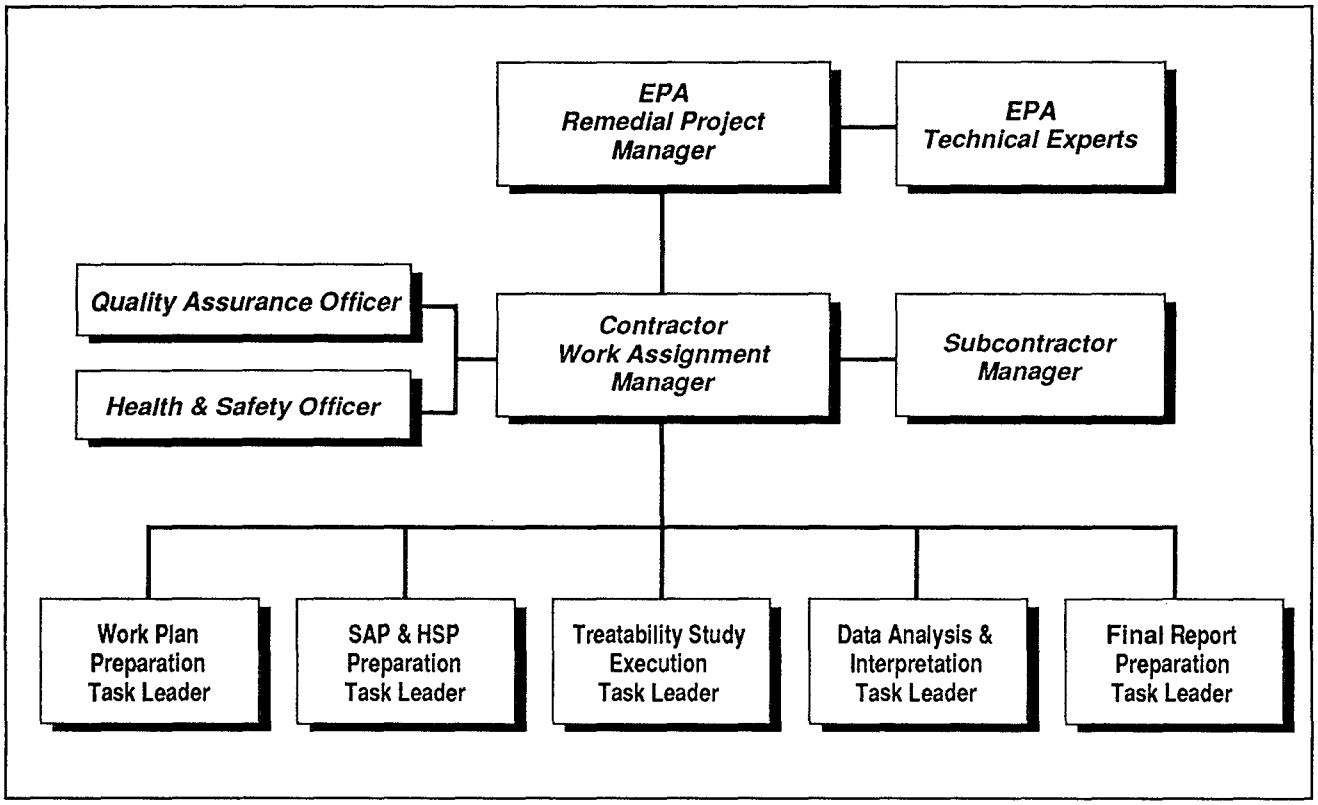


Figure 12. Example project organization chart.

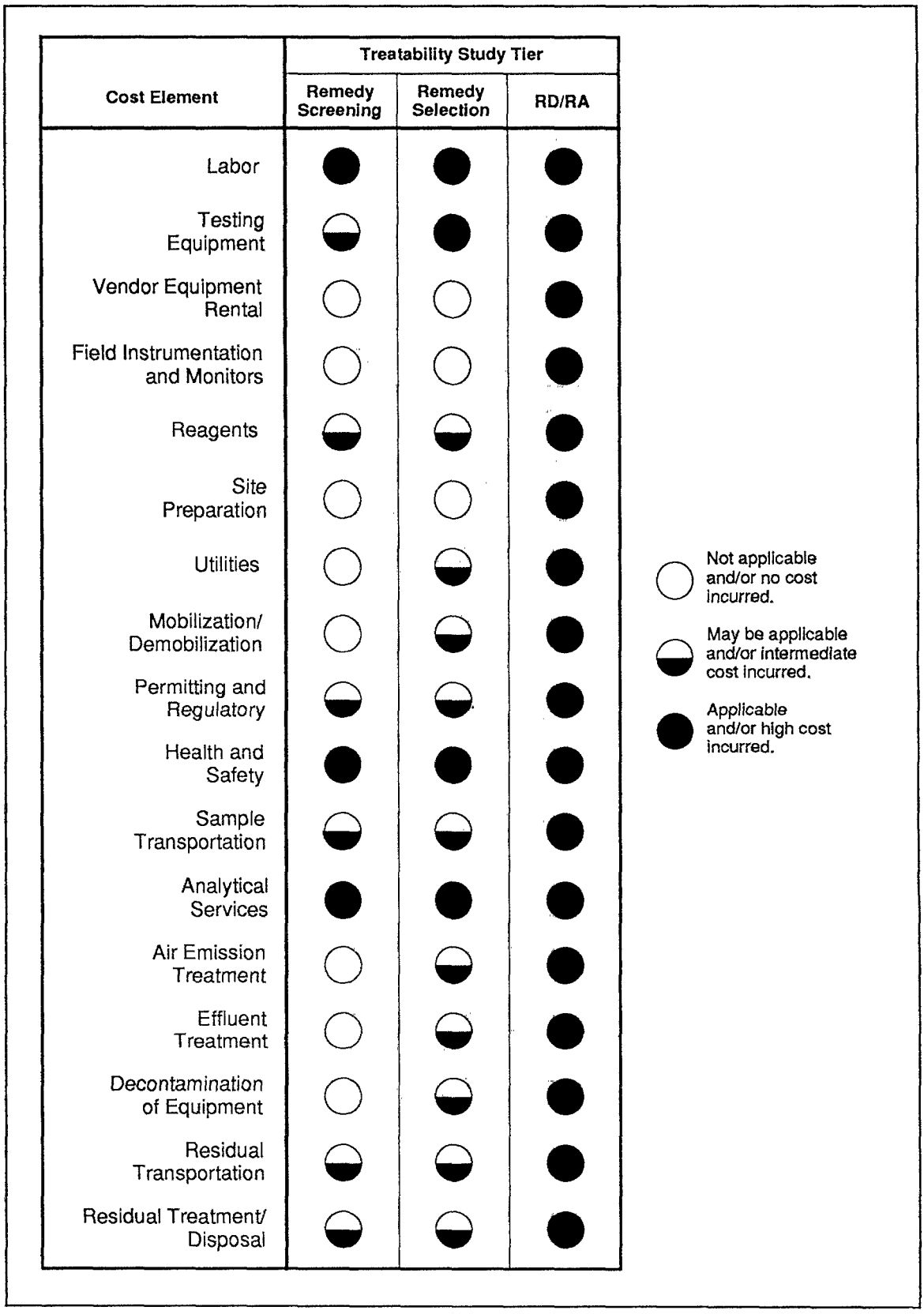


Figure 13. General applicability of cost elements to various treatability study tiers.

SECTION 5
SAMPLING AND ANALYSIS PLAN

Factors associated with sampling and analysis that affect the development of the Work Plan for chemical dehalogenation treatability studies were previously outlined in Subsection 4.4. Section 5 discusses the development of a Sampling and Analysis Plan (SAP) for remedy-screening and remedy-selection treatability studies. The suggested outline of the SAP presented in Table 6 includes a Field Sampling Plan (FSP) and a Quality Assurance Project Plan (QAPjP). General issues associated with the development of an SAP for treatability studies are described in the final generic guide. This section describes issues specific to the chemical dehalogenation process. Subsection 5.1 covers the field procedures used to collect and analyze waste samples. Subsection 5.2 presents an overview of QA/QC procedures used in the laboratory to collect and analyze samples of treated product and treatment residuals.

5.1 FIELD SAMPLING PLAN

This subsection describes procedures for obtaining and characterizing samples in the field. General guidelines for performing sampling and analysis in conjunction with treatability studies are presented in *A Compendium of Superfund Field Operations Methods* (EPA 1987). Issues specific to chemical dehalogenation treatability studies are discussed here.

5.1.1 Field Sampling and Analytical Procedures

Field sampling procedures for soils and sludges believed to contain halogenated organic compounds generally involve the use of stainless steel, glass, or Teflon (rather than polypropylene or polyethylene) sampling equipment and containers. Plastic materials may leach phthalate plasticizers that could interfere with the analyses and introduce new contaminants into the sample matrix.

If, prior to field sampling, available analytical data are insufficient to characterize the distribution of target contaminants and to identify sampling locations, it may be possible to use field analytical techniques (field portable gas chromatographs and gas chromatograph/mass spectrometers, halide-ion selective test kits, or immunoassays) to prescreen and select appropriate and representative sampling locations for collecting worst-case or average-case soil samples. Some field screening methods are neither compound-specific (e.g., halide-ion selective test kits) nor accurate with respect to compound identification and quantification and should not be used to quantify the levels of target contaminants in the waste soil samples. They should only be used to detect and to approximate concentra-

Table 6. Suggested Organization of Treatability Study Sampling and Analysis Plan

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

Quality Assurance Project Plan
1. Project Description
2. Project Organization and Responsibilities
3. Quality Assurance Objectives
4. Site Selection and Sampling Procedures
5. Analytical Procedures and Calibration
6. Data Reduction, Validation, and Reporting
7. Internal Quality Control Checks
8. Performance and Systems Audits
9. Calculation of Data Quality Indicators
10. Corrective Action
11. Quality Control Reports to Management
12. References

Appendices
A. Data Quality Objectives
B. Example of SOP for Chain-of -Custody Procedures
C. EPA Methods Used
D. SOP for EPA Methods Used

tions of the target contaminants. Laboratory analyses must subsequently be performed to verify the presence and to quantify the levels of the target contaminants in the samples. An alternative approach to performing field screening analyses is to conduct an initial site visit to collect samples for characterization in the laboratory and determination of the type, concentration, and location of contaminants at the site.

Decontamination of field equipment in studies involving PCBs or dioxins/furans will require special attention because these compounds are insoluble in water and even low levels may persist after water rinsing. Specific rinsing procedures should be developed to assure thorough decontamination of sampling equipment so as to minimize cross-contamination of samples. Several rinse steps involving hot-water soaks, pesticide-grade solvents, special soap solutions that are free of chlorinated organic compounds, and distilled water may be necessary.

All equipment and procedures used in the field to collect treatability study samples must be outlined in the study's FSP.

5.1.2 Sample Preparation and Handling Procedures

The FSP also must describe the specific sample preparation and handling procedures that precede treatability testing. Sample preparation will generally involve soil sieving (to remove oversize particles and debris) and sample homogenization. Soil sieving may be performed manually in the laboratory as treatability samples are withdrawn from the field sample container, or it can be performed at the site by pouring the soil through stainless steel sieves. For remedy-screening studies, sample compositing and homogenization can be accomplished manually in the field or laboratory by using stainless steel trowels, scoops, and pails. For remedy-selection studies, however, mechanical mixers may be required to yield more homogeneous samples.

Samples may be air-dried before treatment to reduce the moisture content of soils and sludges. If significant concentrations of target volatile organic contaminants (e.g., chlorinated aliphatics) are present, however, special precautions should be taken during sample preparation and handling to minimize volatile losses. These precautions may include mixing small amounts of sample at a time in a closed mixer and placing the samples in cold storage.

5.1.3 Sample Preservation and Holding Times

As outlined in *Test Methods for Evaluating Solid Waste* (EPA 1986), samples believed to contain halogenated organic compounds should be preserved by cooling them to 4EC. The critical holding times for these samples (i.e., the time between collection of the sample in the field and extraction in the laboratory) should not exceed 14 days. The time between sample extraction and analysis should not exceed 40 days.

5.2 QUALITY ASSURANCE PROJECT PLAN

The second component of the SAP, the QAPjP, details the quality assurance objectives (precision, accuracy, representativeness, completeness, and comparability) for critical measurements and the quality control procedures established to achieve the desired QA objectives for a specific treatability study. Guidance for preparing the QAPjP can be obtained from *Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans* (EPA 1980).

Quality assurance/quality control procedures are an integral part of both the field and laboratory sampling and analysis activities performed during a treatability study. These QA/QC procedures must be consistent with the study's test objectives. This subsection describes laboratory QA/QC procedures for chemical dehalogenation treatability studies.

5.2.1 Quality Assurance Objectives and Critical Measurement Data

Specific QA objectives for the precision, accuracy, and completeness of the data generated must be specified for each sample matrix and critical measurement parameter at the outset of the study. Critical measurements include those parameters that will be used to judge the performance of the chemical dehalogenation process. Figure 14 lists example analytical QA objectives for a remedy-selection chemical dehalogenation study (PEI Associates 1988). Precision is determined by comparing analytical results from replicate samples. For studies involving duplicate samples, the relative percent difference (RPD) is calculated. In the case of triplicate samples, the mean and relative standard deviation (RSD) are calculated. Accuracy is determined by calculating the percentage recovery obtained for analytes spiked into the sample matrix (i.e., matrix spike sample). Completeness is calculated by comparing the amount of valid data obtained with the amount that was expected to be obtained under correct normal conditions. Goals for completeness are generally set at 80 percent or higher.

The method detection limit (MDL) depends on the overall sensitivity and specificity of the analytical method used and the presence or absence of interfering compounds in the sample. The applicability of the analytical method proposed for use in a treatability study must be assessed in light of the expected concentrations of target and interference compounds in the

Analytical parameter	Method[a]	Precision, RPD[b]	Accuracy, percent recovery	Completeness, %
Herbicides	8150	<50	20-140	85
2,4-D				
Pesticides				
Heptachlor epoxide	8080	<31	35-130	85
DDE	8080	<50	23-134	85
DDT	8080	<50	23-134	85
DDD	8080	<50	23-134	85
PCBs				
Aroclor 1260	8080	<50	25-125	90
Aroclor 1016	8080	<50	25-125	90
Furans				
TCDF	8280	<25	60-140	85
PeCDF	8280	<25	60-140	85
HxCDF	8280	<25	60-140	85

[a] U.S. Environmental Protection Agency. 1986. Test Methods for Evaluating Solid Waste. 3rd. ed. SW-846.
[b] RPD = Relative percent difference.
Source: PEI Associates 1988.

Figure 14. Example analytical quality assurance objectives for a remedy-selection dehalogenation treatability study.

samples and the cleanup standard determined for the sample matrix. The QAPjP must specify the QA objectives for the MDLs.

5.2.2. Treatability Study Sampling Procedures

Methods for collecting aliquots of treated products and treatment residuals from chemical dehalogenation treatability tests will be specified in the QAPjP. Sample collection requires the use of stainless steel, glass, or Teflon sampling equipment and containers, as discussed previously in Subsection 5.1.1. Sample containers should be filled carefully to prevent any portion of the collected sample from coming in contact with the sampler's gloves, which could cause cross-contamination. Samples should not be collected or stored in the presence of exhaust fumes, and they should be kept cool to minimize losses of volatile organics. Decontamination of the experimental apparatus and sampling equipment involves the same considerations as described for field sampling equipment.

5.2.3 Treatability Sample Preservation and Holding Times

The preservation requirements and critical holding times for treated product and treatment residuals containing halogenated organic compounds are similar to those described in Subsection 5.1.3.

5.2.4 Analytical Procedures

Subsection 4.4 described the waste characterization and treated product and residuals analyses that should be considered during the development of the treatability study Work Plan. The QAPjP should specify the exact analytical procedures that will be followed for each matrix and critical measurement parameter. Table 7 lists standard EPA analytical methods that are generally used for halogenated organic compounds. These methods are compiled in *Test Methods for Evaluating Solid Waste* (EPA 1986). The vendor may propose modified or equivalent test methods for noncritical measurements; however, the EPA RPM must determine the acceptability of these alternative methods with respect to the test objectives and the available method validation data.

5.2.5 Toxicological Screening Procedures

Several standard bioassays are available for investigating the toxic or mutagenic characteristics of chemical dehalogenation products and residuals. The *Protocol for Bioassessment of Hazardous Waste Sites* (Porcella 1983) presents bioassays involving algae (*Selenastrum capricornutum*), macroinvertebrates (*Daphnia magna*), lettuce seed germination/root elongation (*Lactuca sativa*), earthworms (*Eisenia foetida*), and fathead minnow larvae (*Pimephales promelas*). The freshwater algae, daphnid, and minnow assays can be used to evaluate CERCLA soil elutriates; whereas the seed germination and earthworm tests assay the toxic effects of direct soil contact. Standard operating procedures for these and other bioassays, including a modified earthworm (*Eisenia andrei*) test, can be found in the draft *Region IV Standard Operating Procedure for Toxicity Testing Hazardous Waste Assessments* (EPA 1990e).

The Microtox™ (*Photobacterium phosphoreum*) microbial bioassay has been widely investigated for its applicability in

Table 7. Standard EPA Analytical Methods for Halogenated Organic Compounds

Method	Analyte
Gas chromatography	
Method 8010	Chlorobenzenes (halogen-specific detector)
Method 8020	Chlorobenzenes (photoionization detector)
Method 8120	Chlorobenzenes (electron-capture detector)
Method 8040	Chlorophenols
Method 8080	Organochlorine pesticides PCBs
Method 8150	Chlorinated herbicides
Gas chromatography/ mass spectrometry	
Method 8240	Chlorobenzenes
Method 8250/8270	Chlorophenols Chlorinated pesticides PCBs
Method 8280	PCDDs/PCDFs

Source: EPA 1986.

assessing the toxicity of wastewater, leachate, and contaminated ground water. Microtox results have been compared with those from other assays in several studies and found to provide a comparatively reliable indication of the presence of toxic organics. A procedure for this bioassay also is available in the draft Region IV SOP. The Microtox test has been extended to measure the toxicity of sediment and solid waste samples without the requirement of having to prepare sample extracts (Tung et al. 1990). An SOP for this test is available from the manufacturer.

The mutagenicity (Ames, in *Salmonella typhimurium* TA98 and TA100) and toxicity (in male Hartley Guinea pigs) of byproducts from the chemical dehalogenation of 2,3,7,8-TCDD have been evaluated by DeMarini and Simmons (1989). An SOP for the *Salmonella* assay is presented by Maron and Ames (1983).

Standard operating procedures for all bioassessments to be performed must be included in the QAPjP.

5.2.6 Data Validation and Internal Quality Control Checks

Criteria must be set for identifying outlier data (i.e., QC data lying outside the specific QA objectives for precision or accuracy for a given analytical method). Project outlier data are reported, but they generally are not used for interpreting overall project results.

Internal QC checks involve frequent calibration checks of field and analytical instruments used in the treatability studies. During the analyses of the untreated soil and die treated product, other QC checks may include analysis of additional samples such as standards, blanks, and matrix spikes.

Because standards and calibration curves are subject to change and can vary from day to day, a *check standard* should be analyzed with each group of samples. Calibration standards for quantitation of PCBs, PCDDs/PCDFs, and other halogenated organics should be obtained from reliable commercial or public sources.

Blanks are QC samples that are presumed to be. noncontaminated. *Trip blanks* are analyzed to monitor for possible sample contamination during shipment. *Field blanks* provide an indication of sample contamination during the sampling operation. *Rinsate blanks* are collected and analyzed to investigate cross-sample contamination from sampling tools. *Method blanks* verify that interferences caused by contaminants in solvents, reagents, glassware, and other processing hardware are known and minimized. *Reagent blank* samples are analyzed to investigate reagent contamination. If target contaminants are found in any blank samples at levels exceeding the MDL (2 x MDL for method blanks), the source of contamination must be determined and corrective actions implemented.

Spiked samples are prepared and analyzed to provide an indication of the analytical accuracy. For evaluation of the effect of the soil/sediment matrix on the analytical methodology, a separate aliquot of sample should be spiked with a known quantity of analyte. For PCB-contaminated samples, example spiking compounds would be Aroclor 1016 and Aroclor 1260. This *matrix spike* (MS) is then analyzed along with the sample. The percentage recovery of the spiked

analyte should fall within a predetermined QC limit. The relative percent difference between the MS and an MS *duplicate* (MS/MSD) will indicate the analytical precision.

Blank spikes--prepared with uncontaminated soil and appropriate spiking compounds--should be analyzed in conjunction with the MS/MSD. Relative percent recovery of the spiking compound can indicate matrix interferences.

Surrogate standard detennination should be performed on all samples and blanks for GC/MS analyses to monitor extraction efficiency. Samples are spiked with a surrogate analyte not present in the sample. An appropriate *surrogate spike* for PCB analysis may be decachlorobiphenyl. Percentage recoveries of the surrogate should be within predetermined limits. If recoveries are insufficient, corrective actions should be implemented.

SECTION 6
TREATABILITY DATA INTERPRETATION

The purpose of a pre-ROD treatability investigation is to provide the data needed for detailed analysis of alternatives and, ultimately, the selection of a remedial action that can achieve the site cleanup criteria. The results of a treatability study should enable the RPM to evaluate all treatment and nontreatment alternatives on an equal basis during the "detailed analysis of alternatives" phase of the FS.

6.1 USE OF PRE-ROD TREATABILITY STUDY RESULTS IN THE RI/FS PROCESS

The Work Plan outlines the treatability study test objectives and describes how these objectives will be used in the evaluation of chemical dehalogenation for remedy selection. As discussed in Section 3, the RI/FS guidance (EPA 1988a) specifies nine evaluation criteria to be considered in the assessment of remedial alternatives. These criteria were developed to address both the specific statutory requirements of CERCLA and the technical and policy considerations that are important when selecting among remedial alternatives. The nine RI/FS evaluation criteria are as follows:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume through treatment
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

The first two criteria, which relate directly to the statutory requirements each remedial alternative must meet, are categorized as threshold criteria. The next five are the primary criteria upon which the selection of a remedy is based. The final two criteria are evaluated after completion of the RI/FS and the proposed remedial plan.

Treatability studies provide important data for use in the assessment of an alternative against both the primary evaluation criteria and the threshold evaluation criteria. Table 8 lists factors important to the analysis of these criteria and the data from a chemical dehalogenation treatability study that provide information for this analysis. The results of treatability studies also may influence the evaluations against the state and community acceptance criteria. Evaluations against the nine criteria are performed for the overall remedy, of which the treatment technology is only one part. The overall remedy will generally include additional treatment or containment.

6.1.1 Primary Evaluation Criteria

The five primary evaluation criteria should be used for guidance in setting treatability study test objectives. This subsection describes how the results of a chemical dehalogenation treatability study test can provide specific information for evaluations against these criteria.

Long-Term Effectiveness and Permanence

This evaluation criterion addresses risks remaining at the site after the remedial response objectives have been met. Assessment of the residual risks from untreated waste and treated product left on site must involve the same assumptions and calculation procedures as those used in the baseline risk assessment. If engineered controls such as containment systems are to be used to manage these remaining materials, their adequacy and reliability should be evaluated.

Remedy-selection treatability tests provide data on the magnitude of the site's residual risk after chemical dehalogenation treatment. If treated product will remain on site, the contaminant concentrations in this material must meet the

site's cleanup criteria. As discussed in Subsection 4.1, these cleanup criteria translate into specific performance goals for remedy-selection treatability studies. The concentrations of target contaminants in the treated product and treatment residuals, as determined by treatability testing, indicate the ability of chemical dehalogenation to achieve the site cleanup criteria.

A second set of data available from treatability studies that can indicate the magnitude of residual risk is the presence of specific reaction byproducts in the treated product. As discussed in Subsections 4.4.3 and 4.4.4, halogenated organic byproducts may be formed during the treatment of the target contaminants. The presence and concentration of these "new" compounds may affect the residual risks associated with onsite disposal.

If an ecological risk assessment is to be performed, the residual risks posed to biota by the replacement of the treated product on site can be assessed under this criterion. The literature survey may provide adequate data to evaluate the biotoxicity of chemically dehalogenated soils. If little or no biotoxicity data exist in the literature for the contaminants/matrix of interest, however, bioassays can be performed at the remedy-selection tier to address this data need. A treatability study test objective that stipulates a reduction in the toxicity posed by the treated product to test organisms will provide data for the assessment of chemical dehalogenation against the long-term effectiveness and permanence criterion.

Table 8. Applicability of Chemical Dehalogenation Treatability Study Data to RI/FS Evaluation Criteria

Evaluation criteria	Analysis factors	Treatability study data
Long-Term Effectiveness and Permanence	Magnitude of residual risk	• Target containment concentrations in treated product and treatment residuals • Presence of specific reaction byproducts in treated product • Results of bioassays performed on treated product
Reduction of Toxicity, Mobility, or Volume Through Treatment	Reduction in toxicity	• Percent reduction in target contaminant concentrations • Comparison of bioassay results before and after treatment
	Irreversibility of the treatment	• Material balance data combined with target contaminant concentrations in treated product and treatment residuals
	Type and quantity of, and risks posed by, treatment residuals	• Target contaminant concentrations in treatment residuals • Presence of specific reaction byproducts in treatment residuals • Results of bioassays performed on treatment residuals • Volume of treatment residuals
Short-Term Effectiveness	Protection of community during remedial actions	• Physical/chemical characteristics of waste matrix • Physical/chemical characteristics of treatment residuals
	Protection of workers during remedial actions	• Physical/chemical characteristics of waste matrix • Physical/chemical characteristics of treatment residuals • Reagent formulation/material safety data
	Time until remedial response objectives are achieved	• Reaction time
Implementability	Reliability and potential for schedule delays	• Reliability and schedule delays during testing • Reaction time/throughput • Physical characteristics of waste matrix • Contaminant variability in untreated waste

Table 8. (continued)

Cost	Direct capital costs	• Reaction time/throughput • Reagent usage/recovery • Reaction temperature • Physical characteristics of waste matrix • Site characteristics
	Operation and maintenance costs	
	--Chemicals/reagents	• Reagent formulation/loading • Reagent usage/recovery • Volume and characteristics of treated product and treatment residuals
	--Utilities	• Reaction time/throughput • Reaction temperature
	--Residuals treatment/disposal	• Volume and physical/chemical characteristics of treatment residuals
	--Equipment	• Reaction time/throughput • Physical characteristics of waste matrix
	--Labor	• Reaction time/throughput
Compliance with ARARS	Chemical-specific ARARs	• Target contaminant concentrations in treated product and treatment residuals
	Location-specific ARARs	• Target contaminant concentrations in treated product and treatment residuals • Results of bioassay performed on treated product and treatment residuals
	Action-specific ARARs	• Target contaminant concentrations in treated product and treatment residuals
Overall Protection of Human Health and the Environment	Ability to eliminate, reduce, or control site risks	• Target contaminant concentrations in treated product and treatment residuals • Presence of specific reaction byproducts in treated product and treatment residuals • Results of bioassays performed on treated product and treatment residuals

Reduction of Toxicity, Mobility, or Volume Through Treatment

This evaluation criterion addresses the statutory preference for selecting technologies that, according to the RI/FS guidance, "...permanently and significantly reduce the toxicity, mobility, or volume of the hazardous substances as their principal element. This preference is satisfied when treatment is used to reduce the principal threats at a site through destruction of toxic contaminants, reduction of the total mass of toxic contaminants, irreversible reduction in contaminant mobility, or reduction of total volume of contaminated media."

Because chemical dehalogenation reduces the toxicity of halogenated compounds, this evaluation criterion is particularly applicable. Treatability studies should provide detailed performance data on the percentage reduction in the toxicity of the treated product. As presented in Subsection 3.2, a performance goal of greater than 90 percent reduction in the target contaminant concentrations should be achieved at the rernedy-screening tier. If this test objective is met, chemical dehalogenation is considered a feasible alternative. At the remedy-selection tier, the process should be capable of achieving the site cleanup criteria with an acceptable level of confidence.

Another measure of reduction in toxicity is the comparison of bioassay results from tests performed on the waste before and after chemical dehalogenation. If treated product is to remain on site, a reduction in biotoxicity should be identified as a treatability test objective for remedy selection.

Irreversibility of the treatment process is another factor in the evaluation of chemical dehalogenation against this criterion. Material balance data from a treatability study, combined with the target contaminant concentrations found in the treated product and treatment residuals, can indicate the level of irreversibility achieved through treatment. These data can be used to construct a mass balance for the target contaminants, which will accurately describe the target contaminant destruction efficiency of die treatment process.

Taking the treatment residuals into consideration is an important part of the assessment of chemical dehalogenation against the reduction in toxicity, mobility, and volume criterion. Concentrations of target contaminants in these residuals, along with the presence of selected reaction byproducts, indicate the risks posed by their onsite treatment. Data on the biotoxicity and volume of treatability study residuals also provide information for this assessment.

Short-Term Effectiveness

The short-term effectiveness criterion is concerned with the effects of the alternative on human health and the environment during its construction and implementation. The RI/FS guidance outlines several factors that may be addressed, if appropriate, when assessing an altemative against this criterion. Chemical dehalogenation treatability studies can provide information on three of these factors: 1) protection of the community during remedial actions, 2) protection of the workers, and 3) the time required to achieve remedial response objectives.

If a site is located near a population center, any short-term health risks posed by the remedial action must be addressed. The treatability study waste characterization can identify some of these risks. For example, physical characteristics of the waste matrix, such as moisture content and particle-size distribution, could indicate a potential for the generation of contaminated dust during material-handling operations. The presence of volatile contaminants in the waste also could pose risks to community health during material handling and treatment. Treatment residuals must be carefully characterized to permit the design of proper air and water treatment systems.

For the protection of workers during implementation of the remedy, the physical and chemical characteristics of the untreated waste matrix and the treatment residuals are important data to be collected during treatability testing. Material safety data on the reagent formulation to be used and handled by workers also should be collected and reviewed. These data will aid in the assessment of any threats posed to workers and the effectiveness and, reliability of protective measures that will be taken. Treatability systems can also be monitored for any adverse reactions that may occur when the waste is mixed with the chemical reagents and heated.

The time required to achieve the remedial response objectives for the site depends on the volume of soil to be treated and the throughput of the full-scale unit or treatment train system. Estimates of throughput will use treatability data such as the reaction time required to dehalogenate the waste adequately.

Implementability

This evaluation criterion assesses the technical and administrative feasibility of implementing an alternative and the availability of the equipment and services required during implementation. The following factors are evaluated in the analysis of the implementability of chemical dehalogenation:

- Difficulties associated with construction and operation
- Reliability and potential for schedule delays
- Ability to monitor treatment effectiveness
- Commercial availability of the treatment process and equipment

The literature survey should provide historical information regarding many of the preceding factors. If a chemical dehalogenation alternative has been shown to be capable of achieving the desired cleanup levels but has never been demonstrated at full scale, reliability data may be insufficient for its assessment under the implementability criterion. In this case, data from a pre-ROD pilot-scale test must be used.

The reliability of the pilot system, including any schedule delays encountered during its testing, will serve as an indicator of the implementability of the full-scale system. The reaction time and throughput can also provide information on potential schedule delays. Characteristics of the matrix that could lead to equipment failure or diminished treatment effectiveness, such as high clay content, should be investigated during the treatability study. Contaminant variability in the untreated waste could also lead to schedule delays by requiring repeated treatment of some soils. Treatability testing of multiple waste types with differing contaminant concentrations can provide important data for analysis of the reliability factor and the implementability evaluation criterion.

Cost

The cost criterion evaluates the full-scale capital and operation and maintenance (O&M) costs of each remedial action alternative. The assessment of this criterion requires the development of cost estimates for the full-scale remediation of the site. These estimates should provide an accuracy of +50 percent to -30 percent. A comprehensive discussion of costing procedures for CERCLA sites is included in the *Remedial Action Costing Procedures Manual* (EPA 1985).

The cost estimate prepared under this criterion will be based on information obtained from the literature and the technology vendor. Preparation of the estimate may require bench-or pilot-scale treatability study data generated at the remedy selection tier.

Direct capital costs for chemical dehalogenation treatment will include expenditures for the equipment, labor, and materials necessary to install the system. If the technology vendor already has a mobile, full-scale treatment unit constructed, treatability study data will not be required to determine direct equipment costs. If no full-scale system exists, however, treatability studies can provide data necessary for equipment scale-up. Operational data, such as reaction time and throughput, reagent usage and recovery, and reaction temperature, will be required to size and select full-scale equipment. Characteristics of the matrix, such as particle-size distribution and moisture content, that are identified during treatability testing will have an impact on decisions regarding front-end material handling operations and equipment and post-dehalogenation equipment for processing of the product and residuals in a treatment train. Characteristics of the site that may have an impact on the logistical costs associated with mobilization and onsite treatment can be identified during the sample-collection visit.

Treatability studies can provide significant data on such O&M costs as chemicals and reagents, utilities, residuals disposal, and maintenance equipment and labor.

Full-scale chemical and reagent costs can be estimated by using reagent formulation and loading and reagent recovery data from treatability studies. The volume and physical characteristics of the treated product and treatment residuals will affect posttreatment chemical costs (i.e., acid for neutralization, activated carbon for air pollution control, etc.).

The costs of electricity, fuel, and water depend on the throughput of the treatment process. At the remedy-selection tier, throughput can be estimated with data on reaction time and the volume of waste to be treated. Utility costs will also be affected by the reaction temperature.

Treatment/disposal costs for the dehalogenation residuals will depend on the volumes of residuals generated and on the physical/chemical characteristics of these materials. These data are available from remedy-selection treatability studies.

Operation and maintenance equipment costs include replacement parts, tools, and personnel protection equipment.

Estimates of these costs will reflect the physical characteristics of the waste matrix (which affect the difficulty of treatment) and the throughput (which affects the total time for treatment). Operation and maintenance labor can be projected from treatability study reaction time and throughput.

6.1.2 Threshold Evaluation Criteria

In addition to the primary evaluation criteria discussed in the preceding subsection, treatability studies can also provide data for assessing an alternative against the two statutory-based threshold evaluation criteria.

Compliance with ARARs

Applicable or relevant and appropriate requirements are any local, State, or Federal regulations or standards that pertain to chemical contaminant levels, locations, and actions at CERCLA sites. Chemical-specific ARARs that may be applicable to chemical dehalogenation include RCRA LDRs on the placement of treated soil, and Safe Drinking Water Act Maximum Contaminant Levels and Clean Water Act Water Quality Criteria for discharge of treatment wastewater. Applicable location-specific requirements may include the substantive Clean Water Act §404 prohibitions on the unrestricted discharge of dredged or fill material into wetlands and the RCRA location limitations on where onsite storage, treatment, or disposal of hazardous waste may occur. Action-specific ARARs include technology- and activity-based requirements or limitations on actions taken with respect to hazardous wastes. The Toxic Substances Control Act and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) may provide a number of potentially applicable action-specific ARARs for chemical dehalogenation treatment at Superfund sites.

Treatability study test objectives will generally be based on ARARs. Chemical-specific ARARs will be expressed in terms of contaminant concentrations in the treated product and treatment residuals. Often, these ARARs will define the "target" contaminants for the treatability study. Location-specific cleanup criteria may also include biotoxicity requirements for treated product and treatment residuals if, for example, runoff from the disposal site could have an impact on a sensitive wildlife habitat. Action-specific requirements may be particularly applicable to the treatment and discharge of residuals such as wastewater. Target contaminant concentrations in the treatability study wastewater will aid in identifying action-specific ARARs. Performance data indicating how well the process achieved the treatability study test objectives will aid in evaluating chemical dehalogenation against the compliance with ARARs criterion.

Overall Protection of Human Health and the Environment

This evaluation criterion provides an overall assessment of how well each alternative achieves and maintains protection of human health and the environment. The analysis of overall protection will draw on the assessments conducted under the primary evaluation criteria and the compliance with ARARs. Its focus will be on the ability of an alternative to eliminate, reduce, or control overall site risks.

Chemical dehalogenation treatability studies will provide general data for the evaluation under this final criterion. Target contaminant and reaction byproduct concentrations in the treated product and treatment residuals will demonstrate how well the process or treatment train can eliminate site risks. If an ecological risk assessment is being conducted, bioassessments of these materials will generate the data required to evaluate the reduction in risk to site biota.

6.2 USE OF PRE-ROD TREATABILITY STUDY RESULTS IN THE RD/RA PROCESS

Pre-ROD treatability study results provide information for the subsoquent detailed design investigations of the selected remedial technology. Operating conditions in the pre-ROD chemical dehalogenation treatability studies should be completely documented so these data can be used in planning the post-ROD remedy design treatability studies. Pre-ROD data on the chemical, physical, and toxicological characteristics of treatment residuals will be useful in planning remedy design studies in which large volumes of residuals will be handled and disposed of. Problems encountered during remedy-selection treatability studies--such as difficulties in mixing, heating, reagent separation and recovery, and health and safety--should also be carefully documented for post-ROD pilot- and full-scale investigations at the RD/RA tier.

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APPENDIX

SUMMARY OF CHEMICAL DEHALOGENATION TREATABILITY TESTING OF SOILS/SLUDGES

Site	Not available
Region	Not available
Location	Not available
Background	Not available
Waste Type	Neat pure form
Contaminants	HCB, 4,4'-DCBP, HCP, and PCB Aroclor 1254. (The quantities of the compounds ranged from 0.100 to 1200 millimoles.)
Equipment	Reaction flask, thermometer, stirrer, thermostated oil bath, argon gas cylinder
Reagent	Aqueous NaOH or KOH with PEG-400
Conditions	Reaction temperature was varied between 25 and 140EC. Reaction time was varied from 1 to 90 hours. The mixture was treated under purge of argon gas. In most experiments, the reagent was present in tenfold excess.
Results	The anhydrous PEG effectively dechlorinated HCB and converted it to water-soluble products. The substrate reactivity was drastically reduced as the number of chlorine substituents decreased. Dissolving the reagents in toluene improved their reactivity, whereas the presence of air or water decreased their reactivity. Of the chlorinated substrates studied, the reactivity order (maximum chlorides released per molecule) was as follows: HCB(4.5)>> Aroclor 1254(1.3)>>4,4'-DCBP (0.2)>HCP(0).
Reference	MaComber, R., M. Orchin, and G. Garrett. 1983. The Reaction of Alkali Metal Derivative of Polyethylene Glycol 400 With Chlorinated Aromatic Compounds. A report on research conducted for the U.S. EPA, January 1-June 17, 1983.

DCBP = Dichlorobiphenyl
HCB = Hexachlorobenzene
HCP = Hexachlorophene
KOH = Potassium hydroxide
NaOH = Sodium hydroxide
PCB = Polychlorinated biphenyls
PEG = Polyethylene glycol

Site	MGM Brake Site
Region	IX
Location	Cloverdale, CA
Background	The soil from the MGM Brake Site was a heavy clay loam contaminated with PCBs (Aroclor 1242 and 1248). The soil was also found to contain PCTPs (the concentration of PCTPs was not determined in this study).
Waste Type	Soil (heavy clay loam)
Contaminants	PCBs (. 640 ppm Aroclor 1242 and 1248) and PCTPs
Equipment	Bench-scale
Reagent	KOH and PEG-400
Conditions	Sample size was 20 g. Reagent-to-soil ratio was 1:1 by weight. Reaction time was 4 hours. Reaction temperature was varied between 125 to 145EC. Following the reaction, the reaction flask was cooled and the soil was neutralized with 10 to 20 percent hydrochloric acid solution.
Results	The KPEG treatment reduced the concentrations of PCTP in the soil to below the detectable range. The PCB concentrations in the soil were reduced by varying amounts, possibly because of poor mixing.
Reference	Rogers, C., A. Kornel, and H. Sparks. 1989. Treatability Study on Soils From MGM Site. Prepared by the U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, Ohio.

KOH = Potassium hydroxide
KPEG = Potassium polyethylene glycol
PCB = Polychlorinated biphenyls
PCTP = Ploychlorinated triphenyl
PEG = Polyethylene glycol

Site	1) Unidentified; 2) Bengart and Memel; and 3) Brown Boveri, Inc.
Region	II, III
Location	1) New Jersey; 2) Buffalo, NY; and 3) Philadelphia, PA
Background	1) Uncontaminated soil spiked with PCBs; 2) soil; and 3) soil containing 14.5 percent water
Waste Type	1) PCB Aroclor 1260 (~1000 ppm); 2) PCB Aroclor 1260; and 3) PCB Aroclor 1260 (1150)
Contaminants	1) PCB Aroclor 1260 (~1000 ppm); 2)PCB Aroclor 1260 (1150 ppm)
Equipment	Laboratory-scale
Reagent	10 percent (W/W) KPEG or NaPEG
Conditions	Sample size was 100 to 500 g. Reagent-to-soil ration was 10 percent (W/W). Reaction temperatures were ambient, 65EC, and 80EC. Reaction time was 1 to 180 days.
Results	1) The PCB-spiked soil containing 1000 ppm of Aroclor was decontaminated (to <50 ppm) in only a few days by a direct application of KPEG-350-1, and the reagent can be used to treat PCBs in soils containing water and organics. The reagent NaPEG-1.00-N was not as effective as the KPEG-350-1 reagent. The reagents used were ranked as follows: KPEG-350-1>NaPEG-3501>NaPEG-400-1. 2) Significant reductions in PCB concentrations were achieved after the NaPEG treatment. 3) The reagent was unable to reduce the PCB content in a wet soil. Treatment effectiveness increased at higher temperatures (80 vs. 65EC).
Reference	Iaconiani, F.J. 1984, 1985. Destruction of PCBs--Environmental Application of Alkali Metal Polyethylene Glycolate Complexes. Prepared for the U.S. Environmental Protection Agency, HWERL, Cincinnati, OH. Cooperative Agreement: CR 810068. Franklin Research Center, Philadelphia, PA.

KPEG = Potassium polyethylene glycolate
NaPEG = Sodium polyethylene glycolate
PCB = Polychlorinated biphenyls

Site	PCB-contaminated site
Region	II
Location	Buffalo, NY
Background	Not available
Waste Type	Soil
Contaminants	PCBs (28 to 66 ppm)
Equipment	55-gallon drum, heating tape, and mixer
Reagent	KPEG
Conditions	Sample size was 150 lb. Reagent-to-soil ratio was 1:3. Reaction time was 2 to 2.5 hours. Reaction temperature was varied between 75 and 100EC.
Results	The concentrations of PCBs were reduced from between 28 and 66 ppm to less than 1 ppm after 2.5 hours. More than 80 percent of the reagent was recovered for reuse. Preliminary costs for the process were on the order of $200/ton of soil.
Reference	Rogers, C. J., D. L. Wilson, and A. Kornel. Preliminary Report on Treatment/Detoxification Alternatives for PCBs and Chlorinated Organics. Prepared by the U.S. EPA, HWERL, Cincinnati, OH.

KPEG = Potassium polyethylene glycolate
PCB = Polychlorinated biphenyl

Site	Not available
Region	II
Location	Buffalo, NY
Background	Not available
Waste Type	Soil spiked with PCDDs
Contaminants	PCDDs (2000 ppb)
Equipment	Laboratory-scale
Reagent	KPEG
Conditions	Sample size was 250 g. Reaction temperature was 75EC. Reaction time was 1 to 2 hours.
Results	The analysis indicated that the concentration of PCDDs was reduced from 2000 ppb to below 1 ppb in the soil samples.
Reference	Rogers, C. J., D. L. Wilson, and A. Kornel. Preliminary Report on Treatment/Detoxification Alternatives for PCBs and Chlorinated Organics. Prepared by the U.S. EPA, HWERL, Cincinnati, OH.

KPEG = Potassium polyethylene glycolate
PCDD = Polychlorinated dibenzodioxin

Site	New Bedford Harbor
Region	I
Location	New Bedford, MA
Background	Not available
Waste Type	Sediment
Contaminants	PCBs at <500 ppm (low-PCB) and >1000 ppm (high-PCB)
Equipment	Laboratory-scale (500 mL), bench-scale (5000 mL)
Reagent	KPEG with DMSO
Conditions	Sample size was 6 lb (wet weight). Reagent-to-soil ratio was 1:1. Reaction temperature was 165EC. Reaction times were 9 hours (low-PCB) and 12 hours (high-PCB). Number of water washes for treated product was two.
Results	Lab screening was conducted to determine reagent formulation, temperature, mixing conditions, and separation procedures. PCB concentration was reduced to <1 ppm (low-PCB) and 4 ppm (high-PCB). Estimated cost for full-scale treatment was $80 to $104/ton.
Reference	Galson Research Corporation. 1988. Final Report: Laboratory Testing Results: KPEG Treatment of New Bedford Soil. Prepared under REM III Contract No. 68-01 7250.

DMSO = Dimethyl sulfoxide
KPEG = Potassium polyethylene glycolate
PCB = Polychlorinated biphenyl

Site	Not available
Region	Not available
Location	Not available
Background	Uncontaminated soil samples were obtained from the vicinity of a dioxin site in Mississippi and spiked with 1,2,3,4-TCDD prior to tests.
Waste Type	Soil
Contaminants	1,2,3,4-TCDD
Equipment	Laboratory-scale
Reagent	KOH:PEG:DMSO (1:1:1), and KOH:MEE:DMSO (1:1:1)
Conditions	Reagent-to-soil ratio was 1:1. Reaction temperature was varied between 25 and 260EC. Reaction times were 0.5, 2, and 4 hours.
Results	Within as little as 2 hours at 70EC, the concentrations of TCDD were reduced from 2000 ppb to <1 ppb (removal efficiency of >99.95%). The bulk of this removal occurred in the first 30 minutes when >99% of the TCDD had been reacted. Reagent recovery by washing resulted in 94 to 99% recovery of reagent.
Reference	Peterson, R. L., E. Milicic, and C. J. Rogers. 1985. Chemical Destruction/Detoxification of Chlorinated Dioxins in Soils. In: Proceedings of Incineration and Treatment of Hazardous Waste, the Eleventh Annual Research Symposium, September 1985. EPA/600/9-85/028.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
MEE = Methyl carbitol
PEG = Polyethylene glycol
TCDD = Tetrachlorodibenzo-p-dioxin

Site	Not available
Region	Not available
Location	Not available
Background	Uncontaminated soil samples were obtained from the vicinity of a dioxin site in Mississippi and spiked with 1,2,3,4-TCDD prior to tests.
Waste Type	Soil
Contaminants	1,2,3,4-TCDD
Equipment	Laboratory-scale
Reagent	KOH:MEE:DMSO:Water (2:2:2:1, 2:2:2:6, and 2:2:2:30) and KOH:PEG:DMSO (1:1:1)
Conditions	Reagent-to-soil ratio was 1:5. Reaction temperatures were 20 and 70EC. Reaction times were 1, 2, 4, and 7 days.
Results	Results of the analysis indicated that the efficiency of the process increased significantly at 70 versus 20EC (removal efficiency for the process increased from 50% to >80%) and concentration of TCDDs in samples treated at 70EC for 7 days were reduced from 2000 ppb to <1 ppb during the study.
Reference	Peterson, R. L., E. Milicic, and C. J. Rogers. 1985. Chemical Destruction/Detoxification of Chlorinated Dioxins in Soils. In: Proceedings of Incineration and Treatment of Hazardous Waste, the Eleventh Annual Research Symposium, September 1985. EPA/600/9-85/028.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
MEE = Methyl carbitol
PEG = Polyethylene glycol
TCDD = Tetrachlorodibenzo-p-dioxin

Site	Not available
Region	VII
Location	Omaha, NE
Background	Not available
Waste Type	Herbicide waste
Contaminants	2,4-D (17,800 ppm); 2,4,5-T (2800 ppm); and 2,3,7,8-TCDD (1.3 ppm)
Equipment	Pilot-scale, 55-gallon drum, a clamp-on heating band, and a stirring motor.
Reagent	KPEG
Conditions	Sample size was 20 gallons. Reaction temperature was varied between 70 and 85EC. Reaction time was 2 days.
Results	The KPEG reagent reduced concentrations of 2,3,7,8-TCDD in the waste to less than the detectable range. The concentrations of 1.3 ppm 2,3,7,8-TCDD; 17,800 ppm 2,4-D; and 2800 ppm 2,4,5-T were reduced to none detectable, 334 ppm, and 44 ppm, respectively. The study also proved the efficacy of the KPEG process in treatment of the soils without the use of DMSO or TMH.
Reference	Taylor, M. L., et al.. 1989. Field Application of the KPEG Process for Treating Chlorinated Wastes. Prepared for the U.S. EPA, RREL, under contract No. 68-03-3413.

D = Dichlorophenoxyacetic acid
DMSO = Dimethyl sulfoxide
KPEG = Potassium polyethylene glycol
T = Trichlorophenoxyacetic acid
TCDD = Tetrachlorodibenzo-p-dioxin
TMH = Triethylene glycol methyl ether

Site	Wide Beach Development
Region	II
Location	Irving, NY
Background	The Wide Beach Development site is a residential development of the shores of Lake Erie. Waste oil applied to local roads as a dust suppressant contaminated the site with PCBs. Approximately 30,000 yd^3 of PCB-contaminated soil (mainly in the top layer) is present on the site.
Waste Type	Soil
Contaminants	PCBs
Equipment	Bench-scale
Reagent	PEG-400:TMH:DMSO:KOH (1:1:2:2)
Conditions	Sample size was 300 g. Reagent-to-soil ratio was 1:1 (W/W). Reaction temperatures were 140, 150, and 160EC. Reaction times were 4 hours for the soil with an initial PCB concentration of 24 ppm and 8 hours for the soil with an initial PCB concentration of 690 ppm. The optimum reaction temperature for the process was 150EC.
Results	PCB concentrations in each soil were reduced to below 10 ppm. The results of the analyses performed on the reagents and washing liquids indicate that the PCBs were actually destroyed in the soil, not merely extracted.
Reference	Galson Research Corporation. 1988. Laboratory-Scale Testing Report. KPEG Processing of Wide Beach Development Site Soils. East Syracuse, NY. 980-TSI-RT-FCCC.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
PCB = Polychlorinated biphenyl
PEG = Polyethylene glycol
TMH = Triethylene glycol methyl ether

Site	Wide Beach Development
Region	II
Location	Irving, NY
Background	The Wide Beach Development site is a residential development on the shores of Lake Erie. Waste oil applied to local roads as a dust suppressant contaminated the site with PCBs. Approximately 30,000 yd^3 of PCB-contaminated soil (mainly in the top layer) is present in the site.
Waste Type	Soil
Contaminants	PCBs (maximum of 260 ppm)
Equipment	Pilot-scale
Reagent	KOH/Water/PEG/TMH/DMSO (1:1:1:1:2)
Conditions	Optimum feed rate for the reagent and soil was 1200 lb reagent per ton of soil to be processed. Mixing rate was 50 rpm. Reaction temperature was 150EC. Reaction time was 1 to 6 hours (including 2 to 3 hours heat-up time). Number of water washes for treated product was three.
Results	The analytical results indicated that the PCB concentration was reduced from 260 ppm to between 0.7 and 5.7 ppm in 3 to 6 hours. Reagent recoveries for solvents were as high as 100 percent, and KOH recovery was as high as 85 percent. The cost of the process was estimated to vary from \$273 to \$301/yd^3 of soil.
Reference	Ebasco Services, Inc. 1989. Final Design Report. Remedial Design, Wide Beach Development Site, Wide Beach, New York. Prepared for EPA under Contract No. 68-01-7250.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
PCB = Polychlorinated biphenyl
PEG = Polyethylene glycol
TMH = Triethylene glycol methyl ether

Site	Re-Solve
Region	I
Location	Dartmouth, MA
Background	Not available
Waste Type	Silty sand (almost saturated with water)
Contaminants	Several chlorinated and nonchlorinated organic solvents and high concentrations of PCBs (. 3000 ppm).
Equipment	Bench-scale
Reagent	PEG-400:TMH:DMSO:KOH (1:1:2:1.33)
Conditions	Sample size was 300 g (the soil was screened prior to test by using a sieve with 0.25-in. openings). Reagent-to-soil ratio was 1:1. Reaction temperature was varied between 25 and 128EC. Reaction time was 8 hours. Number of water washes for treated product was two.
Results	PCB concentrations were reduced from 2900 ppm to <1 ppm. PCB destruction did not begin until most of the water was distilled out of the reagent/soil slurry.
Reference	Galson Research Corporation. 1987. Treatability Test for APEG Dechlorination of PCBs in Re-Solve Site Soil. 6601 Kirkville Road, E. Syracuse, NY.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
PCB = Polychlorinated biphenyl
PEG = Polyethylene glycol
TMH = Triethylene glycol methyl ether

Site	U.S. Navy Public Works Center (USN-PWC)
Region	IX
Location	Island of Guam, U.S.A.
Background	Soil contamination, which occurred mainly in a nearby storm drainage ditch, resulted from leaks from a building where transformers were reworked.
Waste Type	Soil
Contaminants	PCBs (average was 2500 ppm, peak was 45,860 ppm)
Equipment	Field-scale mixer, platform, liquid reagent, loading system, heating system, nitrogen system, condensate collection system, process cooling water system, reagent collection system, and a neutralization system.
Reagent	KOH:PEG-400 (1.3 to 1 molar ratios)
Conditions	Reagent-to-soil ratio was 0.5:1 (on weight basis). Mixing rate was 60 rpm. Reaction temperature was 150EC. Reaction time was 4 to 6 hours. After treatment, the pH of the soil was adjusted to between 6 and 9 by using sulfuric acid.
Results	Results of analysis indicated that the destruction of the total PCB concentration exceeded 99 percent. In addition, analysis of each of the congener peaks showed that the tetrachlorobiphenyl congeners concentration in a portion of the treated batches was slightly above the R&D permit requirement of 2 ppm or lower per PCB peak.
Reference	Taylor, M. L., et al. 1989. Comprehensive Report on the KPEG Process for Treating Chlorinated Wastes. Prepared for the U.S. EPA, RREL, under Contract No. 68-03-3413.

KOH = Potassium hydroxide
PCB = Polychlorinated biphenyl
PEG = Polyethylene glycol

Site	Not available
Region	Ill
Location	Mechanicsburg, PA
Background	Not available
Waste Type	Soil
Contaminants	PCB Aroclor 1260 (200 to 900 ppm); assorted aromatic and aliphatic hydrocarbons.
Equipment	Bench-scale
Reagent	KPEG and NaPEG
Conditions	Sample size was varied between 10 and 100 g. Reagent-to-soil ratio was varied between 1:1 and 0.5:1 (W/W). Reaction temperatures were 120 and 180EC. Reaction times were between 3 and 6 hours. After the sample was mixed, the reaction flask was allowed to cool for 15 to 45 minutes. The reaction mixture was neutralized with 10 to 20 percent HCI to bring the pH to less than 9.
Results	The PCB-contaminated soil was found to be amenable to KPEG/ NaPEG treatment. The PCB concentrations in the soil were reduced from as high as 900 ppm to less than 2 ppm per residual PCB congener.
Reference	Taylor, M. L., et al. 1989. Comprehensive Report on the KPEG Process for Treating Chlorinated Wastes. Prepared for the U.S. EPA, RREL, under Contract No. 68-03-3413.

KPEG = Potassium polyethylene glycolate
NaPEG = Sodium polyethylene glycolate
PCB = Polychlorinated biphenyl

Site	Timberline Stables
Region	VII
Location	Missouri
Background	Not available
Waste Type	Soil and liquid samples
Contaminants	Organic chlorine (15.3 ppm) and 2,3,7,8-TCDD (277 ppb) in soil samples.
Equipment	Laboratory-scale
Reagent	K-400 and K-120
Conditions	Reaction times were 2 days for neat solutions and 7 and 28 days for soil samples.
Results	With K-400 as the reagent, the concentration of TCDD in the soil samples was reduced by 45 and 35 percent after 7 and 28 days, respectively. With K-120, however, the concentration of TCDD was reduced by 46 and 38 percent after reaction times of 7 and 28 days, respectively.
Reference	Klee, A., C. Rogers, and T. Tiernan. 1984. Report on the Feasibility of APEG Detoxification of Dioxin-Contaminated Soils. Prepared for the U.S. Environmental Protection Agency, IREL. EPA-600/2-84-071.

TCDD = Tetrachlodibenzo-p-dioxin

Site	Denny Farm Site
Region	VII
Location	Missouri
Background	Not available
Waste Type	Soil
Contaminants	Organic chlorine (1380 ppm) and 2,3,7,8-TCDD (330 ppb) in soil samples.
Equipment	Laboratory-scale
Reagent	K-400 and KM-350
Conditions	Reaction times were 7 and 28 days.
Results	With K-400 as the reagent, the concentration of TCDD in the soil samples was reduced by 12 percent after 28 days. With K-120, the concentration of TCDD was released by 51 and 5 percent after 7 and 28 days, respectively.
Reference	Klee, A., C. Rogers, and T. Tiernan. 1984. Report on the Feasibility of APEG Detoxification of Dioxin-Contaminated Soils. Prepared for the U.S. Environmental Protection Agency, IERL. EPA-600/2-84-071.

TCDD = Tetrachlodibenzo-p-dioxin

Site	Bengart & Memel
Region	II
Location	Buffalo, NY
Background	The site was occupied by a wholesaler of nonferrous scrap metals. From 1950 through 1978, Bengart & Memel received and dismantled PCB transformers and capacitors. Analyses of the soil samples indicate that the site is contaminated with PCBs in concentrations greater than 50 ppm.
Waste Type	Soil
Contaminants	PCBs
Equipment	55-gallon drums; no mechanism for agitation
Reagent	Sulfoxide (sulfolane or DMSO); a glycol or capped glycol [e.g., PEG-400, TMH, and/or methyl carbitol (MEE)]; solid or aqueous KOH; and water (2:2:4:9:5 PEG:TMH:DMSO:45 percent KOH: water).
Conditions	Sample size was fifty-one 55-gallon drums of soil, 10 m^3 each. Reagent-to-soil ratio was 1:5 (W/W). Reaction temperature was 105 to 110EC. Reaction time was 2 to 3 days. One group of drums was then held at outdoor temperatures for approximately 5 months.
Results	The APEG processing was successful in reducing PCB levels in 51 of 52 drums to below the 50 ppm control limit set for the site. For those 51 drums, the average PCB levels were reduced 75 percent, from 108 to 27 ppm. The PCB level for the sole remaining drum was reduced by 93 percent, from 1300 to 78 ppm. The total cost was $50,052 without neutralization and $75,056 with neutralization.
Reference	Novosad, C. F., et al. 1987. Decontamination of a Small PCB Soil Site by the Galson APEG Process. Preprint Extended Abstract, 194th National Meeting of the American Chemical Society, August 30-September 4, 1987, 27(2):435-437.

APEG = Alkali metal polyethylene glycolate
DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
PCB = Polychlorinated byphenyl
PEG = Polyethylene glycol
TMH = Triethylene glycol methyl ether

Site	Moreau
Region	II
Location	South Glens Falls, NY
Background	The Moreau site is a former dragstrip. The area was oiled periodically with PCB-contaminated oils. The PCB concentrations at the site ranged from nondetectable up to tens of thousands parts per million.
Waste Type	Soil
Contaminants	PCBs
Equipment	Pilot-scale (40-in.-long x 16-in.-dia. reactor)
Reagent	KOH (0.45), PEG, DMSO, TMH, and water at different ratios were used during the study.
Conditions	Sample size was 32.5 to 39.0 lb. Reagent-to-soil ratio was .1:1 (W/W). Temperature was 150EC. Reaction time was 4 to 8 hours. Gases from the reactor were vented through an ice-cooled air condenser and a Nixton drum.
Results	The results of the analyses performed indicated a 93.9 to 99.8 percent reduction in PCB concentration in the soil. Average reduction was 98.3 percent. The reagent recovery averaged 61 percent and ranged from 47 to 68 percent during the experiments.
Reference	Taylor, M. L., et al. 1989. Comprehensive Report on the KPEG Process for Treating Chlorinated Wastes. Prepared for the U.S. EPA, RREL, under Contract No. 68-03-3413.

DMSO = Dimethyl sulfoxide
KOH = Potassium hydroxide
PCB = Polychlorinated biphenyl
PEG = Polyethylene glycol
TMH = Triethylene glycol methyl ether

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15. SUPPLEMENTARY NOTES

Dave Smith FTS: 330-1475 Commercial #: (303) 293-1475

16. ABSTRACT

Systematically conducted, well-documented treatability studies are an important component of remedy evaluation and selection under the Superfund program. This manual focuses on chemical dehalogenation treatability studies conducted in support of remedy selection that is conducted prior to the Record of Decision (ROD).

This manual presents a standard guide for designing and implementing a chemical dehalogenation treatability study. The manual presents a description of and discusses the applicability and limitations of chemical dehalogenation 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 evaluation of chemical dehalogenation technologies. The specific goals of 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 treatability study.

17. KEY WORDS AND DOCUMENT ANALYSIS

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