United States
Environmental Protection
Agency

Office of
Research and Development
Washington, DC 20460

EPA/625/6-91/026
August 1991

EPA

Handbook

Stabilization Technologies for RCRA Corrective Actions

EPA/625/6-91/026
August 1991

Handbook

Stabilization Technologies for RCRA Corrective Actions

August 1991

Prepared for:
U.S. Environmental Protection Agency
Office of Research and Development
Center for Environmental Research Information
Cincinnati, OH 45268

Prepared by:
Metcalf & Eddy, Inc.
Wakefield, MA

Printed on Recycled Paper

NOTICE

This document is intended to assist regional, state, and facility personnel in identifying, evaluating, and implementing stabilization technologies. However, EPA will not necessarily limit stabilization technology evaluations to those that comport with the guidance set forth herein. This document is not a regulation (i.e., it does not establish a standard of conduct that has the force of law) and should not be used as such. Regional, state, and facility personnel must exercise their discretion in using this guidance document as well as other relevant information in determining whether interim or final stabilization corrective actions meet the regulatory standard.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Environmental Protection Agency.

ACKNOWLEDGMENTS

This document is a compilation of material applicable to RCRA stabilization actions. Mr. Willard Baker of Metcalf & Eddy, Inc., Wakefield, Massachusetts, and Ms. Heidi Schultz of Eastern Research Group, Inc., Arlington, Massachusetts, provided project management. Mr. Edwin Barth of the Center for Environmental Research Information, Cincinnati, Ohio, provided overall technical direction for the project. Editorial and production assistance was provided by Karen Ellzey, Susan Richmond, and Denise Short of ERG.

Development of Material

Stabilization Technology Implementation

Ms. Polly Whitmore, P.E., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Containment

Mr. Nicholas C. D'Agostino, P.E., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Mr. Warren Diesl, C.G., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Soils Treatment

Mr. Karl DeBisschop, Metcalf & Eddy, Inc., Wakefield, Massachusetts

Ms. Diane Dopkin, Metcalf & Eddy, Inc., Wakefield, Massachusetts

Ms. Cinthia McLane, P.E., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Ground-Water Treatment

Mr. Warren Diesl, C.G., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Mr. Donald Dwight, P.E., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Ms. Cinthia McLane, P.E., Metcalf & Eddy, Inc., Wakefield, Massachusetts

Technical Reviewers

Mr. Edwin F. Barth, P.E., U.S. EPA, Center for Environmental Research Information, Cincinnati, Ohio

Dr. Milovan S. Beljin, University of Cincinnati, Cincinnati, Ohio

Mr. John E. Matthews, U.S. EPA, R.S. Kerr Environmental Research Laboratory, Ada, Oklahoma

Dr. Lawrence C. Murdock, University of Cincinnati, Center Hill Solid and Hazardous Waste Research Facility

Mr. Vernon Myers, U.S. EPA, Office of Solid Waste, Washington, D.C.

Mr. Jon Perry, U.S. EPA, Office of Solid Waste, Washington, D.C.

Mr. Reid Rosnick, U.S. EPA, Office of Solid Waste, Washington, D.C.

Mr. Bill Stelz, U.S. EPA, Office of Solid Waste, Washington, D.C.

Dr. Robert L. Siegrist, P.E., Oak Ridge National Laboratory Environmental Science Division

PREFACE

On November 8, 1984, Congress enacted the Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA). RCRA requires a corrective action program that prevents hazardous constituents from exceeding concentration limits at the compliance point (i.e., the boundary of the waste management area) if any contaminant level exceeds the groundwater, surface water, air, and soil protection standards. Among the most significant provisions of HSWA are §3004(u), which requires corrective action for releases of hazardous waste or constituents from solid waste management units (SWMUs) at hazardous waste treatment, storage, and disposal facilities seeking final RCRA permits; and §3004(v), which compels corrective action for releases that have migrated beyond the facility property boundary. Under Subpart S of the RCRA regulations, requirements for corrective action at SWMUs are currently being drafted. The final Subpart S rule will establish the basic direction and goals for the program.

The overall goal of the RCRA corrective action program stabilization initiative is to, as soon as possible, control or abate imminent threats to human health and the environment from releases from RCRA facilities, and to prevent or minimize the further spread of contamination while long-term remedies at facilities are pursued. Using sound engineering judgment, stabilization actions, implemented under the interim measures authority of the RCRA corrective action program, could achieve rapid source control, stabilization, containment, or other results to significantly reduce the severity of a problem at a site. By setting priorities based on the environmental severity of sites, the U.S. Environmental Protection Agency (EPA) plans to include more sampling appropriate to technology selection during the site investigation phase of the RCRA correction action process to allow development of specific corrective action provisions in permits and orders, particularly for interim measures.

Guidance is provided herein on identification of the types of environmental settings that should be the focus of stabilization actions, on technical approaches to accelerate data gathering in support of decisions on appropriate stabilization measures, and on phasing the RCRA Facility Investigation process to gather the necessary data to make timely decisions within the framework of the existing corrective action program.

LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
ATM	Atmosphere
BOD	Biochemical Oxygen Demand
CAP	Corrective Action Plan
CB	Cement-Bentonite
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	Cubic Feet per Minute
CFR	Code of Federal Regulations
CM	Corrective Measures
CMI	Corrective Measures Implementation
CMS	Corrective Measures Study
COD	Chemical Oxygen Demand
DNAPL	Dense Nonaqueous Phase Liquid
DO	Dissolved Oxygen
EP Tox	Extraction Procedure Toxicity Test
EPA	U.S. Environmental Protection Agency
EPI	Environmental Priorities Initiative
FEMA	Federal Emergency Management Agency
HDPE	High Density Polyethylene
HEA	Health and Environmental Assessment
HELP	Hydrologic Evaluation of Landfill Performance
HHE	Human Health and the Environment
HSWA	Hazardous and Solid Waste Amendments (RCRA)
LDR	Land Disposal Restriction
LNAPL	Light Nonaqueous Phase Liquid
m^3/m-min	Cubic meter per meter-minute
MCLs	Maximum Contaminant Levels
NAPL	Nonaqueous Phase Liquids
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System

OD	Outer Diameter
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
pcf	Pounds per Cubic Foot
ppb	Parts per Billion
ppm	Parts per Million
psi	Pounds per square inch
PVC	Polyvinyl Chloride
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
RFA	RCRA Facility Assessment
RO	Reverse Osmosis
RFI	RCRA Facility Investigation
RQD	Rock Quality Designation
SB	Soil-Bentonite
SCFM/ft	Standard Cubic Feet per Minute per Foot
SCS	Soil Conservation Service
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SPT	Standard Penetration Test
S/S	Solidification/Stabilization
SVOC	Semivolatile Organic Compound
SWMU	Solid Waste Management Unit
TCLP	Toxicity Characteristic Leaching Procedure
TOC	Total Organic Carbon
USGS	United States Geologic Survey
UST	Underground Storage Tank
UV	Ultraviolet
VOC	Volatile Organic Compound
VLDPE	Very Low Density Polyethylene
µg/L	Micrograms per Liter

CONTENTS

Page

1 INTRODUCTION 1
1.1 BACKGROUND 1
1.2 RCRA STABILIZATION STRATEGY 1
1.3 CORRECTIVE ACTION PROCESS 2
1.4 IMPLEMENTATION OF STABILIZATION MEASURES 3
1.5 IDENTIFICATION AND SCREENING OF STABILIZATION TECHNOLOGIES 3
1.6 DOCUMENT ORGANIZATION 6
1.7 REFERENCES 7

2 **CONTAINMENT TECHNOLOGIES** 9
2.1 DRAINS/TRENCHES 9
2.1.1 Data Collection Requirements 9
2.1.2 Evaluation 10
2.1.3 Engineering Considerations for Implementation 12
2.2 VERTICAL WELLS 12
2.2.1 Data Collection Requirements 12
2.2.2 Evaluation 12
2.2.3 Engineering Considerations for Implementation 13
2.3 HORIZONTAL WELLS 13
2.3.1 Data Collection Requirements 13
2.3.2 Evaluation 14
2.3.3 Engineering Considerations for Implementation 14
2.4 SLURRY CUTOFF TRENCH/WALL 14
2.4.1 Data Collection Requirements 16
2.4.2 Evaluation 16
2.4.3 Engineering Considerations for Implementation 16
2.4.3.1 Soil-Bentonite Slurry Cutoff Trench/Wall 16
2.4.3.2 Cement-Bentonite Slurry Cutoff Trench/Wall 18
2.5 SHEET PILE CUTOFF WALL 18
2.5.1 Data Collection Requirements 19
2.5.2 Evaluation 19
2.5.3 Engineering Considerations for Implementation 19
2.6 GROUTING 19
2.6.1 Data Collection Requirements 19
2.6.2 Evaluation 19
2.6.3 Engineering Considerations for Implementation 20

2.7 CAPPING 24
2.7.1 Data Collection Requirements 24
2.7.2 Evaluation 24
2.7.3 Engineering Considerations for Implementation 24
2.8 SURFACE WATER CONTROL METHODS 28
2.8.1 Data Collection Requirements 28
2.8.2 Evaluation 28
2.8.3 Engineering Considerations for Implementation 28
2.9 GAS VENTING 29
2.9.1 Data Collection Requirements 30
2.9.2 Evaluation 30
2.9.3 Engineering Considerations for Implementation 31
2.10 HYDRAULIC FRACTURING 32
2.10.1 Data Collection Requirements 32
2.10.2 Evaluation 32
2.10.3 Engineering Considerations for Implementation 32
2.11 REFERENCES 33

3 **SOILS TREATMENT TECHNOLOGIES** 35
3.1 SOLIDIFICATION/STABILIZATION 35
3.1.1 Data Collection Requirements 37
3.1.2 Evaluation 37
3.1.3 Engineering Considerations for Implementation 39
3.2 SOIL FLUSHING 40
3.2.1 Data Collection Requirements 41
3.2.2 Evaluation 41
3.2.2.1 Treatability Testing 41
3.2.3 Engineering Considerations for Implementation 41
3.2.3.1 Introduction and Recovery of the Flushing Solution 41
3.2.3.2 Hydraulic Controls 41
3.2.3.3 Ground-water/Flushing Solution Treatment 41
3.2.3.4 System Performance 41
3.3 BIOREMEDIATION 42
3.3.1 Data Collection Requirements 43
3.3.2 Evaluation 43
3.3.2.1 Treatability Testing 44
3.3.2.2 Mathematical Models 45
3.3.2.3 Field Operation 45
3.3.3 Engineering Considerations for Implementation 45
3.3.3.1 Enhancement of Biological Mechanisms 47
3.3.3.2 Ancillary Equipment 47
3.4 VACUUM EXTRACTION 48
3.4.1 Data Collection Requirements 48
3.4.2 Evaluation 48
3.4.3 Engineering Considerations for Implementation 49
3.5 REFERENCES 53

4 **WATER TREATMENT TECHNOLOGIES** 55
4.1 PUMP-AND-TREAT 55
4.1.1 Data Collection Requirements 56
4.1.2 Evaluation 56
4.1.3 Engineering Considerations for Implementation 56
4.2 GROUND-WATER TREATMENT OPTIONS 61
4.3 REFERENCES 61

TABLES

No.	Title	Page
1-1	Examples of Interim (Stabilization) Measures	4
1-2	Soil and Ground -Water Stabilization	6
2-1	Data Requirements for Drains/Trenches	11
2-2	Soil-Bentonite Permeability Increases Due to Leaching with Various Pollutants	15
2-3	Data Requirements for Slurry Cutoff Trench/Wall	17
2-4	Data Requirements for Sheet Pile Cutoff Wall	20
2-5	Interactions between Grouts and Generic Chemical Classes	21
2-6	Interactions between Grouts and Specific Chemical Classes	22
2-7	Data Requirements for Grouting	23
2-8	Data Requirements for Capping	25
2-9	Quality Control Requirements for Soil-Bentonite Caps	27
2-10	Data Requirements for Runoff/Run-on Control	29
2-11	Data Requirements for Gas Venting	31
2-12	Data Requirements for Hydraulic Fracturing	33
3-1	Data Requirements for Solidification/Stabilization Technology	38
3-2	Data Requirements for Soil Flushing and Chemical Extraction Systems	42
3-3	Critical Environmental Factors for Microbial Activity	44
3-4	Site and Soil Characteristics for In Situ Treatment	45
3-5	Data Requirements for Bioremediation	46
3-6	Data Requirements for Vacuum Extraction	50
4-1	Data Requirements for Pump-and-Treat Systems	57

FIGURES

No.	Description	Page
2-1	Applicability of Containment Technologies to Site Conditions	10
2-2	Schematic Diagram of Horizontal Drilling Well System	13
2-3	Typical Slurry Wall Construction Site	18
2-4	Soil-Bentonite Slurry Cutoff Trench Cross Section	18
2-5	Soil Gradation versus Grout Type	21
2-6	Typical Grout Pipe Layout for Grout Curtain	21
2-7	Soil Permeability versus Vapor Flowrate for Several Values of Applied Vacuum	30
3-1	Applicability of Soils Treatment Technologies	36
3-2	Schematic of a Vacuum Extraction System	52
3-3	Typical Extraction/Air Inlet Well Construction	52
4-1	Flow Chart to Determine the Level of Modeling Required	60
4-2	Applicability of Treatment Technologies to Contaminated Ground Water	62

CHAPTER ONE
Introduction

The overall goal of implementing stabilization technologies within the existing corrective action process is to control or abate imminent threats to human health and the environment from releases at RCRA facilities. The intent is to prevent or minimize the further migration of contaminants while long-term corrective action remedies are evaluated and implemented. Although stabilization measures may be applied to address releases to any medium (soil, ground water, surface water, air), the U.S. Environmental Protection Agency (EPA) anticipates that, as a practical matter, a large proportion of stabilization actions will focus on soil and ground-water media to prevent further degradation. This document emphasizes the containment of contamination and the treatment of contaminated soils. The treatment of contaminated ground water is briefly discussed with references to the many previous publications pertaining to the screening of ground-water treatment options.

1.1 BACKGROUND

The Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA) were enacted into law on November 8, 1984. One of the major provisions (Section 3004(u)) of these amendments requires corrective action for releases of hazardous waste or constituents from solid waste management units (SWMUs) at hazardous waste treatment, storage, or disposal facilities. Under this provision, any facility applying for a RCRA hazardous waste management facility permit will be subject to a RCRA Facility Assessment (RFA). The RFA is conducted by the regulatory agency and is designed to identify SWMUs which are, or are suspected to be, the source of a release to the environment. If any such units are identified, the owner or operator of the facility will be directed to perform a RCRA Facility Investigation (RFI) to obtain information on the nature and extent of the release so that the need for interim corrective measures or a Corrective Measures Study (CMS) can be determined. Information collected during the RFI can also be used by the owner or operator to aid in formulating and implementing appropriate corrective measures. Such corrective measures may range from stopping the release through the application of a source control technique to a full-scale cleanup of the affected area. In cases where releases are sufficiently characterized, the regulatory agency may require the owner or operator to collect specific information needed to implement corrective measures during the RFI (U.S. EPA, 1989a).

Approximately 5,700 Subtitle C facilities, including over 80,000 SWMUs, are regulated by Section 3004 of HSWA to implement corrective actions for the release of hazardous waste. When federal facilities are considered, the scope of the problem is enlarged. To speed up the implementation of corrective actions, the "RCRA Implementation Study" recommended a "stabilization" approach. This approach would control or limit further releases without delay when an immediate threat exists or there is an opportunity to get action underway quickly (U.S. EPA, 1990b).

1.2 RCRA STABILIZATION STRATEGY

The intent of stabilization is to prevent or minimize the further migration of contaminants due to releases at RCRA facilities. This minimizes the complexity, and therefore, the cost, of future corrective actions when long-term corrective action remedies are to be evaluated and implemented. To streamline the process, EPA envisions stabilization measures will be identified and implemented under the interim measure authority, concurrently with the ongoing phases of the RFA and RFI activities.

Implementation of the stabilization initiative will generate substantial costs for RCRA facility owners and operators, but will also create substantial environmental benefits, as well as potential future cost benefits by taking earlier action. The Environmental Priorities Initiative (EPI) is an integrated RCRA/Superfund effort used to identify and evaluate contaminated sites that present the greatest risk to human health and the environment. Focusing resources in the near-term on stabilizing environmental problems at the highest priority facilities, rather than pursuing lengthy investigations culminating in final comprehensive remedies at fewer facilities, should enable EPA and states to quickly control the most serious environmental problems at a greater number of facilities. Furthermore, by imposing such controls more expeditiously, the extent and incidence of continued environmental degradation from existing releases should be significantly reduced. These actions will result in a reduction of future facility liability, including potential contaminant exposure.

Although stabilization measures may be applied to address releases to any medium (soil, ground water, surface water, air), EPA anticipates that, as a practical matter, a large proportion of stabilization actions will focus on soil and ground-water media to prevent further degradation. EPA experience with the corrective action program has shown that a substantial number of RCRA facilities have caused ground-water contamination from past waste management practices. Contaminated aquifers may be a serious health risk when used as a drinking water supply. Migration of contaminants can also result in serious ecological damage to both surface waters and wetlands. In addition, there is growing evidence regarding the technical limitations of restoring contaminated ground water to health and drinking water standards. This further underscores the need to focus remedial efforts on the prevention of new contamination as well as preventing further migration of existing contamination.

With the implementation of stabilization measures at RCRA facilities, EPA may be able to limit active oversight at low-risk facilities for some period of time in order to address other high-priority facilities. In other circumstances, stabilization could simply be a milestone within the remediation process. There may also be a limited number of situations where a stabilization measure could be considered to be the "final" remedy for a facility.

1.3 CORRECTIVE ACTION PROCESS

The RCRA corrective action process was established to investigate and implement cleanup for releases of hazardous wastes and/or constituents to the environment at facilities through permit conditions or by an administrative order or judicial action. As of this writing, the draft RCRA corrective action regulations (40 CFR 264 Subpart S) describing many procedural aspects of the RCRA corrective action process have not been published. However, several documents provide the framework for directing the development of the site-specific work to be performed by the owner/operator in the facility's corrective action program: the RCRA Facility Investigation Guidance Interim Final (U.S. EPA, 1989a), RCRA Corrective Action Interim Measures—Interim Final (U.S. EPA, 1988a), and the RCRA Corrective Action Plan—Interim Final (U.S. EPA, 1988c). From an engineering perspective, these documents provide scopes of work that can assist owner/operators and engineers in identifying each phase of a facility-wide corrective action plan, and in the formulation and implementation of interim measures, respectively (U.S. EPA, 1989b).

Basic activities common to the corrective action process follow:

- **RCRA Facility Assessment (RFA)** - Systematic identification of actual or potential releases through examination of each solid waste management unit
- **RCRA Facility Investigation (RFI)** - Characterization of the nature, extent, and rate of migration of each release, and preinvestigation identification of possible containment/treatment technologies
- **Corrective Measures Study (CMS)** - Identification of appropriate corrective measures, and detailed feasibility evaluation of cleanup alternatives
- **Corrective Measures Implementation (CMI)** - Design, construction, and implementation of corrective measures including performance monitoring

Interim measures are defined as corrective actions to stabilize, control, or limit further releases and can be implemented at any point in the process where there is an immediate threat to human health or the environment.

Health and Environmental Assessments (HEA) are performed concurrently with the corrective action process to identify exposure and action levels for corrective measures. The HEA is a continuous process that begins with the initiation of the RFI. As investigation data (from monitoring and/or modeling) become available, both during and at the conclusion of discrete phases, the regulatory agency should be notified. The regulatory agency compares these data to applicable health and environmental criteria, including an evaluation against qualitative criteria, to determine the need for (1) a stabilization corrective action under the authority of an interim measure(s) and/or (2) a CMS.

The regulatory agency may require both interim (stabilization) measures and a CMS as a result of the HEA. The difference between interim stabilization measures and the final corrective action is timing. The development and implementation of a comprehensive corrective action plan is often a time-consuming process. Between the time of the identification of a contaminant release and the implementation of corrective measures, existing conditions or further contaminant migration could endanger human health and the environment.

Specific health and environmental criteria and procedures to conduct the HEA for interim corrective measures are discussed in the Interim Final RFI Guidance (U.S. EPA, 1989a). The health and environmental criteria provided in the guidance do not necessarily represent target cleanup levels that must be achieved through the implementation of corrective measures. Rather, they establish presumptive levels that indicate that a closer examination is necessary. This closer analysis would generally take place as part of a CMS. The owner or operator has a continuing responsibility to identify and respond to emergency situations and to define priority situations that may warrant interim corrective measures. For these situations, the owner or operator should follow the RCRA Contingency Plan required under 40 CFR Part 264, Subpart D and Part 265, Subpart D.

All steps except the RFA and HEA are conducted by the owner/operator of the facility, with oversight by EPA or state agency; the RFA and HEA are conducted directly by EPA or the state. The steps, which are discussed in detail in the guidance, do not need to be followed rigidly by the EPA Regions. For example, the CMS can be modified or eliminated if a single remedial alternative is obvious.

1.4 IMPLEMENTATION OF STABILIZATION MEASURES

EPA has established a key priority siting process to stabilize releases from the most environmentally sensitive facilities.

The Environmental Priorities Initiative (EPI) is an integrated RCRA/Superfund effort to identify and evaluate sites that present the greatest risk to human health and the environment. EPA's prioritization of sites to determine whether a facility is an appropriate candidate for interim stabilization measures is based on a number of factors. Among the factors considered in deciding the need for stabilization measures are the severity of environmental problems at the site, the site's complexity and compliance history, the level of public involvement, and the availability of resources.

Site history and characterization data may be available before the RFA has been completed, especially data on imminent threats. However, in most situations, data on the fate and transport of hazardous constituents will not be available until the RFI is underway or completed. To streamline the process, it is clear that data needed to make decisions on stabilization should be gathered early in the RFI process.

The amount of information needed to support technical decisions for stabilization will vary greatly. Table 1-1 provides a list of possible stabilization measures for various units and release types. This list is not considered to be all inclusive. More information is available through the RCRA Corrective Action Interim Measures Guidance - Interim Final (U.S. EPA, 1988a). Obvious removal-type situations might often require some information to determine the quantity and location of wastes, after which removal may be done more or less immediately, without extensive studies. However, ground-water contamination in a complex hydrogeologic setting could require an extensive facility investigation where existing site characterization is limited. This would allow development of specific corrective action provisions in permits and orders, before an effective stabilization remedy could be implemented.

1.5 IDENTIFICATION AND SCREENING OF STABILIZATION TECHNOLOGIES

The identification of stabilization technologies may be an ongoing process, conducted in phases as data become available. Each site provides a unique set of constraints. As more site data become available, work completed on earlier tasks may need to be revisited and supplemented to address the newly apparent physical and chemical conditions. The screening and selection of stabilization technologies and the decision for remedial action are usually determined from the sequenced tasks below:

- Identify initial stabilization remediation goals. These goals may be refined and revised during design, or later during startup and operation.
- Identify potential stabilization technology applications.
- Screen technologies using available data.
- Obtain additional data, as necessary, to evaluate technology application further.
- Design, operate, and monitor technology application.

Other EPA documents have been written to assist technical decision-makers with the screening of corrective action technologies. The Risk Reduction Engineering Laboratory published a document to assist users in making preliminary evaluations of the technologies that might be employed to remediate a petroleum release (U.S. EPA, 1990a). The Center for Environmental Research Information and the Office of Solid Waste and Emergency Response have published documents that provide information on the identification, selection, and application of technologies suitable for controlling and treating hazardous waste releases from RCRA facilities (U.S. EPA, 1989b, U.S. EPA, 1988d). The Office of Solid Waste and Emergency Response published a reference guide that profiled various emerging and innovative technologies under the Superfund Innovative Technology Evaluation (SITE) program (U.S. EPA, 1990c). Other documents discuss in situ bioremediation (U.S. EPA, 1990d), and provide the latest information on many in situ treatments of hazardous waste (U.S. EPA, 1990e).

RFI activities conducted at several facilities that have implemented RCRA stabilization actions were reviewed to obtain input for the preparation of this manual. Often, it was found that interim measures were selected and implemented in stages during the RFI process as data were collected that indicated the need for a particular stabilization action. In some cases, stabilization measures taken were strictly of an interim nature, to prevent the migration of contamination, but not necessarily to provide the only corrective action. Other stabilization actions were taken to prevent contaminant migration and also to provide the degree of treatment necessary for site remediation. In the latter case, operational and post-operational performance monitoring provide important feedback for an effective corrective action program.

Successful stabilization actions provide flexibility in the corrective action process. This flexibility allows for some uncertainties in meeting design remediation criteria, and allows for possible future treatment process enhance-

Table 1-1. Examples of Interim (Stabilization) Measures

SWMU	Corrective Measure
Containers	
1	Overpack Container
2	Storage Area Construction; Move to New Storage Area
3	Segregate
4	Sample and Analyze
5	Treatment, Storage, and/or Disposal
6	Temporary Cover
Tanks	
1	Secondary Containment of Overflow
2	Leak Detection/Repair, Partial or Complete Removal
Surface Impoundments	
1	Head Reduction
2	Free Liquids and Highly Mobile Wastes Removal
3	Stabilization/Repair of Side Walls, Dikes, or Liner(s)
4	Temporary Cover
5	Runoff/Run-on Control (Diversion or Collection Devices)
6	Sample and Analyze for Documentation of the Concentration of Constituents Left in Place When a Surface Impoundment Handling Characteristic Wastes Is Clean Closed
7	Interim Ground-Water Measures (see Ground-Water Section of this Table)
Landfills	
1	Runoff/Run-on Control (Diversion or Collection Devices)
2	Head Reduction on Liner and/or in Leachate Collection System
3	Leachate Collection/Removal System Inspection or French Drain
4	Repair Leachate Collection/Removal System or French Drain
5	Temporary Cap
6	Waste Removal (see Soils Section of this Table)
7	Interim Ground-Water Measures (see Ground-Water Section of this Table)
Waste Piles and Contaminated Soils	
1	Runoff/Run-on Control (Diversion or Collection Devices)
2	Temporary Cover
3	Waste Removal (see Soils Section of this Table)
4	Interim Ground-Water Measures (see Ground-Water Section of this Table)

Table 1-1 (Continued)

SWMU	Corrective Measure
Soils	
1	Sampling/Analysis, Disposal
2	Runoff/Run-on Control (Diversion or Collection Devices)
3	Temporary Cap/Cover
Ground Water	
1	Delineation/Verification of Contamination
2	Sampling and Analysis
3	Interceptor Trench/Sump/Subsurface Drain
4	Pump-and-Treat; In Situ Treatment
5	Temporary Cap/Cover
Surface Water Releases (Point and Nonpoint)	
1	Overflow/Underflow Dams
2	Filter Fences
3	Runoff/Run-on Control (Diversion or Collection Devices)
4	Regrade/Revegetate
5	Sample and Analyze Surface Waters and Sediments or Point Source Discharges
Gas Migration Control	
1	Barriers/Collection/Treatment/Monitoring
Particulate Emissions	
1	Truck Wash (Decontamination Unit)
2	Revegetation
3	Application of Dust Suppressant
Other Actions	
1	Fencing to Prevent Direct Contact
2	Sampling Offsite Areas
3	Alternate Water Supply to Replace Contaminated Drinking Water
4	Temporary Relocation of Exposed Population
5	Temporary or Permanent Injunction
6	Suspend or Revoke Authorization to Operate under Interim Status

Adapted from U.S. EPA, 1989b.

ments (retrofits) in a phased program. For example, designing operational flexibility into a pump-and-treat facility would allow for a greater range in design flow or would allow for continued operation if an individual supply well was not on-line.

At a facility in Indiana, initial sampling showed that ground water contaminated with VOCs was entering the facility's storm sewer system and discharging to surface water. Immediate interim measures taken to prevent migration off site included storm sewer repairs, installation of ground-water underdrains beneath replaced storm sewers, and installation of a carbon adsorption system. As additional data confirmed source areas and ground-water flow patterns, more extensive stabilization measures were taken in progression, including surface water isolation and installation of an extensive ground-water collection system, air stripping towers, and a carbon adsorption unit to treat the ground water prior to discharge. Ongoing monitoring activities are being used to determine whether additional stabilization measures must be taken and how best to operate these interim facilities.

At a facility in Utah, stabilization measures were also implemented in phases. At this facility, failure of an underground storage tank (UST) automatic shut-off valve resulted in the release of approximately 27,000 gallons of jet fuel (JP-4). Immediate stabilization measures included removing the underground storage tank and collecting approximately 2,000 gallons of the spilled fuel as free product. A soil vacuum extraction system was then installed to remove the contamination remaining in the overburden soil. Site monitoring and respiration tests conducted during the first 10 months of operation showed some biological activity occurring in the remediation area. Based on this information and subsequent bioremediation treatability studies, operating conditions were modified to promote bioremediation in combination with the existing vacuum extraction system.

1.6 DOCUMENT ORGANIZATION

This document, organized into four sections, provides the technical decision guidance for implementing a number of stabilization technologies. Table 1-2 presents a list of selected stabilization technologies covered in this handbook for containment and treatment of soil and ground-water media. In most cases, these technologies have been widely applied to soil and ground-water contamination. In a few cases, the technology has limited experience in remedial applications, as noted, but has laboratory or bench-scale experience that appears promising. In the remaining three sections, selected containment, soil treatment, and ground-water treatment technologies, respectively, are discussed. The stabilization technology presentations include a description of the containment or treatment technology, benefits and limitations of the technology, critical data requirements, evaluation methods for feasibility and design, and engineering considerations for implementation.

This document uses, to the extent possible, existing guidance and information developed in various EPA programs (e.g., Office of Emergency and Remedial Response, Office of Waste Programs Enforcement, and Office of Water), as well as state material to assist in performing release characterizations for the various environmental media. As such, many references are provided which refer the owner or operator to more complete or detailed information. Where available, identification or ordering numbers have been supplied with these citations.

Table 1-2. Soil and Ground-Water Stabilization

Selected Containment Technologies
Physical Barriers
Slurry Cutoff Trench/Wall
Sheet Pile Cutoff Wall
Grouting*(1)
Capping
Surface Water Control Methods
Hydraulic Barriers
Drains/Trenches
Pumping (Extraction/Recharge)(1)(2)(3)
Gas Venting*(1)(2)
Selected Treatment Technologies
Solidification/Stabilization
Soil Flushing*(1)(2)(3)
Bioremediation*(1)(2)(3)
Vacuum Extraction*(1)(2)(3)
Chemical Extraction
Pump-and-Treat*(1)(2)(3)

Notes:

* Technology enhancements that may be applicable to a number of containment and treatment technologies include:

(1) Horizontal versus vertical well systems

(2) Hydraulic fracturing of contaminated media

(3) Pulsed pumping

1.7 REFERENCES

U.S. EPA. 1990a. Assessing UST Corrective Action Technologies: Early Screening of Cleanup Technologies for the Saturated Zone. EPA/600/2-90/027. Risk Reduction Engineering Laboratory.

U.S. EPA. 1990b. Chapter 7, Corrective Action: A Strategy for Protection. In: The Nation's Hazardous Waste Management Program at a Crossroads: The RCRA Implementation Study. EPA/530-SW-90-069. Office of Solid Waste and Emergency Response. Washington, D.C.

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

U.S. EPA. 1990d. International Evaluation of In Situ Bioremediation of Contaminated Soil and Ground Water. EPA/540/2-90/012. Office of Emergency and Remedial Response. Washington, D.C.

U.S. EPA. 1990e. Handbook on In Situ Treatment of Hazardous Waste Contaminated Soils. EPA/540/2-90/002. Risk Reduction Engineering Laboratory. Cincinnati, Ohio.

U.S. EPA. 1989a. RCRA Facility Investigation (RFI) Guidance - Interim Final. Vols. I - IV, EPA 530/SW-89-031. Office of Solid Waste, Waste Management Division. Washington, D.C.

U.S. EPA. 1989b. Corrective Action: Technologies and Applications. Seminar Publication. EPA/625/4-89/020. Center for Environmental Research Information.

U.S. EPA. 1988a. RCRA Corrective Action Interim Measures Guidance. Interim Final. OSWER Directive No. 9902.4. Office of Waste Programs Enforcement. Washington, D.C.

U.S. EPA. 1988b. Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites. OSWER Directive No. 9283.1-2. Office of Emergency and Remedial Response. EPA/540/G-88/003 Washington, D.C.

U.S. EPA. 1988c. RCRA Corrective Action Plan - Interim Final. EPA/530-SW-88-028. OSWER Directive No. 9902.3. Office of Solid Waste and Emergency Response. Washington, D.C.

U.S. EPA. 1988d. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA/540/2-88/004. Office of Solid Waste and Emergency Response. Washington, D.C.

U.S. EPA. 1986a. RCRA Facility Assessment Guidance. NTIS PB-87-107769. Office of Solid Waste. Washington, D.C.

U.S. EPA. 1986b. Leachate Plume Management. EPA/540/2-85/004. OSWER Directive No. 9380.0-05.

CHAPTER TWO
Containment Technologies

Containment stabilization technologies can be classified by media (ground water or soil). In each medium, several stabilization technologies are commonly used. For ground water, these technologies include a variety of hydraulic and physical barriers. The technologies for soil containment include excavation, capping, and gas venting techniques.

Hydraulic barriers contain contaminated ground water using hydraulic controls. Containment is achieved by either (1) recirculating the water within a limited area to prevent further migration of contamination, or (2) altering the piezometric surface either to decrease the gradient along which migration is occurring or to divert the contamination away from a receptor. This technology differs from a pump-and-treat system in that the pumped or recirculated water in the containment system is not treated prior to reinjection, or it may be uncontaminated water recirculated beyond the boundaries of the plume. The methods of implementing containment through hydraulic control include pumping or diverting ground water to create a depression in the piezometric surface, and reinjection or recharge of water to create a mound or ridge in the piezometric surface. A series of wells is typically used for ground-water extraction, although trenches or drains may also be used. Basins, trenches, infiltration galleries, or injection wells are used for recharging water.

Physical barriers or low permeability vertical barriers can be used to divert ground-water flow away from a waste source or to contain ground water contaminated by a waste source. Three major types of low permeability vertical barriers are discussed herein: slurry cutoff trench/wall, steel sheet pile wall, and grout curtain.

The selection of the appropriate containment technologies is based on an evaluation of each technique in terms of the use and limitations of the technique, hydrogeologic conditions, and contaminant subsurface behavior. The following sections present a summary of the containment technologies, their recommended target use and limitations, hydrogeological and chemical data requirements for evaluation, and evaluation tools for establishing feasibility and a basis for design.

Figure 2-1 summarizes the applicability of the containment technologies under different site conditions. It also summarizes the applicability of different evaluation tools to the technologies.

2.1 DRAINS/TRENCHES

Drains or trenches may be used to collect contaminated or uncontaminated ground water in order to prevent contamination from reaching downgradient receptors. They are typically installed perpendicular to the direction of ground-water flow, although other orientations may be applicable in certain cases.

Drains are generally constructed by excavating a trench and installing perforated pipe on gravel bedding on the bottom of the trench. The trench is then backfilled with gravel or other envelope material, followed by backfilling the remainder of the trench with soil. The gravel may be enveloped in a geotextile fabric to prevent fine soil particles from entering the gravel and clogging the drain. If the surrounding soils have a moderately high to high hydraulic conductivity and there is some question as to whether the drain will be a complete barrier, an impermeable synthetic membrane may be installed on the downgradient side of the drain to prevent water from passing through it.

Interceptor trenches function similarly to drains. Trenches and drains can be either active (pumped) or passive (gravity flow). Trenches and drains may be used in the containment mode for collection of second-phase pollutants that flow on the water table (e.g., light nonaqueous phase liquids (LNAPLs)). Passive systems are usually left open with an installed skimming pump or settlement tank for removal of the pollutant.

The benefits of using interceptor trenches or drains are (1) they have a relatively simple construction, (2) they are relatively inexpensive to install, (3) they are useful for collecting contaminants in poorly permeable soils, (4) they are useful for intercepting landfill seepage and runoff, (5) their large wetted perimeter allows for high rates of flow, and (6) it is possible to monitor them to recover pollutants.

The limitations of interceptor trenches or drains are (1) that open systems require safety precautions to prevent fires and explosions, (2) they are not useful for sites where contamination is deep, and (3) they may interfere with other operations at a facility.

2.1.1 Data Collection Requirements

The decision of whether to use trenches or drains depends largely on the depth of the contamination. If the

	Drains & Trenches	Vertical Wells	Horizontal Wells	Slurry Cutoff Trench/Wall	Sheet Pile Cut Off Wall	Grouting	Capping	Gas Venting	Hydraulic Fractoring
Site Conditions									
High Hyd. Cond.	●	●	●	●	●	●	●	●	O
Low Hyd. Cond.	●	O	O	●	●	●	●	O	●
Shallow WT	●	●	●	●	●	●	●	x	O
Deep WT	x	●	O	O	x	O	O	●	O
Shallow Contamination	●	●	●	●	●	●	●	●	O
Deep Contamination	x	●	O	O	x	O	O	O	●
LNAPL	●	●	O	●	●	●	●	●	O
DNAPL	O	●	O	O	O	O	O	x	●
Confined Aquifer	O	●	●	●	●	●	x	x	●
Unconfined	●	●	●	●	●	●	●	●	O
Complex Stratigraphy	O	●	●	●	●	●	O	O	O
Bedrock	O	●	●	O	x	●	x	O	●
Soils	●	●	●	●	●	●	●	●	O
Evaluation Methods									
Numerical Modeling	●	●	●	●	●	●	O	O	O
Analytical Modeling	●	●	●	O	O	O	O	O	O
Water Budget	●	●	●	●	●	●	●	x	O
Flow Analysis	●	●	●	●	●	●	x	x	O

● Applicable
O Potentially Applicable
x Not Applicable

Figure 2-1. Applicability of Containment Technologies to Site Conditions.

water table at a site is relatively shallow, and if the contamination is near the water table either because it (1) is an LNAPL; (2) is confined to a thin, upper aquifer by underlying strata of low hydraulic conductivity; or (3) is prevented from migrating downward due either to upward vertical gradients or to having had insufficient time for vertical migration, then drains or trenches should be considered as a stabilization technology. Since shallow vertical wells are the main alternative to drains or trenches, soils with relatively low hydraulic conductivities in which vertical wells would perform poorly are particularly good candidates. The areal configuration of the plume may also create an advantage for drains and trenches; for example, a need to create a continuous, linear barrier to ground-water flow is best met with a drain or trench. The data requirements that are listed in Table 2-1 are, in most cases, needed for system design.

2.1.2 Evaluation

The data collected for an evaluation of the feasibility of using trenches or drains as a stabilization measure is essentially the same as that for any ground-water extraction

Table 2-1. Data Requirements for Drains/Trenches

Data Description	Purpose(s)	Source(s)/Method(s)
Depth to aquifer/ water table	Select appropriate extraction system type and design trench/drain	Hydrogeologic maps, observation wells, boring logs, piezometers
Types, thicknesses, and extents of saturated and unsaturated sub-surface materials	Design drains/trenches	Hydrogeologic maps, surficial geology maps/reports, boring logs, geophysical surveys
Hydraulic conductivities and storativities of sub-surface materials	Design drains/trenches	Pumping tests, slug tests, laboratory permeability tests
Contaminant concentrations and areal extent	Locate and select depth of drains	Water quality data
Piezometric surface map, ground-water flow rates, and vertical/ horizontal gradients	Locate and design trenches/ drains	Water level data
Seasonal changes in ground-water elevation	Select depth of drains/trenches	Long-term water level monitoring
NAPL density/ viscosity/solubility	Predict vertical distribution of contamination, design trenches/drains	Literature
Ground water/surface water relationship	Design trenches/drains	Seepage measurements, stream gaging
Locations, screen/ open interval depths, and pumping rates of wells influenced by site	Determine impacts/ interference	Well inventory, pumping records
Precipitation/ recharge	Design trenches/drains	NOAA reports

Note: Table 2-1 applies to hydraulic barrier technology (i.e., well systems).

system. The evaluation of the data is somewhat different, however, for different systems. The primary requirements for trenches or drains are a shallow water table and shallow contamination. Water level and water quality data from monitoring wells in the plume are sources of this information. The direction of ground-water flow must also be determined so that the location for the drain can be determined and evaluated.

2.1.3 Engineering Considerations for Implementation

Trenches or drains used in a recirculation system require excavation of soil along the pathway of the contamination. This may result in the excavation of a large volume of contaminated soil which requires special handling and disposal procedures. In addition, installation of trench liners and piping may require dewatering of potentially contaminated water. This water will also require special handling and disposal, unless it can be recirculated. An alternative would involve the use of a slurry cutoff trench excavation technique, the installation of a 100 mil thick high density polyethylene (HDPE) membrane, and the backfilling of the trench with sand.

Although subsurface drains perform many of the same functions as pumping well systems, drains may be more cost effective in certain circumstances. For example, drains may be particularly well suited to sites with relatively low hydraulic conductivities, where the cost of wells may be high due to the need to locate wells very close together. There are, however, a number of limitations to the use of subsurface drains as a remedial technique. Subsurface drains are not feasible at depths exceeding 40 feet due to the difficulty of shoring during installation. Also, contamination at great depth or in bedrock aquifers may cause construction costs to be prohibitive, particularly if a substantial amount of rock must be excavated. The excavation required for trench or drain installation is complicated in areas where subsurface utilities and piping are ubiquitous, or where tanks, buildings, and roadways exist. Subsurface drains are also not suitable when the plume is viscous or reactive because this type of leachate may clog the drain system. At locations adjacent to an existing or potential recharge feature, the trench or drain might require a downgradient impermeable barrier (U.S. EPA, 1987). Waste compatibility tests are sometimes required to properly select piping and fill material (U.S. EPA, 1985a, 1987).

The design of the trench or drain that is installed as a stabilization measure will probably be based on analytical solutions to determine discharge rate and anticipated drawdowns. Lohman (1972) describes an analytical analysis method. If hydrogeologic conditions are complex (e.g., drain is to be installed near a significant recharge source or annual water table fluctuations are severe), a numerical model may be needed to evaluate the effectiveness of the stabilization action and to alter or expand the system for the final remedial design.

2.2 VERTICAL WELLS

Vertical wells may be used for extraction or injection of water, in accordance with the containment system design. Extraction wells may be either well points, naturally developed wells, or gravel-packed wells. Well points are typically joined to a header pipe and pumped with a suction system. Larger diameter wells are pumped most commonly with submersible pumps, although vertical turbine pumps may also be used. Extraction wells that are to be used in a recirculation system would most likely be constructed near the leading edge of a plume. Extraction wells to be used for gradient control would probably be installed upgradient of the plume.

Injection wells are typically overdesigned in terms of open area in the screened or open interval because of the tendency to clog. The overdesign reduces the frequency of maintenance activities such as well development and well replacement. Injection wells for a recirculation system would most likely be constructed near the origin of the plume of contamination. Injection wells to be used for plume diversion would be located outside of the plume along its path of flow.

One of the benefits of vertical wells is that they are a conventional readily available technology. They can be drilled to essentially any depth, at any location to which access by the required drilling equipment is available. Drilling services can usually be obtained on a competitive bid basis.

The main drawback of vertical wells is the fact that contamination is often spread horizontally more than vertically, so that vertical wells are oriented perpendicular to the typical contaminant distribution.

2.2.1 Data Collection Requirements

The data collection requirements for vertical extraction or injection wells are the same as those listed for drains and trenches in Table 2-1. When making a decision on whether or not to use vertical wells in a stabilization action, the primary considerations are the depth and nature of the contamination and its extent.

2.2.2 Evaluation

The vertical and horizontal extent of contamination, as determined from the water level and water quality data measured in monitoring wells, must first be estimated. The decision of whether or not to use vertical wells can then be made. If the contamination is too deep to be reached by trenches or drains, or if property ownership or land use and utilities preclude their construction, then vertical wells should be considered. If the contamination is vertically distributed through the aquifer, then vertical wells will be an efficient extraction technology. If dense nonaqueous phase liquids (DNAPLs) have accumulated deep in the aquifer and are a source of contamination, vertical wells will be a logical choice to remove or control them. Reinjection of treated water through vertical wells

may be chosen in various situations, such as when aquifer replenishment is needed or when excessive drawdowns would result from extraction without recharge.

2.2.3 Engineering Considerations for Implementation

Wellpoint systems are best suited for shallow, unconfined aquifers where extraction below a depth of 20 feet is not required. Deep wells and ejector well systems are used for deeper aquifer systems. Operation and maintenance costs for pumping systems are high, which may limit their use for long term containment.

2.3 HORIZONTAL WELLS

The application of horizontal drilling and well installation technology to enhance containment and treatment stabilization technologies is gaining acceptance by industry. Its main use in the past has been in the petroleum industry and in civil engineering applications. The possibility of using horizontal drilling as a tool for containing or remediating contaminated soils and ground water is currently being explored with increasing frequency (Karlsson and Bitto, 1990). Production rates from horizontal wells are typically higher than those expected from vertical wells in the same formation, due largely to the greater screen lengths possible with horizontal wells (Langseth, 1990).

A custom-equipped drill rig with a slanting rig mast capable of being oriented from the vertical to 60°-from-vertical in 15° increments is used in horizontal drilling. The rig and downhole tools are designed to work as a system, as shown in Figure 2-2, to drill horizontally on a 100 foot radius (Karlsson and Bitto, 1990). The drilling assembly is steerable, and manufacturers indicate that horizontal sections of screen of greater than 500 feet in length can be accurately placed at target depths from 18 feet to greater than 300 feet.

The downhole drilling assembly consists of a dual-wall drill string and an expanding bit that drills a hole large enough to permit casing to be installed during drilling. The casing protects the hole from collapse. Once the well is drilled to the desired length, an inner drilling assembly is withdrawn and an HDPE well casing is left in place. The downhole system is guided using measurements from a tool face indicator which records the inclination of the drilling assembly and transmits readings to the surface.

The benefits of horizontal drilling are related to the ability to install horizontal wells or barriers without the need to excavate. For example, a series of horizontal wells could be used to place a pressure curtain of pumped air or water as a hydraulic barrier or to inject a floor of grout, epoxy, or cement to create a physical barrier. In applications such as the recovery of contaminated ground water beneath structures where vertical wells are less practical, horizontal wells are a definite advantage (Karlsson and Bitto, 1990). The use of numerical models (Langseth, 1990) to predict contaminant capture performance indicates that horizontal wells may be advantageous over vertical wells in certain situations, such as with contaminant plumes that are not vertically dispersed.

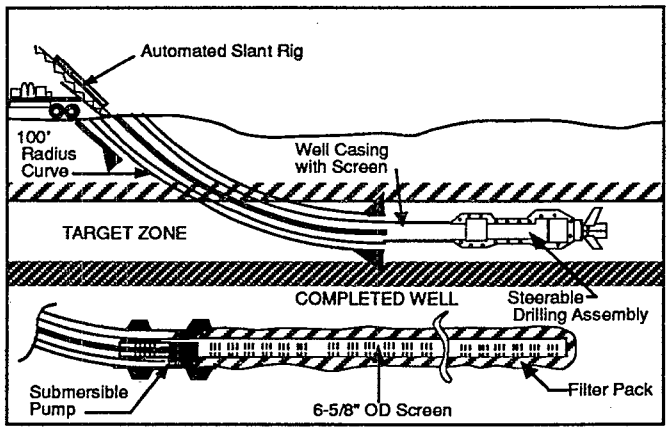


Figure 2-2. Schematic Diagram of Horizontal Drilling Well System (Eastman Christensen Systems, 1991).

In addition to pump-and-treat systems and grouting applications, horizontal wells can be used to facilitate the following treatment-oriented stabilization technologies:

- Soil gas vacuum extraction
- Steam injection remediation
- In situ remediation
- Soil flushing

The drawbacks of horizontal drilling are that relatively specialized equipment is required and it has not yet been widely used at waste remediation sites. Horizontal drilling is being used, however, in a soil gas vacuum extraction system at the Savannah River site in Aiken, South Carolina (Kaback et al., 1991). Two horizontal wells were installed beneath a leaking pipeline. The lower well will be used to inject air, while the upper well will be used to extract the air stream along with volatile organic compounds (VOCs) that have been stripped from the soil (Karlsson and Bitto, 1990). Soils in the unsaturated zone and ground water containing the VOCs will be therefore concurrently remediated using the paired horizontal wells.

2.3.1 Data Collection Requirements

General data requirements needed to evaluate horizontal drilling and well installation are the same as those for hydraulic barriers, which are listed in Table 2-1. The technical issues are primarily whether the contamination is configured such that a horizontal collection system offers a significant advantage over a vertical one, and whether trenches, drains, or horizontal wells are more appropriate. Nontechnical considerations include the availability and cost of horizontal well construction services at the remediation site. One comparison of horizontal and vertical well performance in a pump-and-treat system, based on

modeling results, indicated that the increased efficiency of horizontal wells and the resulting savings from a lower treatment duration can affect the greater capital cost of well construction (Langseth, 1990). The plume configuration must be well known to correctly position the horizontal well, however, and realize this advantage. The level of knowledge of contaminant distribution at the stabilization phase of the site remediation may not be sufficient to place a horizontal well optimally.

2.3.2 Evaluation

The technical evaluation of a horizontal well system for containment or remediation can be performed using analytical models. Equations that predict the behavior of flow to horizontal wells are present in the literature (Hantush, 1964; Hantush and Papadopulus, 1962) and were developed for the petroleum industry. Horizontal well performance may also be approximated by assuming a series of closely spaced vertical wells with short screens. Since the available technical and economic comparison of horizontal wells with vertical wells is not based on actual sites but on theoretical studies, the evaluation should be based on access issues and on plume configuration and contaminant depth.

2.3.3 Engineering Considerations for Implementation

Space requirements for horizontal well bores may require additional site access considerations. The wellhead is typically 30 to 60 feet behind the horizontal well screen, as shown in Figure 2-2.

The use of geophysical techniques, particularly seismic methods, has been shown to be helpful in determining the feasibility of using horizontal wells, determining well placement, and correlating data. The determination of the lateral extent of lithologies in the vicinity of the proposed horizontal well, particularly aquitards such as clay lenses, is essential in designing the specifications of the well. Geophysical methods and soil borings would be helpful in obtaining this information.

2.4 SLURRY CUTOFF TRENCH/WALL

Slurry walls are often utilized in combination with hydraulic controls or pump-and-treat technologies to focus ground-water recovery on a particular area or to enhance containment measures. This results in optimal concentration of treated water, lower treatment costs, and shorter cleanup times. Slurry walls are also used with capping technologies to fully confine a waste area and to prevent clean water from leaching through the wastes.

A slurry cutoff trench/wall is constructed by excavating a narrow vertical trench, typically 2 to 4 feet wide, and backfilling with a low-hydraulic conductivity material to contain a waste source and to prevent contamination from migrating offsite. The trench, as excavation proceeds, is filled with a bentonite-water slurry which stabilizes the walls of the trench, thereby preventing collapse. The slurry penetrates into the permeable soils, creating a filter cake on the trench walls that seals the soil formations, prevents slurry loss, and also contributes to the low permeability of the completed cutoff wall. This narrow trench is then backfilled with a slurry mixture. Slurry walls are differentiated by the materials used to backfill the slurry trench. If a mixture of soil and bentonite is used, then the wall is known as a soil-bentonite (SB) slurry cutoff wall. In some cases, the trench is excavated under a slurry of portland cement, bentonite, and water, and this mixture is left in the trench to harden into a cement-bentonite (CB) slurry wall. This technique is used at sites where there is inadequate open area available for the mixing and placement of the soil-bentonite backfill, where increased wall strength may be necessary, or where extreme topography changes make it impractical to level-grade a site.

Slurry walls can be installed in several configurations. Circumferential installations (totally surrounding the wastes) are the most common and offer several advantages (U.S. EPA, 1985b). This placement can reduce the amount of uncontaminated ground water entering the site, thus reducing the amount of leachate generated. If pump-and-treat systems are also used, this placement would reduce the amount of water to be treated. This placement could enhance containment measures if used in conjunction with hydraulic controls by helping to maintain an inward gradient and thus prevent leachate escape. Capping technologies are often used in conjunction with slurry walls to prevent leachate generation. An example of a circumferential slurry wall used in conjunction with capping and pump-and-treat is the system currently operating at the Gilson Road Superfund site in New Hampshire (Weston, 1989). Downgradient placement of a slurry wall can be used to prevent downgradient migration of contaminated ground water. Examples of downgradient placement are the systems installed at the Rocky Mountain Arsenal in Denver, Colorado (CSU, 1988). A slurry wall could also be installed upgradient of a contaminated area to divert clean ground water around a site.

Vertical configurations of slurry cutoff walls may be "keyed-in" or "hanging." A keyed-in slurry cutoff wall is excavated into a continuous low-permeability horizontal confining layer, such as a clay deposit or competent bedrock. The confining layer forms the bottom of the contained site. A penetration into the confining layer of 2 to 3 feet is essential for adequate containment. The depth of the confining layer will also impact the type of excavation equipment used and the completed wall costs. Hanging slurry walls are not tied into a confining layer, but extend to a hydraulically calculated depth to act as a barrier to the movement of floating contaminants (such as oil, or fuels) or migrating gases, or for creating an inward hydraulic gradient used in conjunction with a ground-water treatment system.

A number of factors may limit the application of slurry cutoff walls. Site topography can limit the use of a soil-ben-

Table 2-2. Soil-Bentonite Permeability Increases Due to Leaching with Various Pollutants

Pollutant	Backfill
Ca^{++} or Mg^{++} @ 1,000 ppm	N
Ca^{++} or Mg^{++} @ 10,000 ppm	M
NH_4NO_3 @ 10,000 ppm	M
Acid (pH>1)	N
Strong acid (pH<1)	M/H*
Base (pH<11)	N/M
Strong base (pH>11)	M/H*
HCl (1%)	N
H_2SO_4 (1%)	N
HCl (5%)	M/H*
NaOH (1%)	M
$Ca(OH)_2$ (1%)	M
NaOH (5%)	M/H*
Benzene	N
Phenol solution	N
Sea water	N/M
Brine (SC=1.2)	M
Acid mine drainage ($FeSO_4$, pH 3)	N
Lignin (in Ca^{++} solution)	N
Organic residues from pesticide manufacture	N
Alcohol	M/H

N - No significant effect; permeability increase by about a factor of 2 or less at steady state.
M - Moderate effect; permeability increase by factor of 2 to 5 at steady state.
H - Permeability increase by factor of 5 to 10.
* - Significant dissolution likely.
\+ - Silty or clayey sand, 30 to 40% fines.

Source: D'Appolonia, 1980a; D'Appolonia and Ryan, 1979 (from U.S. EPA, 1984b)

tonite wall because the excavation slurry and the backfill will flow under stress. Thus, the trench line must be within a few degrees of level. Cement-bentonite walls that harden quicker are better suited to irregular topography. If a keyed-in slurry wall is considered, the depth to and nature of the confining layer becomes a concern. The layer must have sufficiently low permeability to prevent leakage underneath the wall, it must have adequate thickness to allow an adequate key (2 to 3 feet), and it must be of moderate depth (50 to 70 feet) or excavation of the trench may not feasible.

A major limitation to the application of a slurry cutoff wall/trench as a physical barrier is the compatibility of the cutoff trench backfill mixture with site contaminants. SB backfills are susceptible to attack by strong acids or bases, strong salt solutions, and some organic chemicals. Organic chemicals can cause desiccation (drying) and cracking in soil-bentonite backfill mixtures, resulting in permeability increases of several orders of magnitude over time (U.S. EPA, 1984b). Table 2-2 presents permeability increases on soil-bentonite due to exposure to various contaminants (U.S. EPA, 1984b). Cement-bentonite slurry mixtures are more susceptible to chemical attack than most soil-bentonite mixes.

CB backfills are susceptible to attack by sulfates, strong acids and bases, and highly ionic substances. In order to minimize this problem, compatibility testing should be performed using soil and ground-water samples with the highest concentrations of contaminants from the site. The major bentonite suppliers have developed a bentonite that is resistant to chemical attack. The concentration of bentonite in the mix can be adjusted, or a chemically resistant bentonite or sulfate-resistant cement can be used, to provide a satisfactory solution.

Testing parameters to be evaluated in choosing a bentonite should include free-swell, filtrate loss, and permeability. The free-swell test would indicate the impact of the contaminant's effect upon the natural swelling characteristics of the bentonite. Filtrate loss tests indicate the degradation of the seal when exposed to the contaminants.

The hydraulic conductivity of a SB wall, with good construction quality control, is approximately 1×10^{-8} cm/sec. The hydraulic conductivity of a good CB wall is typically 1×10^{-6} cm/sec or less (U.S. EPA, 1985b).

2.4.1 Data Collection Requirements

Table 2-3 lists the data needed for design of a slurry cutoff trench or wall, along with its purpose and potential sources.

2.4.2 Evaluation

Because this technology is often implemented in conjunction with hydraulic controls or pump-and-treat technology, the evaluation of data generally involves a quantitative analysis of ground-water flow and contaminant transport. In the initial stages of the decision process, when it must be determined whether slurry cutoff walls are applicable, simplified methods such as a water budget analysis, applications of Darcy's law, and flow net analyses can be employed. These analyses should focus on flow within the aquifer and flow underneath the key in the confining layer. Once the applicability of the technology has been established, more sophisticated tools such as analytical or numerical models should be employed to design and evaluate effectiveness. The combination of cutoff walls with hydraulic controls usually results in a complex framework that is difficult to evaluate using simplified methods. The user is referred to Section 3.1 for a discussion on evaluation techniques.

Other evaluations that must be performed include determining compatibility of wall construction material with the existing environment. This involves testing grain size and permeability of surrounding soils to determine suitability as backfill materials and determining compatibility of plume and natural ground-water chemistry with backfill materials. Laboratory compatibility testing may be required if published data are not available.

Finally, construction limitations must be evaluated. This would involve evaluating the amount of area available for construction site accessibility, irregularities, site topography, and potential wetlands issues.

2.4.3 Engineering Considerations for Implementation

One problem often encountered with keyed-in slurry cutoff walls is leakage underneath the wall. Leakage has been observed at the Gilson Road site and the Rocky Mountain Arsenal (Weston, 1989, and CSU, 1988). This is often caused by leakage through bedrock fractures existing beneath the key. The ability to construct an adequate key and maintain overall slurry wall integrity are key considerations for implementation. Other considerations for both types of slurry cutoff trench/walls are discussed below.

Costs for slurry walls are usually expressed in costs per unit area of wall. Thus, the deeper and longer the trench, the more costly it is. Operation and maintenance costs are negligible. Monitoring of slurry walls usually involves monitoring ground-water levels inside and outside the wall to ensure that design head levels are not exceeded. Ground-water quality monitoring is used to determine the effectiveness of the entire remedial effort.

2.4.3.1 Soil-Bentonite Slurry Cutoff Trench/Wall. A SB cutoff trench/wall requires a relatively flat area for construction with a parallel earth berm constructed to confine the movement of slurry from the mixing operation away from the construction area. A typical SB slurry cutoff trench/wall installation requires space for bentonite storage, slurry preparation equipment, water storage tanks, hydradation pond, circulating pumps and slurry storage pond, de-sanding area (if required), a trench spoils area where excavated soils are placed adjacent to the trench,

Table 2-3. Data Requirements for Slurry Cutoff Trench/Wall

Data Description	Purpose(s)	Source(s)/Method(s)
Site accessibility	Select wall type	Site inspection
Topography	Soil-bentonite walls require large land area with relatively flat topography	USGS topography map, site inspection, site-specific topographic/contour maps, water level maps
Depth to continuous impermeable strata or competent bedrock	Selection of keyed-in or hanging wall	Borings, geophysical survey, bedrock and surficial geology maps
Heterogeneity of subsurface formation	Selection of wall type; excavated material may not be appropriate to mix	Surficial geology maps, test pits, soil borings, geophysical survey
Vertical and horizontal hydraulic conductivity of confining layer	Determine suitability of layer as a key	Slug tests, laboratory tests
Excavated soil type	Suitability for use as trench backfill material	Gradation analyses, permeability tests
Degree of bedrock fracturing	Evaluate potential for contaminants to migrate underneath the key	Rock cores, boring logs, geology maps
Ground-water depth, rate and direction of flow	Establish potential for installation of hanging wall with design of inward gradient for pump-and-treat scheme	Existing hydrogeologic maps, boring logs, observation wells, piezometers
Hydraulic conductivity of contaminated soil	Evaluate effectiveness of slurry wall pump-and-treat systems	Pumping tests, slug tests
Soil chemistry	Cement and bentonite can be modified to accommodate chemistry	Soil sampling and analysis
Chemistry of waste and ground water	Compatibility testing of cement or bentonite and wall material with contaminated ground water and soil	Ground-water sampling and chemical analysis, filtrate loss, free swell, and permeability testing

and a backfill mixing area where bentonite is mixed with the backfill soils. A typical slurry wall construction site is shown in Figure 2-3. Figure 2-4 shows a cross section of a soil-bentonite slurry cutoff trench, including excavation and backfill operations.

The type of trench excavation equipment used depends upon the depth and length of the cutoff wall. For soil-bentonite walls, a backhoe is typically used to depths of up to 50 feet. Crane-operated clamshells attached to a kelly bar can excavate to depths of up to 200 feet. Percussion tools or chisels are used when boulders, cobbles, and other hard consolidated materials are encountered which cannot be removed with standard equipment or when "keying-in" of the trench into bedrock is required.

Field quality control during installation is essential during the installation of a slurry cutoff trench/wall.

2.4.3.2 Cement-Bentonite Slurry Cutoff Trench/Wall. The principal difference between CB slurry cutoff trenches/walls and SB slurry cutoff trenches/walls is the backfill. This main difference produces differences in applications, compatibility, and costs. The initial excavation process for the CB wall is conducted in the same manner as the SB wall; however, the excavated soils from the trench are not reused to form the wall. Instead, the material is removed to a disposal area. Backfilling is performed using a cement-bentonite water mixture with set retarders, which are added so that the wall will slowly set.

The trench for a CB cutoff wall can be excavated with a clamshell bucket. This method involves the excavation of a series of primary panels 6 to 10 feet in length. Once the primary panels have set, secondary panels are excavated through the gaps in the primary panels and keyed into them. The cement-bentonite of the secondary panels bonds with the primary panels to create a tight cutoff. As with a SB wall, field quality control (QC) during testing is essential.

2.5 SHEET PILE CUTOFF WALL

Sheet pile cutoff walls can be used to contain contaminated ground water or to divert ground-water flow around or below contaminated areas. Sheet piles can be interlocking steel, precast concrete, or wood sections. The use of wood or precast concrete sections as a ground-water barrier is not appropriate for interim stabilization because wood is an ineffective water barrier, and precast concrete is used only in a situation where great lateral resistance is required. Sheet pile cutoff walls are constructed by driving individual sections of interlocking steel sheets into the ground using single, double-acting impact or vibratory pile drivers to form a thin impermeable barrier to ground-water flow. Initially, this type of wall is porous at the section interlocks, but will fill with fine sand and silt. If there are little or no fines present in the soil, tremie grouting along the interlocks can be used to create a barrier.

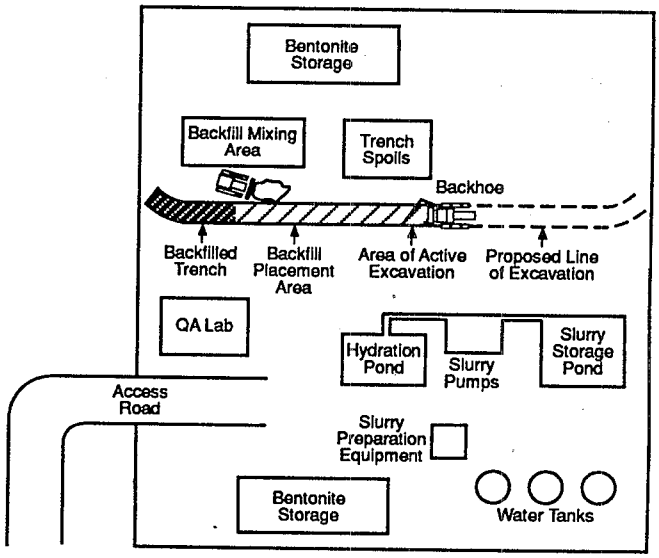


Figure 2-3. Typical Slurry Wall Construction Site (U.S. EPA, 1985b).

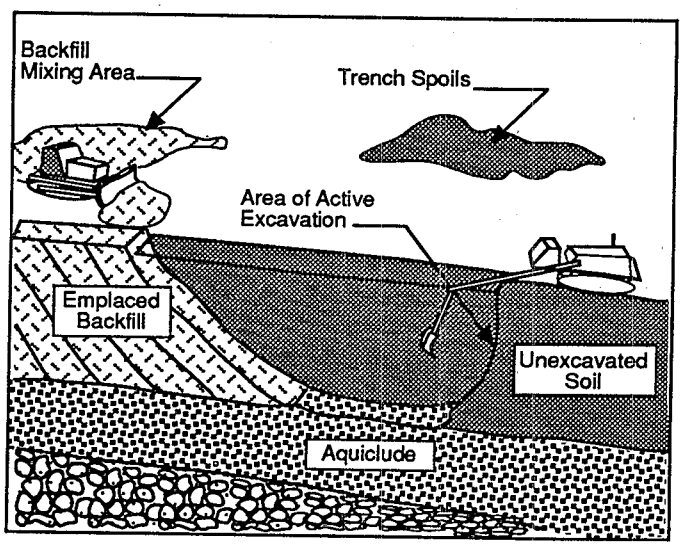


Figure 2-4. Soil-Bentonite Slurry Cutoff Trench Cross Section (U.S. EPA, 1985b).

Sheet piling is typically a less permanent measure than slurry walls and may be installed quicker with less effort and costs. Because of unpredictable wall integrity, sheet piling is seldom used in hazardous waste applications except for temporary dewatering for construction or excavation purposes. However, sheet piling could be effective as a short-term immediate measure to enhance recovery or containment. One of the largest drawbacks of sheet piling is that it is difficult to install in rocky soils. Damage to or deflection of the piles is likely to render a sheet pile ineffective as a ground-water barrier. Furthermore, it is

difficult to use sheet piling for deep ground-water problems due to the pile driving limitations. Sheet piles can be driven into bedrock, but the adequacy of the key formed would be questionable. Grouting could be employed to seal the bottom of the pile; however, applications have not been documented.

2.5.1 Data Collection Requirements

Table 2-4 lists the data required, the purpose, and possible sources of information for designing a sheet pile cutoff wall.

2.5.2 Evaluation

The evaluation of this technology would involve determining if the pile could be driven to the desired depth. If cobbles or boulders exist or if the ground-water problem is deep, this technology may not be feasible. It must also be determined whether the type of piling is compatible with the surrounding environment. If the environment is too corrosive, then long-term application of this technology should be avoided.

2.5.3 Engineering Considerations for Implementation

Soil type and waste characteristics are important factors to consider in the use of steel sheet pile walls as a physical barrier, because there is a high potential for leakage through interlocking piles or if individual sheets encounter boulders. Sheet piles are typically used in loose to medium dense granular soils that predominantly consist of sand and gravel. To serve as an effective cutoff, sheet pile walls should extend to bedrock or into a low-permeability soil strata. The maximum depth to which sheet piles can be driven without damage to the interlocks between individual sections is typically about 40 feet. The characteristics of the waste constituents strongly affect the expected service life of the sheet-pile wall (particularly the pH and conductivity of the waste material). Sheet piles are not suitable for very dense soils or soils with boulders present because the sheet piles will be damaged during installation. They are also not suitable for ground water containing high concentrations of salts or acids unless they can be coated with a coal tar epoxy or cathodic protection can be used.

2.6 GROUTING

Grouting is a process by which a fluid material is pressure injected into soil or rock to reduce fluid movement and/or impart increased strength. Grouts accomplish this through their ability to permeate voids and gel or set in place. Grouting can be used to control the movement of ground water and to solidify or stabilize a soil mass. Grouts injected into a soil mass reduce the permeability of the deposit. Grout curtains can be created in unconsolidated materials by pressure injection.

Grout types are divided into two general classifications—particulate or suspension grout and chemical grout. Particulate grouts are fluids that consist of a suspension of solid material such as cement, clay, bentonite, or a combination of these materials. These materials are usually the more viscous of the available grouting materials and have the largest particle size. Chemical grouts are frequently classified into two major groups: silica or aluminum based solutions and polymers. Chemical grouts rely on polymerization reactions to form hardened gels. They have initially low viscosities and can therefore be used in finer grained soils. Types of grouts include portland cement grouts, cement-bentonite grouts, silicate grouts, and organic polymer grouts.

Because of costs, grouted barriers are seldom used for containing ground-water flow in unconsolidated materials around hazardous waste sites. Slurry walls are less costly and have lower permeability than grouted barriers. Consequently, for waste site remediation, grouting is best suited for sealing voids in rocks. The compatibility of grouts with hazardous waste has not been thoroughly studied, and only general incompatibilities are known. However, some data suggest that organic chemicals can be detrimental to several types of grout.

The chemical compatibilities of various types of grouts are presented in Tables 2-5 and 2-6.

2.6.1 Data Collection Requirements

Table 2-7 is a list of data needed to design a grouting program. It also lists the purposes for the data and possible sources.

Field investigations for a grouting scheme for overburden soils involve (1) obtaining an accurate definition of the soil profile (i.e., depth and extent of soil strata), and (2) obtaining specific information concerning soil properties that control groutability (i.e., field permeability tests, porosity or void ratio, and laboratory permeability tests). Field permeability can be determined from falling-head or rising-head permeability tests or pumping tests.

For bedrock grouting, key information is (1) the recording of water loss during drilling, and (2) rock core logging which describes in detail jointing, fracturing, weathering, and Rock Quality Designation (RQD).

2.6.2 Evaluation

Soil laboratory testing would be performed to determine grain size and permeability. The soil samples should be reclassified to ensure that proper stratigraphy of the site is identified. The stratigraphy is used to determine the appropriate grouting methods and procedures.

Grain size analysis is used to determine whether the deposit can be grouted. Although soils with greater than 10 percent by weight passing a No. 200 sieve can be grouted, it is generally very expensive to do so. This is due to the fact that chemical grouts are more expensive per gallon of solution than particulate grouts.

The geochemistry of a site, including that caused by contaminants from waste disposal, is extremely important to

Table 2-4. Data Requirements for Sheet Pile Cutoff Wall

Data Description	Purpose(s)	Source(s)/Method(s)
Subsurface soil conditions	Determine feasibility. If boulders or very dense soils are present, very difficult to install wall for cutoff purposes	Surficial geology maps, test pits, borings
Depth to bedrock (impermeable strata)	Optimal wall depth	Geologic maps, borehole logs
Grain size distribution	Determine potential for fine grained soil particles to fill interlocks between sheet pile sections	Sieve analysis
In-situ soil density	Penetration resistance affects depth	Standard penetration test (SPT) Results from borings
Depth to ground-water table	Maximum depth to which steel sheet piles can be effectively driven is approximately 40 to 50 feet	Hydrogeologic maps, observation wells, data boring logs, geophysical survey
pH of ground water and waste	Determine if corrosive setting, establish need for coating piles or using cathodic protection	pH analysis and conductivity testing during borehole drilling

a grouting program. Among the geochemical data that should be determined during a design phase are the nature and extent of waste/contaminants at the site and the presence of soil or rock layers (such as salt deposits) that may impact grout solution chemistry.

2.6.3 Engineering Considerations for Implementation

A key consideration for implementation of the technology is the compatibility of the grout with the wastes. In theory, grouting could control contamination migration. However, in many cases, the waste/grout interaction and compatibility cannot be predicted and extensive testing is required (U.S. EPA, 1984b).

Grouting is typically a specialty operation. It is performed by a limited number of contractors, and each program is highly site specific. Explanations of different grouting applications are provided in the following section.

The selection of a grout type must include an evaluation of required soil permeability as well as grout, gel time, setting characteristics, volume of grout, and penetration. The applicability of different classes of grouts, based on soil grain size, is presented in Figure 2-5. Layout of grout injection pipes depends upon soil types, grout viscosity, injection pressure, and gel time. Spacing will depend upon grout penetration and desired grouted soil properties.

Grout curtains are formed by pressure injecting the grouting material through a pipe into the strata to be sealed. The injection points are typically arranged in a triple line of primary and secondary grout holes. A predetermined amount of grout is pumped into the primary holes. After the grout in the primary holes has had time to set or gel, secondary holes are injected. The secondary grout holes are intended to fill in any gaps left by the primary grout injection. A typical grout pattern is shown in Figure 2-6. Primary holes are typically spaced at intervals of 3 to 5 feet.

Table 2-5. Interactions between Grouts and Generic Chemical Classes

Grout Type	Portland Cement					
Chemical Group	Type I	Type II and V	Bentonite	Cement-Bentonite	Silicate	Acrylamide
Acid	1d	1a	?c	?c	3a	2c
Base	1a	1a+	?c	?d	2c	3d
Heavy Metals	2c	2a	?d	2c	3?	2?
Nonpolar Solvent	2d	2d	?d	?	?	?a
Polar Solvent	2c	2?	?d	?	?	?a
Inorganic Salts	2c	2a	2d	?d*	3?	3d**

KEY: Compatibility Index

Effect on Site Time

1 No significant effect.
2 Increase in set time (lengthen or prevent from setting).
3 Decrease in set time.

Effect on Durability

a No significant effect.
b Increase durability.
c Decrease durability (destructive action begins within a short time period).
d Decrease durability (destructive action occurs over a long time period).
* Except sulfates, which are ?c.
\+ Except KOH and NaOH, which are 1d.
\> Modified bentonite is d.
? Data unavailable.
** Except heavy metals, which are 2.

Source: U.S. EPA, 1984b.

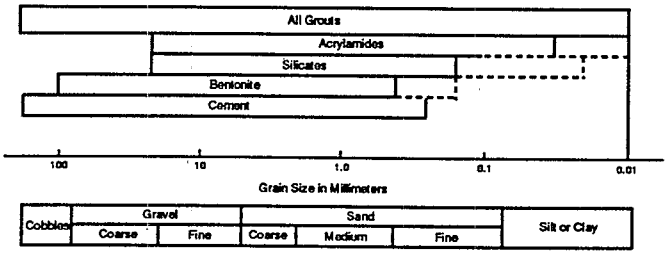


Figure 2-5. Soil Gradation versus Grout Type (Adapted from U.S. EPA, 1985).

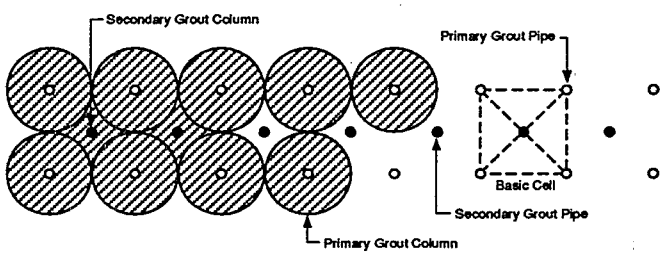


Figure 2-6. Typical Grout Pipe Layout for Grout Curtain (U.S. EPA, 1984a).

Table 2-6. Interactions between Grouts and Specific Chemical Classes

Grout Type	Portland Cement					
Chemical Group	Type I	Type II and V	Bentonite	Cement-Bentonite	Silicate	Acrylamide
Organic Compounds						
Alcohols and Glycols	?d	?d	?d	?d	?	?d
Aldehydes and Ketones	?	?	?d	?	?	?a
Aliphatic and Aromatic Hydrocarbons	2a	2?	?d	?	?	?a
Amides and Amines	?	?	?	?	?	?
Chlorinated Hydrocarbons	2d	2d	?	?	?	?a
Ethers and Epoxides	?	?	?	?	?	?a
Heterocyclics	?	?	?d	?	?	?a
Nitriles	?	?	?	?	?	?
Organic Acids and Acid Chlorides	1d	1d	?d	?a	?	2a
Organometallics	?	?	?	?	?a	?
Phenols	1d	?	?d	?	?	?
Organic Esters	?	?	?	1a	?	?
Inorganic Compounds						
Heavy Metals, Salts, and Complexes	2c	2a	?d	2c	?a	2?
Inorganic Acids	1d	1a	?c>	?c	?	2c
Inorganic Bases	1a	1a+	?c>	?d	?	3d
Inorganic Salts	2d	2a	2d	?d*	1a	3d

KEY: Compatibility Index

Effect on Site Time

1 No significant effect.
2 Increase in set time (lengthen or prevent from setting).
3 Decrease in set time.

Effect on Durability

a No significant effect.
b Increase durability.
c Decrease durability (destructive action begins within a short time period).
d. Decrease durability (destructive action occurs over a long time period).
* Except sulfates, which are ?c.
+ Except KOH and NaOH, which are 1d.
> Modified bentonite is d.
? Data unavailable.

Source: U.S. EPA, 1984b.

Table 2-7. Data Requirements for Grouting

Data Description	Purpose(s)	Source(s)/Method(s)
Soil permeability	Determine grout types applicable for subsurface conditions	Laboratory permeameter testing on soil samples; falling head field permeability testing in borings
Grain size distribution	Determine if soils are within range of soils that can be grouted and type of grout applicable	Sieve analysis
Chemistry of soil, waste, and ground water	Compatibility with grout determination of design mix	Ground-water sampling and chemical analysis
Heterogeneous nature of surficial geology	Determine type of grout and installation technique, i.e., reduce pressure for cement grout injection; adjust set time for chemical grout	Surficial geology maps, test pits, borehole soil sampling
Depth to and type of bedrock	Determine depth of wall and need for grouting of fractured zones to competent bedrock	Bedrock geology maps, geophysical surveys, bedrock outcrop mapping, borehole logs, bedrock coring
Depth to ground-water table	Determine depth pressure grouting to stop	Existing hydrogeologic maps, observation wells and piezometer records, borehole logs
Direction and rate of ground-water flow	High ground-water flow adversely affects certain integrity	Regional hydrogeologic maps/reports, water level records in borings, monitoring wells
Ground-water pH, sulfides, and calcium	Integrity of grout curtain	Sampling and analysis

Grout curtains are keyed into impermeable soil strata or competent bedrock. Grout curtains, like the other physical barriers, are applied to a site in various horizontal configurations, the most common being circumferential and downgradient.

Area grouting is a low pressure technique used to form a grout blanket. This is accomplished by injecting grout into a series of closely spaced injection holes on a grid pattern. Area grouting may be appropriate to in situ waste immobilization by injecting into the wastes, depending upon the compatibility of the wastes with the grouts.

In situations where a waste has migrated beneath buildings or other facilities, horizontal drilling can be used for injecting grout under pressure to seal/immobilize the contaminants.

2.7 CAPPING

Capping or surface sealing is part of a closure process in which a buried waste or contaminant plume is isolated to avoid surface water infiltration, thereby minimizing the generation of leachate. Capping may also be used to control the emission of gases and odors, reduce erosion, and improve aesthetics. Capping provides a stable surface which prevents direct contact with wastes, and is necessary when contaminated materials are to be buried or left in place at a site. In situations where the waste is entirely above the zone of ground-water saturation, a properly designed cover can prevent the entry of water into the closed landfill or into a surface impoundment that has been closed as a landfill. In general, capping is performed when extensive subsurface contamination at a site precludes excavation and removal of wastes due to potential hazards and/or unrealistic costs. Capping is often performed in connection with ground-water extraction or containment technologies (i.e., physical barriers or hydraulic barriers).

2.7.1 Data Collection Requirements

General data requirements for capping are summarized in Table 2-8.

2.7.2 Evaluation

Surface water runoff rates for landfills, surface impoundments closed as landfills, or other areal sources can be estimated with several methods. Fenn et al. (1975) discuss the "water balance method." Given monthly values for precipitation and potential evapotranspiration, estimates of monthly evapotranspiration, runoff, and infiltration can be obtained for different types of soils. Seepage rates through multilayered soil columns can be estimated through successive applications of the method. Thus, the water balance method is applicable to an areal source with a cap. Dass et al. (1977) reported on a similar method.

A somewhat more sophisticated method is incorporated in the Hydrologic Evaluation of Landfill Performance (HELP) model (U.S. EPA, 1984c). The HELP program is an easy-to-use model that was developed to assist landfill designers and regulators by providing a tool to allow rapid, economical screening of alternative designs. HELP is a quasi-two-dimensional model that computes a daily water budget for a landfill represented as a series of horizontal layers. Each layer corresponds to a given element of a landfill design (e.g., cap, waste cell, leachate collection system, and liner). HELP considers a broad range of hydrologic processes including surface storage, runoff, infiltration, percolation, evapotranspiration, lateral drainage, and soil moisture storage. The HELP model requires climatologic data, soil characteristics, and design specifications as inputs. Climatologic data consist of daily precipitation, mean monthly temperatures, mean monthly solar radiation, leaf area indices, root zone or evaporative zone depths, and winter cover factors. Soil characteristics include porosity, field capacity, wilting point, hydraulic conductivity, water transmissivity, evaporation coefficient and Soil Conservation Service (SCS) runoff curve numbers. Design specifications consist of the number of layers and their type, thickness, slope, and maximum lateral distance to a drain, if applicable, or whether synthetic membranes are to be used in the cover and/or liner.

While the water balance method can be solved by hand, the large number of calculations performed by HELP are most efficiently done on a computer. The program is operational on EPA's National Computer Center in Research Triangle Park, North Carolina (U.S. EPA, 1985b). Bicknell (1984) has modified HELP to simulate chemical losses from a landfill. Both leaching and volatilization losses can be estimated. HELP has been used in the analysis of existing landfills and the design of new sites. The results of HELP may be used to compare leachate-production potential of alternative designs, select and size appropriate drainage and collection systems, and size leachate-treatment facilities. The HELP model is available on diskette from the EPA Office of Research and Development in Cincinnati, Ohio.

2.7.3 Engineering Considerations for Implementation

The final cover minimum thicknesses recommended by EPA for a multilayered cap (U.S. EPA, 1989) from final grade are as follows:

- Vegetative and protective layer—A 24-inch thick layer of topsoil or soil fill
- Drainage layer—12 inches of sand (permeability 1×10^{-2} cm/sec)
- First barrier layer component—Synthetic membrane (20 mil thickness minimum)
- Second barrier layer component—24 inches of low permeability compacted soil with a maximum in-place permeability of 1×10^{-7} cm/sec
- Gas vent layer (optional based upon site-specific conditions)—12 inches of native soil or sand to act as a foundation for the cap or to vent/control gas
- Waste

Table 2-8. Data Requirements for Capping

Data Description	Purpose(s)	Source(s)/Method(s)
Extent of contamination	Determine cost effectiveness of cap vs. excavation/removal	Surficial soil and bore-hole sampling and analysis to determine depth and lateral extent of contamination
Depth to ground-water table	May not be effective in areas with a high ground-water table	Hydrogeologic maps, observation wells, and borehole logs
Availability of cover/ capping materials	Implementability and cost	Local borrow pits/quarries, surficial geology maps
Soil characteristics	Suitability for: - drainage layers - impermeable soil layer - mixing with bentonite	Laboratory testing of soil samples
- Gradation		- Sieve analysis, Atterberg Limits
- Permeability (percent compaction, moisture content)		- Moisture/density relationships, permeability testing in triaxial cell per Army Corps of Engineers procedure
- Strength	Slope stability	- Triaxial shear, direct shear testing
Climate (precipitation)	Expected infiltration rate; design criteria	NOAA records; local rainfall records
Final land use	Selection of proper cap design	

The final design profile of a typical multilayered or RCRA cap will also include geotextiles as a filter between the vegetative/protective layer and drainage layer and/or a protective layer over the synthetic membrane.

These performance standards may not always be appropriate, especially in instances where a cap is intended to be temporary, where there are very low amounts of annual precipitation, or when the capped waste is immobile. In such cases, the layer thickness of the cap can be reduced, and only one low permeability layer may be necessary. Alternate designs must provide long-term performance at least equivalent to the recommended RCRA design. All alternative designs must be approved by EPA.

The selection of capping materials and a cap design are influenced by site-specific factors such as local availability and costs of cover materials, desired function of the cover, the nature of the wastes being covered, local climate (rainfall), site topography, hydrogeology, and projected future use of the site.

The most commonly used materials for the impermeable or barrier layer are low-permeability soils such as silty clay and synthetic membranes. The low-permeability soils are typically fine-grained natural soils (silts and/or clay) that can achieve a minimum in-place compacted permeability of 1×10^{-7} cm/sec.

At sites where these soils are not readily available, admixtures to granular soils have been utilized to achieve the required permeability. Recently, bentonite mixed with granular soils has been accepted as an alternative to clay by state agencies for use as bottom containment systems and caps for municipal solid waste landfills.

A soil-bentonite cap is a barrier composed of granular soil and bentonite. When contacted with water, bentonite swells and fills the voids in the soil, thus preventing the passage of water and other liquids. The two principal advantages of a bentonite cap are the low permeability imparted to readily available granular soils by the addition of the bentonite and the self-healing nature of the cap. The base material in the bentonite is a high-swelling sodium montmorillonite that has a unique molecular structure enabling the clay to absorb many times its own weight in water. Good quality sodium bentonite will swell 10 to 15 times the dry bulk volume. The molecular structure of bentonite accounts for its ability to swell to a much greater volume than other natural clays.

Typically, the higher the permeability of the soil to be sealed, the larger the quantity of bentonite required. For hazardous waste sites, soil, bentonite, and water should be fully blended in a computer-controlled pugmill. Soil is dropped onto a conveyor belt and is continuously weighed. Bentonite is then added to the soil at the specified rate. The bentonite and soil are mixed in a pugmill with a metered amount of water, bringing the mixture to the optimum moisture content. After mixing, the soil-bentonite is transferred to the area for application by an asphalt paving machine which precisely distributes the blended soil-bentonite mixture. The mixture is then compacted to the specified density using smooth steel drum vibratory roller/compactors to achieve the required in-place permeability. Quality control testing requirements for the installation of soil-bentonite caps are presented in Table 2-9.

The advantage to using a soil-bentonite admixture is the high degree of quality control and compaction that can be achieved. When properly mixed, the soil-bentonite will have the hydraulic characteristics of a clay but the physical characteristics of the granular soil with which the bentonite was mixed.

Flexible synthetic membranes typically used for capping operations are polyvinyl chloride (PVC), HDPE, very low density polyethylene (VLDPE), and Hypalon. Synthetic membranes range in thickness from 20 mil to over 100 mil, and are available in sheets of varying width and length. Adjacent sheets are overlain in the field and bonded or welded together depending upon manufacturers' specifications. The chemical resistance of a synthetic membrane used for a cap is usually not critical. The thickness and flexibility of a synthetic membrane should be carefully evaluated during material selection. The synthetic membrane should be of adequate thickness to prevent failure under potential stresses during the postclosure care period or from construction. The adequacy of the selected thickness should be demonstrated by an evaluation of the type, strength ,and durability of the membrane; and of site-specific factors such as steepness of slopes, physical compatibility with the material used in the underlying and overlying layers, stresses of installation, expected overburden, climate conditions, and settlement or subsidence. Field seaming of the membrane must be performed by qualified and experienced installers.

The design of the low permeability compacted soil layer will depend upon site-specific factors including the physical properties and engineering characteristics of the soil being compacted, the degree of compaction obtainable, the expected loadings, and expected precipitation. A minimum 24-inch thick layer is recommended in RCRA guidance (U.S. EPA, 1989). This thickness is based upon constructability considerations and the ability to provide uniform permeability for the natural soils of the entire area. For example, silty clay deposits can have fine sand lenses, which can result in localized areas of in-place compacted permeabilities of greater than 1×10^{-7} cm/sec.

Recently, bentonite panels consisting of a dry granular sodium-bentonite layer approximately 1/4-inch thick with a woven polypropylene geotextile on each side have been used to cap an NPL site in New York State (Hudson River PCB Remnant Sites). These panels have the same self-healing and self-sealing characteristics of soil-bentonite. The advantages of this method are flexibility allows rapid and easy installation; a small crew can easily perform the installation; all seams are simple overlap (6-inch) seals; panel can be cut or trimmed with a utility knife; permeability is less than 1×10^{-7} cm/sec (can achieve 1×10^{-9} cm/sec); material is uniform, contained, and rehydrates quickly; subgrade bearing capacity is not a factor; and less truck traffic is required.

The following are key design considerations for a cap (a detailed discussion is provided in U.S. EPA, 1989):

- The slope of the low-permeability layer should be between 3 and 5 percent to prevent erosion and ponding of rain water on the top of the cap. The perimeter side slopes are final grades and should be no steeper than three (horizontal) to one (vertical). For each 20-foot increase in vertical heights, a bench should be constructed in the slope to control surface water runoff and subsequent erosion (U.S. EPA, 1985b).
- The impermeable barrier portion of the cap should be located beneath the average depth of frost penetration

Table 2-9 Quality Control Requirements for Soil-Bentonite Caps

Item	Source(s)/Method(s)	Frequency
Develop bentonite application rate to soil to achieve required permeability for specified compaction		
- Grain size distribution	ASTM D 422, D 1140	Minimum 3 tests per source
- Moisture density relationship	ASTM D 1557	Minimum 3 tests per source
- Permeability testing	Triaxial method with back pressure measurements per U.S. Army Corps of Engineers procedures EM-1110-2-1906	Minimum 3 tests per source
Field construction quality control		
- Moisture density relationship	ASTM D 1557	One 5-day shift
- In-place density	ASTM D 1556	Sample on grid, spacing of 50 feet
- In-place moisture content	ASTM D 2216	Sample on grid, spacing of 50 feet
- Grain size distribution	ASTM D 422, D 1140	One per 300 cy placed measured at mixing plant
- Bentonite content test	ASTM D 1140	One per 200 cy placed measured at mixing plant prior to mixing with water

for the site, as determined by the U.S. Department of Agriculture mapping.

- The vegetative layer should be thick enough to contain the effective root depth or irrigation depth for the type of vegetation planted.
- The drainage layer should be designed and constructed to discharge flow freely in the lateral direction to exit the cap.

Several materials and designs are available for capping. Factors influencing the proper selection of materials and design include desired functions of cover materials, waste characteristics, climate, hydrogeology, projected land use, and availability and costs of cover materials. More detailed sources of information concerning design considerations for specific types of caps are Lutton (1979), U.S. EPA (1985b), U.S. EPA (1985a) and U.S. EPA (1989).

Surface seals require long-term maintenance. Periodic inspections should be made for settlement, ponding of liquids, erosion, and invasion of deep-rooted vegetation. Concrete barriers and bituminous membranes are vulnerable to cracking, but the cracks can be relatively easily repaired (U.S. EPA, 1987).

2.8 SURFACE WATER CONTROL METHODS

Surface water controls are required in instances where runoff from a site requiring remedial actions may transport contaminants from the previously contaminated area. There are several different methods for the control of run-on and runoff. These methods include grading and various forms of surface water diversion. A number of methods may be used in combination to obtain the appropriate degree of surface water control.

Grading describes the reshaping of the surface of a particular site in order to reduce infiltration and erosion while redirecting runoff from the site. This is accomplished through the use of earth-moving machinery and the addition of fill where necessary. The benefits of grading include:

- Relatively low cost if cover materials are readily available
- Reduction of ponding so as to minimize infiltration
- Reduction of runoff velocity and soil erosion

Limitations of grading are:

- It is not applicable to smaller areas of land where there is no room for gradual grading
- Costs increase significantly if appropriate fill is not available within a reasonable distance

Dikes and berms are one method of surface water diversion used for surface areas no greater than 5 acres. These can be used to divert surface water from a site or to prevent mixing of different types of wastes. A dike or berm is constructed by the addition of several lifts of soil, each being adequately compacted, until the desired size is obtained. These structures are constructed around the contaminated area so as to redirect surface flow to drainage ways and away from the contamination.

Benefits of dikes and berms include:

- Construction costs are low assuming that the required soil is readily available
- They can be used to provide protection against site flooding
- They can be constructed quickly with readily available contractors and equipment

Limitations of dikes and berms include:

- Structures are temporary and are usually not used for a period greater than 1 year
- If improperly designed, constructed, or maintained, dikes or berms may increase the infiltration into the ground water

An additional method of surface water diversion is the use of channels and waterways. Channels are excavated ditches that can be used to intercept runoff. Waterways are usually either sodded or lined with rip-rap and are used to carry larger amounts of flow (usually from areas larger than 5 acres). Construction of channels and waterways is simply a matter of excavating to the desired dimensions and lining the channel or waterway appropriately.

Benefits of channels and waterways include:

- Simple, well-established construction techniques minimize construction costs and use readily available contractors and equipment
- They are more appropriate for the collection and transfer of water than berms and dikes.
- They are more permanent than berms or dikes.

Limitations of channels and waterways include:

- Maintenance is required, especially in sodded waterways
- Improperly constructed, designed, and maintained channels and waterways can increase erosion and the rate of surface water infiltration

There is a great variety of channels and waterways, and costs and capacities will vary from one to another

2.8.1 Data Collection Requirements

Data required for selection and design of a method of surface water diversion are included in Table 2-10, along with the reasons that the data are required.

2.8.2 Evaluation

Surface water controls will be required under certain circumstances. Cases when surface water controls might be necessary would include:

- Where an impermeable cap is used. Surface waters should be directed away from such a cap so that water does not pond directly above the contaminants.
- If the contaminants are on the surface or contaminated soil is on or near the surface. Surface waters flowing over the site could become tainted with the chemicals present.
- If infiltration through or to contaminated soils or ground water is a significant problem.

2.8.3 Engineering Considerations for Implementation

There are several other issues to consider when determining whether or not to use surface water controls and what type of surface water controls to use.

Grading is usually performed in conjunction with revegetation. The vegetation may further decrease infiltration

Table 2-10. Data Requirement for Runoff/ Run-On Control

Data Description	Purpose(s)	Source(s)/Method(s)
Topography	To determine quantity of runoff, necessity of surface water controls	Site survey
Local soil conditions	Determine usability as fill; infiltration rates	Topographic maps/ percolation testing
Availability of fill	To determine costs of alternatives	Site survey
Climate	To determine amount of rainfall; amount of surface water flow	National Weather Service

and erosion, but without revegetation grading may increase erosion. Periodic regrading may be necessary if subsidence occurs.

Dikes and berms do not usually require a detailed design before construction begins. It is important to remember, however, that they are not usually used to control drainage from an area greater than 5 acres. In addition, they must be designed so that there is sufficient grading for runoff along the length of the dike or berm and the outlet should be directly onto a stabilized area or drainage structure.

Channels and waterways usually require a slightly greater design effort than berms and dikes. They are often designed according to the Manning formula which can calculate the flow capacity of a given channel. Waterways can be either permanent or temporary depending upon the design, and costs can vary significantly.

2.9 GAS VENTING

Gas venting, which may be active or passive, is applicable to the containment (control of migration) of VOCs in soil and, to a lesser extent, bedrock. The effectiveness of a gas venting system is contingent upon soil type, soil density, depth of ground water (saturated zone), and specific gravity of the contaminant. Past applications have primarily been in relation to control of methane gas from landfills and interception of vapor plumes for gasoline or similar releases.

As a containment measure, the goal of gas venting is to create a subsurface air flow pattern that confines hazardous vapors to an area in which potential impacts are minimal, or intercepts vapor flow before it reaches an area where impacts are likely to be significant. The use of vapor extraction systems is best suited for permeable, unsaturated soils such as sand and gravel. Clayey soils usually lack the conductivity necessary for effective vapor extraction (U.S. EPA, 1990b).

The essential component of a gas venting system is a gravel-packed vented trench or a series of vent wells. The vent may be pumped (active) or may be simply open to the atmosphere (passive). A passive vent system is used, where permitted by state regulations, for situations in which gas generated at a source area is lighter than air (i.e., methane), which creates a driving force from the source to the atmosphere. Active vent systems are also used for methane recovery from landfills and for the interception of volatile contaminants migrating from a source in the unsaturated zone of the soil. Typical ranges of gas flow rates expected in natural in situ soils can vary from 0.5 cubic feet per minute (cfm) to 2 cfm per linear foot of well screen.

Additional vent system components include a vacuum blower (for active systems), a manifold (to connect multiple wells), off-gas treatment such as an enclosed flare or carbon adsorption (to meet air quality criteria), a condensate holding tank, and monitoring and control equipment.

Some of the benefits of gas venting are:

- Rapid response time can be achieved
- System is installed in situ and can be operated with relatively little disturbance to other operations and structures
- The required equipment and services are readily available
- Venting has relatively few secondary impacts, as no chemicals or reagents are introduced into the soils

Some of the limitations to gas venting are:

- Venting can cause flow of unrelated vapor contamination, if present.
- Off-gas may require treatment; treatment residuals may be RCRA-regulated waste.
- The technique is only applicable to volatile contaminants migrating in the vapor phase, and will not intercept free-phase liquid contamination. However, continued venting will induce volatilization of the free phase.

2.9.1 Data Collection Requirements

The data required for assessment and design of waste containment by gas venting are primarily related to the distribution of the contaminant of concern and the ability of the unsaturated zone to transmit vapor flow. In addition, some environmental factors are also important in determining whether gas venting should be pursued. Table 2-11 summarizes the data requirements for implementation of this alternative and relevant data collection methods.

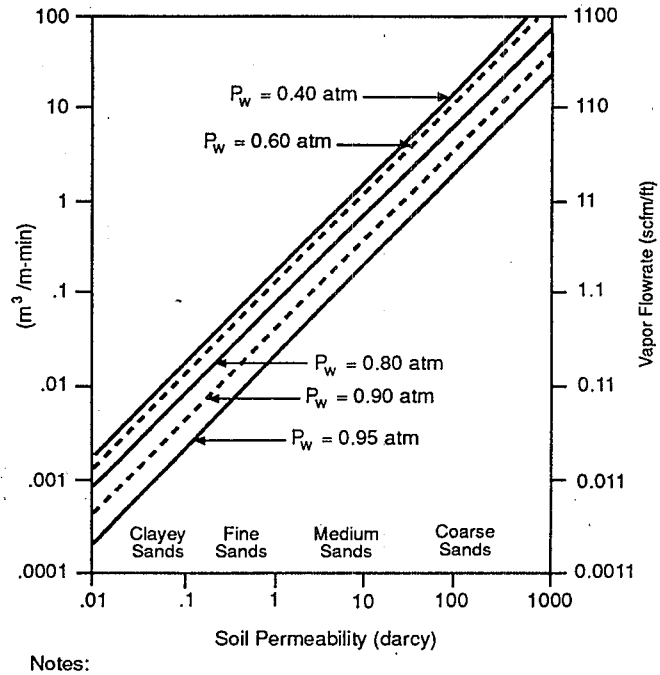
2.9.2 Evaluation

In most situations where vapors migrating through the unsaturated zone have the potential to adversely affect human health or the environment, gas venting has the potential to reduce risk. The following discussion assumes that initial evaluation of the site has indicated that significant vapor concentrations are present, which have potential to migrate in the vapor phase to a point of impact (structures may be damaged or injury caused in the case of explosive gases, or employees or local residents may be harmed in the case of toxic gases). Under these conditions, the relative economic feasibility of the technique depends on its projected cost as compared to other stabilization measures. The cost of a gas venting system depends on:

- The number and depth of wells to be drilled and the amount of associated piping
- The flow rate and pressure at which active wells will be pumped
- The type and extent of off-gas treatment required

The arrangement of wells and projected pumping rates can, for the screening process, be estimated from permeabilities derived from soil descriptions and laboratory testing. Figure 2-7 shows the predicted extraction rates for a range of soil permeabilities and applied vacuums, assuming a well radius of 2 inches and a 40-foot radius of influence during pumping. Similar results for other parameter values can be obtained from the formulae in Johnson et al. (1990).

Pumping rates and expected discharge concentrations are compared to applicable air discharge criteria to determine what off-gas treatment is likely to be required. These data are then used to develop order-of-magnitude costs for installation and operation of the system. These costs can then be compared to any other potentially applicable remedial costs to determine which technique is most feasible. The data required for screening will typically be available shortly after the initiation of RFA activities.



Notes:

Well Radius = 2 inches
Radius of Influence = 40 ft
P_w = Pressure in Extraction Well

Figure 2-7. Soil Permeability versus Vapor Flowrate for Several Values of Applied Vacuum (Adapted from Johnson et al., 1990).

In order to develop the final design of a gas venting system, accurate data regarding soil permeability and the ability of air to move through the soil are required. One method to determine air permeability is the air pumping test. Air pumping tests are similar to ground-water pumping tests used to determine aquifer yield, except that the wells are screened above the ground-water table. A single well is pumped with a vacuum blower at a known, constant flow rate, and the resulting changes in air pressure are measured in surrounding well(s). This information is used to determine the range over which a well will intercept vapor flow, as a function of pumping rate, and is used to select a suitable vent (extraction well) system geometry for containment and sizing of equipment.

The geometry and method to be used at a site are determined primarily by the thickness of the permeable zone and the soil air permeability. Excavation conditions that are not difficult, a shallow permeable zone, and high in situ soil permeability all favor the use of trenching methods. A deep, highly permeable unsaturated zone and difficult excavation conditions favor the use of wells. Pressurized systems (air injection) must be used with caution, because contaminants are forced away from the point of containment (injection well or trench) and can then migrate toward other potential receptors.

Table 2-11. Data Requirements for Gas Venting

Data Description	Purpose(s)	Source(s)/Method(s)
Physical Characteristics		
Permeability	Determine radius of system influence; estimate pumping rate for active venting systems	Estimate from soil descriptions Laboratory: Evans, 1965. Field (pumping test): Johnson et. al., 1990.
Depth of air permeable zone	Determine depth of system necessary to contain or intercept flow	Soil boring program
Moisture content	Estimate effects of expected moisture variations on air permeability	ASTM D2216
Soil temperature	Estimate effect of temperature changes on air viscosity and resulting flow velocity	Appendix V of U.S. Army (1972)
Soil type/gradation	Estimate flowrates in soil	ASTM D422
Chemical Characteristics		
Contaminated area	Determine size and location of system	Soil gas sampling
Phase distribution of contaminant	Non-gaseous phases will not be intercepted, but may be affected	Soil borings/ monitoring wells; literature study
Environmental Characteristics		
Proximity of other contaminant sources	Determine whether vent system can induce migration of additional contamination on site, or controlled contamination off site	Site survey and historical records; Soil sampling program

2.9.3 Engineering Considerations for Implementation

The implementation of a soil-venting system includes general site preparation, installation and operation, and maintenance.

General preparations include making the site accessible to equipment and materials and dust and volatile emissions controls, if necessary.

During installation, waste removal and disposal in accordance with RCRA regulations will be required for drilling and trenching operations in contaminated areas. Waste may also be generated by off-gas treatment, i.e., condensate.

There are several issues concerning implementation, which are as follows:

- Potentially hazardous vapor may not be contained, or may be driven to unanticipated receptors, when using pressurized wells or trenches
- Numerical modeling has shown that in many typical landfill situations, venting may not be effective if the vents do not penetrate the full thickness of the unsaturated permeable zone

- Extraction well systems should be installed such that the influence of each well overlap; numerical modeling has shown that inadequately spaced wells can aggravate vapor migration (Moore et al., 1982)
- Active systems using a collection manifold should be designed to drain condensate to a central collection point, and to prevent freezing in colder climates
- Passive vents are not generally effective except along the perimeter of landfills where methane is generated
- Gas treatment and condensate collection produce waste that may require special handling and must comply with RCRA disposal regulations
- Gas can be collected for use after extraction, i.e., methane collected from a landfill can be used to generate electricity or steam if at adequate concentrations (i.e., 35 to 55 percent)

2.10 HYDRAULIC FRACTURING

Hydraulic fracturing refers to the injection of fluid into soil or rock under pressure to create fractures, and thereby increasing the hydraulic conductivity. A proppant, which is generally a permeable material such as sand, is injected with the fluid to keep the fractures open after the pressure is released. This technology is not a containment or treatment technology in itself; however, it may be used to modify a formation of low hydraulic conductivity in order to permit or enhance other technologies requiring a permeable medium such as pump-and-treat, vacuum extraction, soil flushing, or bioremediation.

In the case of hydraulic fracturing of bedrock, much experience has been gained from the oil industry, where this technology was initially developed. The hydraulic fracturing of soils is a less-developed technology. The Center Hill Research Facility at the University of Cincinnati has an ongoing project to test the feasibility of hydraulically fracturing soils and using the newly formed fractures to enhance other remediation technologies, particularly bioremediation. To date, feasibility of hydraulic fracturing has been demonstrated only in an unsaturated glacial till soil in Ohio.

A potential benefit of hydraulic fracturing is that it can be used to develop a larger framework of interconnected pore space, and consequently enhance the zone of influence of a particular remediation technology. This technology, when further developed and proven, may be useful for remediating soils in cases where contaminants have migrated by slow advection or diffusion into materials with very low hydraulic conductivities. Its application in cases of contamination of bedrock aquifers, in which it is used to increase the yields of extraction wells, has been well demonstrated by similar applications in potable water well construction.

The principal drawback of using this technology in soils is that it has not yet been demonstrated in a wide range of soil types or at any waste sites.

2.10.1 Data Collection Requirements

Since this technology is still in the developmental stages for applications in soils, the data collection requirements are not well documented. Many of the requirements in Table 2-12 are common to containment or pump-and-treat technologies that would be enhanced by hydraulic fracturing.

2.10.2 Evaluation

The first steps in the evaluation of the applicability of this technology are (1) determination of the need to increase hydraulic conductivity and (2) determination of the containment or treatment technology that is going to be used after enhancement by hydraulic fracturing. The usefulness of hydraulic fracturing has been well documented in increasing well yields in rock. Thus, its usefulness in enhancing pump-and-treat systems in low-yielding rock formations is that larger yields may result and a more widespread area may be impacted by a single well. This will result in fewer overall wells and shorter cleanup times. Its usefulness in enhancing bioremediation of saturated and unsaturated soils and ground water, soil flushing, and vacuum extraction is potentially the same but has yet to be demonstrated.

The orientation of the fractures created by hydraulic fracturing depends largely on the in situ state of stress in the material to be fractured. The plane of fracture will be perpendicular to the direction of least principal compression (U.S. EPA, 1991b). The reference cited contains a detailed explanation of the theoretical analysis of fracture propagation.

The evaluation that has been performed at experimental fracturing sites in soil has consisted of excavating test pits or trenches around the hole from which the fractures were propagated to determine their configuration and width. It is conceivable that the evaluation of this process at any given site would include a pilot study to determine if the actual fracture pattern matches the predicted one.

2.10.3 Engineering Considerations for Implementation

The applicability of hydraulic fracturing to remediation of waste sites through the enhancement of containment or treatment technologies such as bioremediation, pump-and-treat, vacuum extraction, or soil flushing is dependent on site conditions. Although the method has been widely demonstrated to increase well yields in bedrock and therefore to be applicable to low-yielding pump-and-treat enhancement, it has not yet been widely tested in soils alone or with the other technologies. A potential drawback to this technology in soils and bedrock includes creating undesirable pathways of contaminant migration into previously unimpacted areas. Also, it does not result in a

Table 2-12. Data Requirements for Hydraulic Fracturing

Data Description	Purpose(s)	Source(s)/Method(s)
Bedrock type, degree of fracturing and weathering	Determine applicability of method to bedrock conditions	Geologic maps, bedrock outcrop mapping, rock coring of bedrock in borings, bedrock trench mapping
Depth to aquifer/ water table	Select appropriate depths for fractures	Hydrogeologic maps, observation wells, boring logs, piezometers, geophysical surveys
Types, thicknesses, and extents of saturated and unsaturated subsurface materials	Design fracturing system	Hydrogeologic maps, surficial geology maps/reports, boring logs, geophysics
Hydraulic conductivities and storativities of subsurface materials	Determine need for hydraulic fracturing	Pumping tests, slug tests, laboratory permeability tests
Contaminant concentrations and areal extent	Locate and design fracturing system	Water quality data
NAPL density/ viscosity/solubility	Predict vertical distribution of contamination, design fracturing system	Literature

completely permeable medium but instead creates pathways by which otherwise inaccessible fractures or soil masses may be reached by remedial technologies.

2.11 REFERENCES

Bicknell, B.R. 1984. Modeling Chemical Emissions from Lagoons and Landfills, Final Report. U.S. EPA Environmental Research Laboratory, Athens, CA.

Cole, C.R. 1982. Evaluation of Landfill Remedial Action Alternatives through Groundwater Modeling. Proc. of 8th Annual Research Symposium on Land Disposal of Hazardous Waste. EPA-600/9-82-002.

Colorado State University. 1988. Digital Operational Management Model of the North Boundary System at the Rocky Mountain Arsenal Near Denver Colorado. Technical Report No. 16, Dept. of Civil Engineering.

Dass P. et al. 1977. Leachate Production at Sanitary Landfills. Proceedings of the American Society of Civil Engineers. *Journal of the Environmental Engineering Division.*

Eastman Christensen Company. 1991. Horizontal Wellbore System for Ground-Water Remediation. Informational Circular.

Fenn, D.G. et al. 1975. Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites. Report SW-168. U.S. EPA.

Hantush, M.S. 1964. Hydraulics of Wells. In: Advances in Hydroscience (V.T. Chow, ed.). Academic Press, New York, NY.

Hantush, M.S. and I.S. Papadouplos. 1962. Flow of Groundwater to Collection Wells. Proc. Am. Soc. Div. Engrs., pp. 221-244.

Johnson, P.C., C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colhart. 1990. A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems. Groundwater Monitoring Review, Vol. 10, No. 2.

Kapack D.S., B.B. Looney, C.A. Eddy, and T.C. Hazen. 1991. Innovative Groundwater and Soil Remediation. In Situ Air Stripping Using Horizontal Wells. NWWA Third Outdoor Action Conference Proceedings, pp. 47-58.

Karlsson, H. and R. Bitto. 1990. New Horizontal Wellbore System for Monitor and Remedial Wells. HMCRI 11th National Superfund Conference Proceedings, pp. 357-362.

Langseth, D.E. 1990. Hydraulic Performance of Horizontal Wells. HMCRI 11th National Superfund Conference Proceedings, pp. 398-408.

Lohman, S.W. 1972. Ground Water Hydraulics. U.S. Geological Survey Professional Paper 708. U.S. Government Printing Office.

Moore, Charles A., Iqbal S. Rai and John Lynch. 1982. Computer Design of Landfill Methane Migration Control. *Journal of the Environmental Engineering Division*, ASCE. Vol. 108, No. EE1.

Moore, Charles A., Iqbal S. Rai, and Ayad A. Alzaydi. 1979. Methane Migration Around Sanitary Landfills. *Journal of the Geotechnical Engineering Division*, ASCE. Vol. 105, No. GT2.

Osiensky, J.L. 1983. Groundwater Withdrawal Schemes for Uranium Mill Waste Disposal Sites. *Groundwater Monitoring Review.*

Quince, J.R. and G.L. Gardner 1982. Recovery and Treatment of Contaminated Groundwater. *Groundwater Monitoring Review.*

Spooner, P.A., R.S. Wetwell, and W.E. Grube, Jr. 1982. Pollution Migration Cut-Off Using Slurry Trench Construction. Conference Proceedings, Management of Uncontrolled Hazardous Waste Sites.

U.S. Air Force. 1971. Dewatering and Groundwater Control for Deep Excavations. TM-5-818-5 NAV FAC P-418, AFM 88-5 Chap. 6.

U.S. EPA. 1991a. Conducting Remedial Investigation/Feasibility Studies for CERCLA Municipal Landfill Sites. EPA/540/P-91/001.

U.S. EPA. 1991b. Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions. Risk Reduction Laboratory. Cincinnati, OH.

U.S. EPA. 1990a. Ground-Water Handbook. Volume I: Ground Water and Contamination. EPA/625/6-90/016a.

U.S. EPA. 1990b. Handbook on In Situ Treatment of Hazardous Waste-Contaminated Soils. EPA/540/2-90/002.

U.S. EPA. 1989. Technical Guidance Document: Final Covers on Hazardous Waste Landfills and Surface Impoundments. EPA/530-SW-89-047.

U.S. EPA. 1987. Technology Briefs: Data Requirements for Selecting Remedial Action Technology. EPA/600/2-87-001.

U.S. EPA. 1985a. Modeling Remedial Actions at Uncontrolled Hazardous Waste Sites. EPA/540-2-85/001.

U.S. EPA. 1985b. Handbook for Remedial Action at Waste Disposal Sites. EPA/625/6-85/006.

U.S. EPA. 1984a. Slurry Trench Construction for Pollution Migration Control. EPA 540/2-84-001.

U.S. EPA. 1984b. Compatibility of Grouts with Hazardous Wastes. EPA 600/2-84-015.

U.S. EPA. 1984c. The Hydrologic Evaluation of Landfill Performance (HELP) Model, Volume 1. EPA/530-SW-84-009.

U.S. EPA. 1983. Methods for Chemical Analysis of Water and Wastes. EPA 600/4-79-020.

Weston, Inc. 1989. Remedial Program Evaluation, Gilson Road Site. Nashua, NH. Prepared for NHDES, February.

CHAPTER THREE
Soils Treatment Technologies

Treatment of contaminated soils is conducted as a means of source control to reduce volume, toxicity, or mobility of contaminants. A specific goal of treating contaminated soils is to prevent contaminants from leaching into ground water, migrating off site, and threatening drinking water supplies or other significant resources. Soils may be treated in situ (i.e., in place) or by excavating and then treating. The decision to treat in situ or to excavate depends on the areal extent, depth and volume of contamination, type and concentration of contaminants present, soil characteristics, site hydrogeology and other site characteristics.

The selection of the appropriate treatment technology is dependent upon the properties of the contaminant and the physical and chemical properties of the soil matrix. In situ treatment may be physical, chemical, thermal, biological, or a combination thereof. A thorough knowledge of the site characteristics is essential in determining whether in situ treatment can be utilized and estimating the success of the selected treatment technology. An advantage to in situ treatment is that the RCRA land disposal restrictions (LDRs) are not applicable.

In situ treatment is preferred over soil excavation at sites where contamination is widespread, in both area and depth, or where the contaminated material is not easily excavated. In order for in situ treatment to be effective, however, the site characteristics and soil properties must allow for the injection of air, steam, water, or treatment chemicals, as necessary, to implement the technology under consideration. In many cases, it is desirable to excavate contaminated soil because it is an active source for ground-water contamination. Excavation should be considered under the following conditions:

- The need to remove the contaminant source is immediate
- The site conditions prohibit or limit the effectiveness of in situ treatment
- The treatment technology under consideration requires or would be enhanced by excavation (i.e., solidification/stabilization)

Figure 3-1 presents the technologies applicable for certain site conditions and contaminants. This figure is provided as a preliminary screening tool, to direct the reader to the technologies that may be considered for a specific set of conditions.

The treatment technologies described in the following subsections may be used independently, in combination with each other, or in series with other technologies. The technologies presented herein have been included since they are applicable to a number of potential site conditions that could require a stabilization action. This does not imply, however, that other technologies could not be considered for soils treatment. All of the stabilization technologies presented herein are for in situ treatment, with the exception of the solidification/stabilization process, which may be applied to either excavated or in situ soils.

3.1 SOLIDIFICATION/STABILIZATION

The solidification/stabilization (s/s) process, sometimes referred to as immobilization, fixation, or encapsulation, uses additives or processes to physically or chemically immobilize the hazardous constituents of a contaminated soil.

The basic s/s procedure involves three steps: (1) the mixing of a reagent with the soil, (2) the curing of the mixed product, and (3) the storage or landfilling of the treated soil. Mixing of the soil and reagent can occur in situ either by using a backhoe to apply and mix additives, or by using a more sophisticated injector device with augers to inject the reagent into the soil and a paddle assembly to mix the materials. Due to increasingly stringent volatile and particulate collection requirements, in-vessel mixing is often preferred.

Vessel-type mixers include drums, pug mills, and ribbon blenders. Both mobile and fixed installation systems with emissions control devices are available for mixing and curing of s/s wastes. Curing of the s/s waste may take place in situ, in the mixing vessel, or in a separate storage area/facility. The treated soil is subsequently landfilled or backfilled on site.

Solidification/stabilization processes are applicable to soils contaminated with metals and other inorganics, in addition to nonvolatile and semivolatile organic compounds. The processes are not currently viewed by EPA as applicable for remediation of soils contaminated solely with volatile organic compounds, because these com-

		In-Situ Solidification/Stabil.	Ex-Situ Solidification/Stabil.	Soil Flushing	Chemical Extraction (see Soil Flushing)	In-Situ Bioremediation-Aerobic	In-Situ Bioremediation Anaerobic	Bioremediation-Land Farming	Vacuum Extraction
Site Conditions									
Soil Permeability	High	O	●	●	●	●	●	●	●
	Low	O	●	x	x	x	x	●	x
Depth to Contamination	<15'	●	●	●	●	●	●	●	●
	>15'	x	x	O	O	O	O	x	O
Highly Organic Soils		O	O	O	O	O	O	●	O
Hetergeneous Soils		O	●	x	x	x	x	O	O
Contaminants									
Nonhalogenated Volatile Organics		x	x	●	●	●	x	●	●
Halogenated Volatile organics		x	x	●	●	x	●	O	●
Semivolatile Organics		O	O	x	O	O	O	O	x
PCBs/Pesticides/Dioxins		O	O	x	O	x	x	x	x
Metals		●	●	●	●	x	x	x	x
Other Inorganics		●	●	O	O	x	x	x	x

References: See References for Individual Technologies

● Applicable
O Potentially Applicable
x Not Applicable

Figure 3-1. Applicability of Soils Treatment Technologies.

pounds will be released during the mixing and curing process (U.S. EPA, 1991).

The benefits of using this technology include:

- Additives and reagents are widely available and relatively inexpensive
- The resulting solidified/stabilized material may require little or no further treatment if proper conditions are maintained
- Leaching or mobility of contaminants is greatly reduced
- Soils contaminated with both metals and semivolatile or nonvolatile organic compounds may be treated in one step

The limitations of s/s technologies include:

- S/s technologies do not destroy contaminants
- Volume of treated material may increase significantly with the addition of reagents
- Delivery of reagent to the subsurface and achieving uniform mixing for in situ treatment may be difficult

- Emission of volatile organic compounds and particulates may occur during mixing procedures, requiring extensive emission controls
- In situ solidification of sensitive areas, e.g., wetlands, may inhibit their restoration for future use
- Compliance with RCRA LDRs must be demonstrated if s/s materials are to be landfilled

3.1.1 Data Collection Requirements

Data regarding both physical and chemical characteristics of the contaminated soil should be obtained to assess the feasibility and design of the s/s process. The physical characteristics of the soil will determine handling requirements; the chemical characteristics will determine the degree of hazard in handling or treatment procedures, identify s/s process inhibitors so that pretreatment alternatives can be developed, and assess the compatibility of the soil and s/s processes. Information regarding the environmental setting of the site to be treated and planned future land use should also be collected. Elements of the environmental setting of a contaminated site affect the design of a s/s treatment scheme, particularly if the waste is treated in situ or if the treated waste is backfilled on site. Table 3-1 summarizes the data requirements for the s/s technology.

3.1.2 Evaluation

The effectiveness of proposed s/s processes is waste and site specific and cannot be predicted without treatability testing. At a minimum, the selected s/s treatment process should be evaluated on a bench-scale study to determine:

- Compatability of the soil to be treated with s/s processes
- Safety problems in handling the contaminated soil
- Soil uniformity and mixing and pumping properties
- Volume increases associated with processing
- Development of processing parameters and the level of processing control

Although bench-scale studies will yield such information, a pilot-scale study of the process will provide more accurate, realistic testing and information to predict the feasibility of the proposed s/s treatment process.

Chemical analyses of the soil are needed to determine if the contaminants are amenable to treatment by s/s processes. Most inorganics and semivolatile organic compounds can be effectively immobilized, but s/s technologies are not applicable to soils contaminated solely with volatile organic compounds.

Chemical analyses are also important to determine whether the soil contains constituents that could inhibit the effectiveness of s/s processes. Potentially interfering constituents are specific to the particular s/s process under evaluation, and include oil and grease, halides, and sulfates.

The use of s/s technologies for soil remediation is most appropriate for soils contaminated with only inorganics, or with inorganics and low levels of semivolatile or nonvolatile organic compounds. The use of these technologies for treatment of soils containing high levels of organics is not as well developed.

Safety problems associated with handling the soil during the s/s process include fuming, heat development, volatilization of organic contaminants, and dust evolution. The generation of gases or high heats of reaction or hydration will be identified in bench and pilot studies.

Variations in the soil sample can alter mix viscosity and cause mixing or pumping problems. Pilot studies should be used to evaluate the effectiveness of various types of mixers and pumps.

An increase in volume of a treated soil over the untreated soil is normally associated with the s/s procedure. The degree of volume increase will be best predicted by the results of pilot testing. Processing parameters such as mix ratios, mix times, setting times, and curing conditions can be optimized during bench and pilot testing.

In addition to a process evaluation, the stabilized/solidified product must also be evaluated to determine the effectiveness of the s/s process. The following criteria should be included in the evaluation:

- Leachability of hazardous constituents
- Hydraulic conductivity
- Compressive strength
- Freeze/thaw and wet/dry properties

The leachability of contaminants from the treated soil should be reduced due to chemical or physical binding with the additive.

The hydraulic conductivity of the s/s product is a measure of the rate of movement of water that can pass through the waste. Thus, hydraulic conductivity should be low to minimize the quantity of water capable of contacting the treated soil.

The compressive strength of the treated soil should be sufficient to support structures planned for future uses of the backfilled site. The required compressive strength of the treated soil should be at least 50 psi (U.S. EPA, 1986a).

The treated soil should retain its integrity when subjected to expected freeze-thaw and wet/dry cycles. Fracturing of the treated soil exposed to these cycles increases the surface area over which water contact can be made, thus increasing the potential for contaminant leaching.

Examination of the treated soil on a microscopic scale by methods such as scanning electron microscopy or x-ray diffraction can characterize crystallization contacts, porosity, uniformity, and degree of hydration of the s/s product.

Table 3-1. Data Requirements for Solidification/Stabilization Technology

Data Description	Purpose(s)	Source(s)/Method(s)
Physical Characteristics of Waste		
Percent moisture or water content	To identify pretreatment requirements (i.e., settling or drying) or to design solidification procedures	ASTM D2216-80
Bulk density	To convert weight to volume in materials handling calculations	ASTM D2937-83, D1556-82 D2922-81, D3402.025
Grain size distribution	To design remedial actions and identify pretreatment requirements; very fine-grain wastes create dust problems and lower the ultimate strength of stabilized cement composites; boulders or debris must be crushed or removed.	Appendix V of ASTM D422-63
Cone Index	To determine the ability of in-place wastes to support a load	Sowers and Sowers (1970) ASTM D3441-79
Unconfined compressive strength	To determine the load-bearing capacity of the waste	ASTM D2166-85
Chemical Characteristics of Waste		
Leachability of hazardous constituents	To determine the hazard due to toxicity of a waste	Several leaching and extraction tests are available (U.S. EPA, 1989a)
Bulk chemical analyses including organic solvents and oils, solid organics, acid wastes, oxidizers, sulfates, halides, heavy metals, and radioactive materials	To identify s/s inhibitors and to assess the compatibility of wastes and s/s processes	U.S. EPA SW-846 (1986c) U.S. EPA (1979)

Table 3-1 (Continued)

Data Description	Purpose(s)	Source(s)/Method(s)
Environmental Setting		
Water table elevation	To determine whether dewatering of waste is necessary in in situ applications	Use existing local wells or install observation wells and/or piezometers to determine average and maximum water table elevations at the site
Climate	To determine if temperature is suitable for proper curing	Contact National Weather Service or obtain values of average temperature and temperature range for the site
Frost line depth	To assess whether backfilled treated waste will undergo freeze-thaw cycles	Consult local Soil Conservation Service
Floodplain locations	To avoid backfilling treated waste within a floodplain to minimize contact with water	Refer to Flood Insurance Rate Map for site area; consult town planning bureau or state environmental agency

These microstructural elements affect the durability and leachability of the s/s product.

3.1.3 Engineering Considerations for Implementation

The implementation of a selected solidification/stabilization process typically involves the following steps:

- Pretreatment of contaminated soils
- Removal of contaminated soils
- Storage of materials
- Mixing and metering of materials
- Landfilling of the s/s product

Pretreatment of a soil is often required to facilitate the s/s process or to increase its effectiveness and/or safety. Pretreatment may include the removal of boulders, dewatering of the waste source area, neutralization or homogenization of the soil, or removal of volatile organic compounds through processes such as soil venting.

Soil removal is an implementation step required at sites where in situ mixing is not conducted. Typical earth-moving equipment (backhoes, drag lines, bulldozers, and front-end loaders) are usually utilized, although specific equipment depends on the physical nature of the soil.

Removed soils must be transported to the treatment facility which may be located on or off site. Typical transport systems include pumps/hoses for liquid wastes, conveyor belts for soils treated on site, screw augers, and dump trucks. Vehicles transporting soils off site must be lined to prevent the leakage of wastes.

Storage of materials is required for both in situ and excavation type s/s treatment processes. Storage areas must be allotted for soils awaiting treatment, chemical reagents, and treated soils. Sufficient space is needed so that the treatment operation is not delayed due to the lack of materials. The storage space must also be dry and protected from wind to avoid dispersion of materials. Chemical reagents may require tanks, bins, or hoppers; waste materials may require lined pits and water collection systems.

Mixing of the soil and reagent may occur in situ or in-vessel and is probably the most important step in implementing an s/s process. In situ mixing is commonly accomplished using a backhoe or an injector-type mixer. The volume or weight of a chemical reagent must be measured before mixing is begun. Vessel-type mixers such as pug mills or ribbon blenders may have a specialized metering system to add reagents during mixing. Drums may be used as mixing vessels in small-scale treatment systems.

The final implementation process is the on or off site land disposal of the stabilized/solidified soils. Compliance with RCRA LDRs must be demonstrated for soils contaminated with a restricted RCRA hazardous waste. The treated soil may be transferred to the final disposal area prior to or following the curing period. If the treated soil is fluid-like, it may be pumped to an excavated area on site or to dump trucks for transportation to an off site landfill. Otherwise, it may be backfilled using traditional earth-moving equipment.

3.2 SOIL FLUSHING

Soil flushing is used for removal of a number of organic and inorganic materials from vadose zone soils. A variation of soil flushing, referred to as chemical extraction, may be used to remove non-water soluble organics from the saturated zone.

Soil flushing involves the addition of a solvent or surfactant to contaminated soil to enhance contaminant mobility. The contaminants are then recovered in the ground water by strategically placed extraction wells and pumped to the surface for treatment. Soil flushing is most applicable when soils must be remediated but other technologies such as vacuum extraction, bioremediation, or physical removal (i.e., excavation) are not feasible. High water tables, deep contamination, and high-permeability soils that require dewatering are conditions in which these technologies would be less feasible. Soil flushing is not feasible for soils with low-hydraulic conductivities (e.g., less than 1 ft/day) and for strongly adsorbed contaminants (e.g., PCBs, dioxin). The addition of chemicals to the flushing solution that will increase contaminant mobility are necessary, if strongly adsorbed, hydrophobic contaminants are present in the soil. The extraction of strongly adsorbed contaminants may not be desirable for a stabilized action, however, unless there is an imminent threat to human health and the environment. The more permeable the soil, the more water that can be flushed through the soil and the more practicable this technology. Soil flushing strategies can be incorporated into pump-and-treat or containment systems to accelerate the contaminant removal processes. Soil flushing can be accomplished using sprinkling systems or, more aggressively, by flooding the contaminated area. Chemical extraction involves extracting ground water, amending it with solvents and/or other chemicals, and reinjecting it at strategic locations into the aquifer (U.S. EPA, 1990b). With any soil flushing system, proper controls must be incorporated to prevent migration of extractant-contaminant mixtures.

The flushing solution to be used at a site depends on the type of contamination present. Flushing solutions may include water, acidic aqueous solutions (sulfuric, hydrochloric, nitric, phosphoric, and carbonic acids), basic solutions (e.g., sodium hydroxide), surfactants (e.g., alkylbenzene sulfonate), chelating agents, oxidizing agents, or reducing agents. Water can be used to extract water-soluble or water-mobile constituents. Acidic solutions are used for metals and certain organic constituents (including amines, ethers, and anilines) that are soluble in an acidic environment (U.S. EPA, 1990b). Surfactants can be used for hydrophobic organics, such as oils and petroleums (U.S. EPA, 1990b and c).

The level of treatment that can be achieved will vary depending on the contact of the flushing solution with waste constituents, the appropriateness of the solutions for the wastes, the soil adsorption coefficients of the waste partitioning coefficients, and the hydraulic conductivity of the soil. This technology should produce the best treatment results in highly permeable soils with low organic content. Despite the varying level of treatment accomplished by soil flushing, however, once the waste components have been removed from the soil, results are not reversible.

Soil flushing may be used as a pretreatment for, or in combination with, bioremediation. As a pretreatment step, soil flushing may be used to remove inhibitory compounds or reduce contaminant levels, making the soil media more amenable to biological activity. In combination with bioremediation, the flushing solution can be amended with nutrients to enhance biological activity.

The benefits of using soil flushing include:

- Removal of contaminants is permanent
- Removal of soils is not necessary
- The technology is easily applied to permeable soils

The limitations of soil flushing technologies include:

- The technology introduces potential toxins (the flushing solution) into the soil system. Therefore, containment may be needed.
- Physical/chemical properties of the soil system may be altered because of the introduction of the flushing solution.
- A potential exists for solvents to transport contaminants away from the site into uncontaminated areas. Therefore, containment may be needed.
- A potential exists for incomplete removal of contaminants due to heterogeneity of soil permeability.
- Contaminants are not destroyed. Onsite treatment is required to remove contaminants from extracted solvents.

- Flushing agents usually cannot be recycled.
- It may take a long period of time for remediation below cleanup standards to be achieved.

3.2.1 Data Collection Requirements

Both physical and chemical characteristics of the waste and site soils must be known to assess the feasibility of soil flushing. In addition, hydrogeological data are needed for placement of extraction wells and, in the case of chemical extraction, reinjection wells. Data collection requirements are presented in Table 3-2.

3.2.2 Evaluation

Several factors to consider when evaluating a treatment technology for stabilizing a site include (1) how well the technology will work on the contaminated media; (2) how long the stabilization process will take using this technology; (3) the residuals produced by the process; and (4) the cost of the technology as compared to a technology capable of producing comparable results.

Once it has been established that site hydrogeology is amenable to soil flushing, and the nature and solubility of contaminants are known, the technology can be evaluated in more depth. How well the technology will work and the length of time it will take depends to a great degree on the flushing solution selected. An additional factor in determining duration of stabilization is the number of pore volumes, or flushes, required to remove contamination. The residuals produced will depend on the type of treatment required for recovered flushing solution. For instance, an acidic flushing solution used to remove metals from soil could be treated by pH adjustment, metals precipitation and clarification, or reacidification and then reused. In this case, a metal hydroxide or sulfide sludge may be produced. If the solution cannot be treated and reused, it will require disposal. Cost of the process will depend greatly on the flushing solution used and whether or not it can be recovered and recycled, the method of flushing (e.g., extraction and reinjection or flooding), number of pore volumes necessary, and the controls required.

3.2.2.1 Treatability Testing. The optimum flushing solution(s) for a particular site should be determined experimentally before proceeding on to full-scale remediation. This can be done by conducting shake flask tests or column tests. The flask tests are conducted by filling 500-mL Erlenmeyer flasks with contaminated site soil and various flushing solutions or surfactants, selected based on the nature of the contaminants, and mixing to allow contact between the solution and the soil. Flask tests do not simulate in situ treatment, but provide screening information to select a potential flushing solution.

In situ conditions are best simulated at the bench-scale by column tests rather than flask tests. A column test is performed by packing contaminated soil into a column and applying the flushing solution to the soil. Replicate columns can be used to determine the number of pore volumes required to remove contamination with a particular flushing solution. Replicate columns can be sacrificed after different numbers of flushes, so that soil analyses may be performed. The analyses provide data on contaminant removal as a function of the number of pore volumes flushed.

3.2.3 Engineering Considerations for Implementation

Information on the design and performance of full-scale soil flushing systems is limited. There are a number of factors that must be considered for the design and implementation of a soil flushing system.

3.2.3.1 Introduction and Recovery of the Flushing Solution. How the solvent or surfactant is to be applied to the contaminated media is a critical part of system design. A sprinkling or, more frequently, a flooding system must be designed to ensure saturation of the soil with the flushing solution without spreading the contamination beyond the area of concern. An in situ chemical extraction system must include strategically placed injection wells. Both soil flushing and chemical extraction systems must include a ground-water extraction system designed to hydraulically capture the flushing solution and the contaminants. Vadose zone and ground-water flow modeling may provide useful information for designing these systems.

3.2.3.2 Hydraulic Controls. For some systems, particularly those that involve flooding a contaminated area, a ground-water extraction system may not be sufficient to prevent migration of contamination from the work area during the flushing process. Actual hydraulic barriers, such as slurry walls (see Section 2.2), may be necessary to minimize or prevent migration.

3.2.3.3 Ground-Water/Flushing Solution Treatment. Once the flushing solution has been recovered, treatment for the removal of contaminants and, if necessary, separation of the ground water and the solvent or surfactant must be accomplished. The type of treatment will depend not only on the nature of the contaminants but also on the type of flushing solution. It is not possible to separate most surfactants from water as easily as to separate other flushing agents. Excess surfactant storage capacity and the method and cost of disposal of spent surfactant must then be considered during design. Disposal of treatment system residuals must also be considered.

3.2.3.4 System Performance. A program should be developed to monitor system performance during operation. The program should include sampling and analysis of both the remediation area and the bordering areas. This will provide data on whether contamination is migrating as a result of the flushing process and alert operators when system modifications may be required, as well as provide data on changes in contaminant concentrations in the remediation area. The monitoring program may include both sampling and analysis, and ongoing vadose zone and ground-water flow modeling, using the sampling results to continually update the models.

Table 3-2. Data Requirements for Soil Flushing and Chemical Extraction Systems

Data Needed	Purpose	Collection Method
Contaminant characterization	Necessary for selection of flushing solution(s)	U.S. EPA SW-846 (1986d)
Equilibrium partition coefficient or octanol/water coefficient, K_{ow}, or water solubility	Unfavorable separation coefficient will require excessive volumes of surfactant; also used to select flushing solution $K_{ow} < 10$: amenable to natural flushing $K_{ow} = 1000$: somewhat amenable $K_{ow} > 1000$: requires a surfactant(1)	Values available in references such as U.S. EPA, 1986d
Aqueous solubility	Used to determine whether contaminants can be flushed with water	Values available in references such as U.S. EPA, 1986d
Soil mapping	Used to determine variable soil conditions that could result in inconsistent flushing	Soil sampling
Hydraulic conductivity, ground-water flow pattern	Ground water must permit recapture of flushed contaminants and flushing solutions	Slug tests, pumping tests
Organic content of soil	High organic content could inhibit desorption of contaminants	U.S. EPA SW-846 (1986d)

(1) U.S. EPA, 1990a.

3.3 BIOREMEDIATION

Bioremediation is the process of using bacteria to biodegrade organic compounds in soils. Under favorable conditions, microorganisms may be capable of completely degrading many organic compounds into carbon dioxide and water or organic acids and methane.

The applicability of bioremediation depends on the biodegradability of site contaminants. Petroleum compounds, such as gasoline and diesel fuel, are known to be readily biodegradable. Other biodegradable contaminants include alcohols, phenols, esters, and ketones. Chlorinated compounds become more difficult to biodegrade as the number of chlorine molecules increases. The biodegradation rate, or half-life, of large, heavily chlorinated compounds such as PCBs is very slow. This makes bioremediation an impractical stabilization technology for soil contaminated with these compounds.

Bioremediation should not be considered as a stabilization measure if the soil contains high levels of metals and is not first pretreated, or if the soil is highly impermeable. Bioremediation of contaminated soils is accomplished by the degradation of specific organic constituents, or "parent" compounds, to a number of intermediate compounds. It is a stepwise process, which may involve many enzymes, many species of organisms, and many intermediate compounds before the parent compound is mineralized.

Mineralization is the complete degradation of organic compounds under aerobic conditions to CO_2, H_2O, inorganic compounds, and cell proteins or, under anaerobic

conditions, to organic acids, methane, and/or hydrogen gas. Under normal degradation conditions, a constituent may not be completely mineralized but may be transformed to intermediate products. These intermediate products may be just as hazardous as the parent compound. The goal of controlled onsite bioremediation is degradation of the parent compound to yield products which are not hazardous to human health or the environment.

This handbook focuses on land-based bioremediation methods, with soil itself used as the treatment medium, in contrast to reactor-based systems. Particular emphasis is on in situ treatment. Methods requiring excavation of the contaminated soil are not addressed since the effort required for implementation may not be appropriate for an interim measure. The bioremediation methods to be discussed, due to their applicability for stabilization in place, include land farming and in situ treatment.

Landfarming involves the aeration of oil and other hazardous materials in soil and sludges by tilling or other cultivation methods, with the addition of nutrients. This method has been used by the oil refining industry for the disposal of oily sludges for many years. The methods can be applied in situ, where soil contamination is relatively shallow. Addition of microbial cultures can be used to augment the indigenous microbial population and speed up the rate of biodegradation.

In situ bioremediation of subsurface materials generally involves the stimulation of naturally occurring, or indigenous, microorganisms to degrade organic contaminants. The microorganisms are stimulated by addition of agricultural fertilizers, such as manure; aqueous solutions of nutrients, such as ammonia and orthophosphate; and possibly an oxygen source, such as hydrogen peroxide. This is typically done by pumping ground water from the aquifer, treating it to remove contaminants, and adding nutrients and an oxygen source before reinjecting it into the aquifer. Water is withdrawn faster than it is reinjected, creating a pressure sink at the withdrawal point which hydraulically contains the contamination and increases the flow rate of nutrients through the aquifer (Hazardous Waste Consultant, 1989). In some cases, other environmental parameters such as pH and temperature can be optimized to stimulate biological activity.

Both aerobic and anaerobic processes are applicable to the degradation of hazardous materials. Aerobic biodegration, which relies on the presence of oxygen, is applicable to remediation of soils contaminated with nonchlorinated organics, such as fuel oil components, and some chlorinated materials.

Many chlorinated solvents, such as tetrachloroethene (PCE), trichloroethene (TCE) and 1,1,1-trichloroethane (TCA) are resistant to aerobic biodegradation. These compounds may, however, be degraded under anaerobic conditions. The degradation of these compounds involves reductive dehalogenation, where chlorine is replaced with hydrogen, to form new compounds that may be more mobile and toxic than the original compound before being mineralized (Wilson, undated; Ehlke, undated). Chlorinated alkenes have been mineralized by cometabolism, or methane-utilizing bacteria (methanotrophs). In other contaminated soil systems, some chlorinated compounds can be reductively dehalogenated to produce intermediate products that can then be degraded further aerobically. An example is the anaerobic reductive dehalogenation of 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) to 2,4-dichlorophenoxyacetic acid (2,4-D), which can then be treated aerobically (U.S. EPA, 1990c).

Very often bioremediation is combined with other technologies, either by design as with pump-and-treat and in situ bioremediation, or as part of a treatment train, such as posttreatment following soil flushing or vacuum extraction.

The benefits of in situ bioremediation include:

- Excavation of contaminated materials is not required
- It may result in complete degradation of organic contaminants to nontoxic byproducts ($C0_2$, CH_4, H_2O)
- There are minimal mechanical equipment requirements

The limitations of in situ bioremediation include:

- There is a potential for partial degradation to equally toxic, more highly mobile byproducts
- It may be difficult to contain volatile organic compounds emitted during remediation
- The process is highly sensitive to toxins and environmental conditions

3.3.1 Data Collection Requirements

Data needs that are critical for evaluating whether soil conditions are favorable for bioremediation are presented in Table 3-3. Soil conditions may be more easily manipulated to increase the potential for microbial activity for landfarming, where surface soils may be tilled to distribute oxygen and nutrients. This may not be possible for in situ bioremediation due to heterogeneous soils or low hydraulic conductivity. Soil characteristics specifically important to the success of in situ treatment are presented in Table 3-4. Data collection requirements are identified in Table 3-5.

3.3.2 Evaluation

Several factors to be considered when evaluating a treatment technology for stabilizing a site include (1) how well the technology will work on the contaminated media, (2) how long the stabilization process will take using this technology, (3) the residuals that are produced by the process, and (4) the cost of the technology as compared to a technology capable of producing comparable results. For bioremediation, the first two factors, how well the

technology will work and how long it will take, are most important in determining the feasibility of this technology for a particular site.

A test has been developed for assessing the feasibility of in situ bioremediation (Hazardous Waste Consultant, 1989). The test consists of a simple scoring system which weighs the relative influence of three factors:

- Nature and biodegradability of contaminants
- Permeability, thickness, and location of aquifer
- Soil and ground-water geochemistry

Since in situ bioremediation is often implemented in conjunction with a pump-and-treat system, the ability to extract and recharge ground water should be evaluated to determine process feasibility.

Information on degradation rates, or half-lives, of the specific compounds to be degraded should be obtained in order to evaluate the feasibility of bioremediation. Data on degradation rates are available in several of the referenced EPA documents (U.S. EPA, 1988a; U.S. EPA, 1990c). Degradation rates can also be determined experimentally by treatability testing.

Methods for evaluating the feasibility of bioremediation and for providing data for implementation are discussed in the following subsections.

3.3.2.1 Treatability Testing. EPA has developed a bench-scale interim protocol for determining the aerobic biodegradation potential of organic contaminants in soils. The protocol is designed to permit evaluation of biodegradation rates under different environmental conditions, e.g., pH, moisture content, and nutrient level. Removal of contaminants due to abiotic mechanisms (volatilization, chemical transformation, or adsorption) is also evaluated under the protocol. The test method is referred to as a flask test or slurry test. A detailed description of the test protocol is presented in *Determination of Aerobic Degradation Potential for Hazardous Organic Constituents in Soil-Interim Protocol* (U.S. EPA, 1988b).

The EPA protocol does not simulate in situ bioremediation; however, flask or slurry tests are appropriate for assessing the feasibility of bioremediation, whether in situ or by landfarming. The tests do not yield information on the biodegradation rates likely to be observed in situ.

In situ conditions are best simulated at the bench scale by column tests rather than flask tests. A column test, however, may not provide a completely representative model of subsurface conditions if heterogeneous soils are present. A column test is performed by packing contaminated soil into a column and applying water to the soil. The water may be amended with nutrients, an oxy-

Table 3-3. Critical Environmental Factors for Microbial Activity

Environmental Factor	Purpose/Optimum Levels
Available soil water	Degradation can be limited by insufficient or excess moisture 25 to 85% of water holding capacity; -0.01 MPa
Oxygen	Aerobic metabolism: greater than 0.2 mg/L dissolved oxygen, minimum air-filled pore space of 10%; anaerobic metabolism: O_2 concentrations less than 1%
Redox potential	Aerobes and facultative anaerobes: greater than 50 millivolts; anaerobes: less than 50 millivolts
pH	5.5 - 8.5
Nutrients	Sufficient nitrogen, phosphorus, and other nutrients so as not to limit microbial growth (suggested C:N:P weight ratio of 120:10:1, limiting ratio 300:15:1)
Temperature	15 - 45°C

Adapted from U.S. EPA, 1988a; U.S. EPA, 1990c.

Table 3-4. Site and Soil Characteristics for In Situ Treatment

Site location/topography and slope
Soil type, and extent
Soil profile properties
Boundary characteristics
Depth
Texture*
Amount and type of coarse fragments
Structure*
Color
Degree of mottling
Bulk density*
Clay content
Type of clay
Cation exchange capacity*
Organic matter content*
pH*
Eh*
Aeration status*
Hydraulic properties and conditions
Soil water characteristic curve
Field capacity/permanent wilting point
Water holding capacity*
Permeability* (under saturated and a range of unsaturated conditions)
Infiltration rates*
Depth to impermeable layer or bedrock
Depth to ground water,* including seasonal variations
Flooding frequency
Runoff potential*
Geological and hydrogeological factors
Subsurface geological features
Ground-water flow patterns and characteristics
Meteorological and climatological data
Wind velocity and direction
Temperature
Precipitation
Water budget

* Factors that may be managed to enhance soil treatment.
Source: Adapted from U.S. EPA, 1984.

gen source, or microbial inocula. Replicate columns are sacrificed at different times so that soil analyses may be performed. The soil analyses provide data on contaminant concentrations as a function of time. These data are used to calculate biodegradation rates. Testing procedures for column testing can be found in Stroo et al. (1989).

Anaerobic systems have been tested by using microcosms. Test methods are described in the referenced literature (Wilson, undated; Ehlke et al., undated; Gibson et al., undated).

3.3.2.2 Mathematical Models. Modeling, when integrated with site characterization and treatability study results, can provide information on the rates and extent of treatment that may be expected at the field scale under varying conditions and on degradation and partitioning processes within a system. Several comprehensive mathematical models are available for evaluating behavior of an environmental system. The Regulatory and Investigative Treatment Zone Model (RITZ Model) developed at the U.S. EPA Robert S. Kerr Environmental Research Laboratory has been used to describe the fate and behavior of organic constituents in a contaminated soil system (U.S. EPA, 1988c). The Vadose Zone Interactive Processes (VIP) model simulates dynamic behavior of organic constituents in unsaturated soil systems under variable conditions (Stevens et al., 1988c).

3.3.2.3 Field Operation. In some cases, it may be beneficial to proceed with implementation of a bioremediation system and evaluate the system during operation. Although this method of evaluation can be risky, it may expedite the stabilization process and may ultimately reduce costs. This method should be considered for nonhalogenated hydrocarbon-contaminated soils (such as fuel oil spills) with little or no inhibitory constituents, such as heavy metals. For an in situ system, site hydrology and soil and water chemistry should be known to be favorable for biological activity.

Evaluation of such a system can be accomplished by monitoring components such as total petroleum hydrocarbons (TPH), TOC, and any other representative components in the soil and ground water prior to and during remediation. The contaminants of concern must always be monitored.

It is also recommended that a control area be established upgradient of contamination. This should be done in order to compare natural levels of biological activity to the enhanced biodegradation provided by nutrient and oxygen additions (U.S. EPA, 1990c).

3.3.3 Engineering Considerations for Implementation

There are a number of factors that should be considered for the design and implementation of a bioremediation system. Although these factors generally pertain to any system, the mechanism by which they are implemented depends greatly on the type of system, i.e., landfarming,

Table 3-5. Data Requirements for Bioremediation

Data Description	Purpose(s)	Source(s)/Method(s)
Organic contaminant characterization: VOCs/SVOCs/PAHs/ PCBs/Pesticides	Type and concentration of materials in soil matrix necessary to evaluate potential for degradation; determine potential toxicants, potential need for mutant bacteria, need for ancillary VOCs treatment	Organics analyses U.S. EPA SW-846 (1986)
Metals	Needed to determine potential for microbial inhibition	Metals analyses U.S. EPA SW-846 (1986)
pH	Needed to determine whether adjustment is necessary for treatment	Soil pH U.S. EPA SW-846 (1986)
Nitrogen/Phosphorus	Needed to determine whether supplemental nutrients are necessary	Soil analyses for $NO_3/NH_3/PO_4$ Standard methods for analysis of water and wastewater
Microbial characterization	Provides information on micro-organisms present in the soil	Plate count
Soil permeability	Necessary for in situ treatment	Percolation testing, slug tests, pumping tests
Soil water content	Needed to determine whether irrigation or drainage is necessary for microbial growth	ASTM D2216-71 (1973)
Seasonal temperature fluctuations	Needed to determine length of season available for bioremediation	Contact National Weather Service or obtain values of average temperature and temperature ranges for the site

Adapted from U.S. EPA, 1988a; U.S. EPA, 1988d; U.S. EPA, 1990c.

aerobic in situ degradation, or anaerobic in situ degradation. Soil enhancement methods are described below.

3.3.3.1 Enhancement of Biological Mechanisms. Since biological activity may be greatly improved by enhancing certain soil properties or site conditions, it may be beneficial to design such enhancements into the system. However, treatment intended to enhance soil properties or site conditions must not be implemented in such a way that it would severely restrict microbial growth or biochemical activity, or increase mobility of contaminants in an in situ system.

Soil Moisture. Soil moisture can be increased using standard agricultural irrigation practices such as overhead sprinklers or subirrigation. To remove excess water or lower the water table to prevent water-logging, drainage or well point systems can be used. Soil moisture control can be combined with a pump-and-treat system where contaminated ground water is extracted, treated to remove contamination, and amended with nutrient and an oxygen source, if desirable, before it is reinfiltrated or used for irrigation.

Oxygen Control. Generally, supplying sufficient oxygen for microbial activity is a greater implementation concern for in situ treatment than for other aerobic methods, such as landfarming. Air can be supplied in situ by injection of aerated water through well points. Although this is the most economical method, the oxygen supply is limited by the solubility of oxygen in water. The addition of hydrogen peroxide to reinjection or irrigation water is a common method of supplying oxygen. This can be accomplished with basic chemical feed and mixing equipment. High concentrations of hydrogen peroxide are toxic to microorganisms; however, the microorganisms can usually be acclimated. An advantage to using hydrogen peroxide in an injection well system is that it helps keep the wells free of heavy biogrowth. An alternative approach is the addition of nitrate to the system, rather than an oxygen source. This approach has been found to be effective and more economical in some studies (U.S. EPA, 1990c). Tilling is used to aerate landfarming systems.

Nutrients. Commercial agricultural fertilizers and nutrient solutions can be used to supply supplemental nitrogen and phosphorus. Power implements, tillers, and applicators can be used to apply the nutrients to land-based systems, or nutrients can be added to treated water from a pump-and-treat system and applied through reinfiltration or irrigation. Nutrients are necessary for both aerobic and anaerobic degradation.

Soil Temperature. Land-based bioremediation must be planned to take advantage of the warm season in cooler regions of the country and the cooler season in hot, arid regions. Temperature can be controlled to limit excess heat loss and gain by several methods. Vegetation can be used as an insulator to reduce heat loss and limit frost penetration during cold weather for in situ systems. Application of mulches can help control heat loss and gain, as well as loss of moisture. For instance, a black paper or plastic mulch absorbs radiant energy during the day and reduces heat loss at night. A sprinkle irrigation system can help provide frost protection during the winter and cooling during the summer, increase thermal conductivity of the soil, and provide moisture.

Addition of Commercial Bacteria. Although bioremediation using indigenous bacteria is desirable, augmentation of biological systems with specifically acclimated or mutant commercial bacteria may be desirable under certain conditions. Addition of commercial bacteria may be desirable when sufficiently large populations of naturally occurring bacteria cannot be developed or when the presence of a specific hazardous organic compound requires use of a specific microorganism. Microbial inoculants with a broad range of metabolic capabilities are commercially available. Before applying these bacteria, however, the actual need must be confirmed. Often, if an indigenous bacteria population cannot be developed, conditions are not favorable for bioremediation. Application methods are determined in consultation with the supplying vendor (U.S. EPA, 1988d).

Creating a Reducing Environment for Anaerobic Degradation. In order to stimulate anaerobic microbial activity, a relatively oxygen free, reducing environment is necessary. Methods of limiting the oxygen concentration in the soil system and creating a reducing environment include soil compaction to reduce oxygen diffusion through large soil pore spaces, keeping the soil wet, deep mulching to impair oxygen diffusion to the soil, or a combination of these techniques. A reducing environment can be further stimulated by the addition of a reducing agent, or electron donor, or by adding excessive amounts of readily biodegradable organic matter, which will result in oxygen depletion. Reducing agents include sulfate and sulfide compounds, which can be added with water. Other electron donors include fatty acids; however, depending on the material to be degraded, these materials may either accelerate or inhibit bioremediation (Ehlke, undated, and Gibson et al., undated). The addition of methane in an air stream is beneficial in stimulating methanotrophs, or the methane-utilizing microorganisms.

3.3.3.2 Ancillary Equipment. For in situ treatment, design of a pump-and-treat system may be required (see Chapter 4). It is necessary to determine placement of the extraction wells, the rate of extraction, the treatment processes necessary to treat water to the desired quality and remove inhibitory substances, and the disposition of excess water. The portion of the treated ground water to be infiltrated or reinjected must be determined. The point of discharge and the discharge criteria must be determined for any portion of water not returned to the system.

In the event that volatilization of organics is occurring during remediation, collection and treatment of the volatile organics should be considered. Use of an inflatable plastic dome erected over a contaminated site has been used to contain volatile emissions. A portable greenhouse with an air collection system could be used as well. The volatile emissions can be treated with a vapor-phase activated carbon system or catalytic oxidation unit. An air discharge permit may be required depending on the particular state regulations.

3.4 VACUUM EXTRACTION

Vacuum extraction, also known as soil vapor extraction and forced air venting, consists of the removal of contaminants by drawing clean air through a zone of contaminated soil. Contaminants desorb from the soil and are carried away with the exhausted air. Continued flushing with clean air can result in a significant decrease in the concentration of volatile compounds in soil.

The basic components of a vacuum extraction system are extraction wells and a blower. In most cases, moisture separation and off-gas treatment will also be required in order to meet air discharge requirements. Recharge wells, an impermeable cover, conditioning of recharge air, flow control and measurement instrumentation, vapor concentration monitoring, and other enhancements are also frequently added in order to improve system performance and flexibility.

The physical basis of the technique rests on the tendency of many volatile compounds to diffuse from the soil matrix to the air in pore spaces as result of the concentration difference between the soil and the clean air that is introduced. Once the contaminants have become entrained in the soil atmosphere, they are carried out of the soil through the circulation of fresh air. The effectiveness of vacuum extraction is therefore related to those properties that determine the extent to which contaminants diffuse into the soil atmosphere and the effort required to remove the contaminant-laden air from the soil.

Vacuum extraction is most likely to be successful at sites where highly volatile contaminants are present in homogeneous soils of high permeability and porosity. The benefits of using vacuum extraction include:

- Implementation can be conducted in situ and requires relatively little disturbance to existing facilities or operations
- The process reduces contaminant concentration and mobility at the treated area
- Implementation can be flexible, allowing for adaptation to changing site conditions or additional analytical and subsurface data
- In situ installation and operation requires little handling of contaminated materials, limiting the risk of exposure to workers and the public
- Vacuum extraction has few secondary impacts; only ambient air need be introduced into contaminated soils, and potentially harmful reagents are not required

Vacuum extraction is only applicable to volatile contaminants; alternative treatment will be required for nonvolatile compounds. Vacuum extraction will be costly and may require prohibitive operation times to achieve cleanup at sites where soil is heterogeneous or has a low air permeability. Other disadvantages of using vacuum extraction include:

- Soils must be permeable and fairly homogeneous for the technique to be efficient; impermeable lenses may adversely affect the results of the process
- Cleanup to low levels can be difficult and require lengthy remediation time with the potential for greater than anticipated operation and maintenance costs, particularly in heterogeneous soils
- Verification of complete cleanup effectiveness can be difficult, particularly in heterogeneous soils
- Off-gas treatment may produce RCRA-regulated wastes, which will require special handling and disposal practices

3.4.1 Data Collection Requirements

Several chemical and physical characteristics of the soil to be treated should be determined or estimated in order to assess the applicability of vacuum extraction to a particular release. These characteristics can be grouped into physical factors which control the rate of air flow through the contaminated portion of the soil and chemical characteristics which determine the amount of contaminant that partitions from the soil to the air. There are environmental considerations which must be evaluated in the design of a vacuum extraction system. The specific data that should be collected and evaluated in assessing the feasibility and developing the design of the technique are presented in Table 3-6.

3.4.2 Evaluation

The feasibility of vacuum extraction at a particular site can usually be evaluated with data that can be easily estimated or obtained from a limited boring program, which is frequently conducted as part of the initial stages of a RCRA facility assessment. Vacuum extraction will typically be applicable if the majority of the following conditions are met (U.S. EPA, 1990a):

- Dominant contaminant form is vapor phase
- Soil temperature is greater than 20°C (in the absence of external heating, soils seldom reach this temperature)
- Soil air conductivity is greater than 10^{-4} cm/s
- Moisture content of soil is less than 10 percent by volume

- Contaminated soil is homogeneous
- Surface area of soil matrix is less than 0.1 square meters per gram of soil
- Vapor pressure of contaminant is greater than 100 millimeters of mercury
- Water solubility of contaminant is less than 100 milligrams/liter

Under the following conditions, vacuum extraction will typically not be feasible (U.S. EPA, 1990a), unless other remedial actions are not available:

- Dominant contaminant phase is solid or is strongly sorbed to soil
- Soil temperature is below 10°C (true at depth in many northern climates)
- Soil air conductivity is less than 10^{-6}cm/s
- Soil moisture content is greater than 30 percent by volume or near saturation
- Contaminated soil is heterogeneous
- Surface area of soil matrix is greater than 1 square meter per gram of soil
- Depth to ground water is less than 1 meter
- Vapor pressure of contaminant is less than 10 millimeters of mercury
- Water solubility of contaminant is greater than 1,000 milligrams/ liter

If site conditions fall between these ranges or are approximately equally split between the lists, vacuum extraction may warrant further evaluation, particularly if other technologies which are well suited to the situation cannot be identified. The formulae and discussion presented by Johnson et al. (1990) and Wilson et al. (1988) can be used for more detailed evaluation and preliminary design of vacuum extraction systems, including development of information required for rough cost estimates. For situations that do not allow a technology to be selected on the basis of the screening approach above, additional investigations will typically be required for detailed evaluation.

After it is determined that vacuum extraction may be applicable to the specific site conditions, additional data will be required to confirm the feasibility of the technology and to prepare a final system design. The most important pieces of data are:

- The extent of contamination; ideally, a comprehensive study requiring an extensive boring and sampling program would be possible for use as an interim measure; however, many sites may be characterized by a relatively inexpensive soil-gas survey augmented with chemical data from a limited boring program.
- More accurate estimates of soil permeability; initial values can be estimated from air flow through vapor sampling ports during a soil-gas survey and/or from laboratory measurement methods. Final design should include a pump test with one or more observation wells ("interference test").
- The potential effects of ground-water mounding below the extraction system and required response.
- The proximity of receptors.
- The proximity of additional potential sources.

The flexibility of the vacuum extraction technology suggests an alternate development path which has been used at many sites. The process of adaptive or incremental design allows the information gained from previous phases of remediation to be directly applied to system improvements. In this type of response, based on limited data (i.e., a limited boring and sampling program and a soil-gas survey), a preliminary system design can be developed. This preliminary system is then implemented, and performance closely monitored during the initial phases of operation. Based on air flow and contaminant recovery data during initial operation, modifications can be made to enhance system operation. This process has two major advantages; a treatment system can be implemented rapidly due to reduced needs for detailed study, and due to modifications a better site-specific system can be built at lower cost. The greatest limitation of this approach is that it requires timely agreement between the regulator, the site operator, and the contractor performing the work.

3.4.3 Engineering Considerations for Implementation

The key elements of a vacuum extraction system are shown in Figure 3-2. The system consists of extraction well(s) and a vacuum pump. The extraction well is installed near the center of the contaminated area, and a vacuum is applied to the well. The resulting flow of air strips contaminants from the soil, which are then discharged to the atmosphere after treatment, if required.

Extraction wells are typically constructed in a fashion similar to ground-water monitoring wells, with the exception that the well is screened in the unsaturated zone (see Figure 3-3). If multiple extraction wells are used, they may be pumped through a manifold connected to a single vacuum pump or to multiple pumps. Piping and manifolds should be sloped to drain condensate to a central storage tank or other discharge point. In cooler climates, piping should be buried below the frost level or heat-traced to prevent blockage of the pipe by frozen condensate.

In most situations, control of vapor emissions will be required prior to discharge of collected gases. The primary means of treating off-gases are catalytic incineration for relatively high contaminant concentrations, and vapor-

Table 3-6. Data Requirements for Vacuum Extraction

Data Description	Purpose(s)	Source(s)/Method(s)
Physical Characteristics		
Permeability	Determine whether sufficient air flow rates can be established; estimate system operating parameters for design (permeability will change with the moisture content of the soil)	Laboratory: Evans (1985) Field: Johnson et al. (1990)
Heterogeneity	Characterize extent and frequency of impermeable zones which will be more resistant to cleanup	Soil boring program
Depth of air permeable zone	Determine depth of zone that will be cleansed by extraction process	Soil boring program
Depth to water table, if different from above	Determine need for lowering water table if contamination is below height of anticipated water table rise	Monitoring wells
Porosity	Determine air velocity in soil pore space	Vomocil (1965)
Moisture Content	Determine need for and effectiveness of moisture control measures to maintain adequate permeability	ASTM D 2216
Particle size distribution/ soil structure and surface area	Determine adsorptive capacity of soil	ASTM D 422 ASTM D 1140
Soil temperature	Will affect volatility of contaminant	
Chemical Characteristics		
Extent of contamination	Determine area to be remediated; determine baseline affected area prior to treatment	Soil-gas survey Soil sampling program

Table 3-6 (Continued).

Data Description	Purpose(s)	Source(s)/Method(s)
Degree of contamination	Determine whether sufficient concentrations are present; determine baseline concentrations prior to treatment	Soil sampling program
Vapor pressure/ Henry's law constant octanol/water partition coefficient	Determine ability of method to strip contaminant from soil	Literature study. Sources include Johnson et al. (1990), U.S. EPA (1989a), Verschueren (1983).
Organic fraction of soil	Estimate retention of contaminant in soil at low concentrations	SW-846 method 9060
Diffusivity	Estimate diffusion rate through low permeability heterogeneities	Fuller et al. (1966)
Environmental Setting		
Proximity of other contaminant sources	Determine whether vacuum extraction system can cause migration of additional contamination to the site	Site survey and historical records; soil-gas survey; soil sampling program

phase carbon adsorption for lower concentrations. Carbon may be regenerated (on site or off site) or disposed of after a single use. In some situations, carbon disposal will be regulated under RCRA land disposal regulations. Industrial facilities can frequently incorporate the waste air stream into other site processes, i.e., as air supply to an existing incinerator or as part of the air stream to an existing treatment unit. Moisture control can also be an important consideration in off-gas treatment, particularly if the treatment option involves carbon adsorption. Condensate from moisture removal may also be a RCRA-regulated waste.

In order to increase control of subsurface air flow and efficiently remediate larger areas, vacuum extraction systems are frequently augmented with a system of air injection wells (usually at the perimeter of the contaminated area). Air injection wells can increase the soil air flow rate and the area through which clean air will flow. To further increase removal efficiencies, the recharge air can be warmed by heat exchangers (electrical or steam) or through addition of steam to the recharge air. Addition of large quantities of steam should be used with caution; however, due to the potential for steam to condense in the soil and facilitate migration of the contaminants into the ground water.

The effectiveness of vacuum extraction can sometimes be increased by the installation of an air-tight cover over the site. The effect of the cover is to prevent surface air flow near recovery wells from providing a disproportionate amount of total air flow in the well, which is of major importance for shallow extraction systems. Surface covers are typically sloped to provide surface water drainage and to limit the migration of contaminants to the ground water through infiltration of rain water.

As noted at one site in Utah, vacuum extraction may be combined with bioremediation to accelerate the stabiliza-

tion process. This process, which involves the addition of moisture and nutrients to the soil during venting, can be particularly useful for remediation of low volatility contaminants and can reduce contaminant concentrations in exhaust gases (Dupont et al., 1991).

For sites where ground water is at or near the zone of soil contamination, it will often be necessary to conduct ground-water pumping concurrently with vacuum extraction. Ground-water pumping will counteract the water table rise caused by reduced air pressure near extraction wells. Lowering the ground water may also expose additional contaminated soil and increase the degree of treatment by vacuum extraction. The technical considerations relevant to ground-water pumping are addressed in Section 4.1.

Ground-water contamination may be present at many release sites where vacuum extraction is applicable. In such situations, concurrent ground-water cleanup may be necessary due to the potential for adverse effect on receptors, the need to remediate or contain the ground-water plume, or the potential for contaminated ground water to recontaminate the unsaturated zone.

A variety of ground-water cleanup technologies can be applied in conjunction with vacuum extraction, including pump-and-treat, bioremediation, and chemical extraction, which are described in other sections of this document. Installations can be constructed to allow concurrent use of a single well for both vacuum extraction and ground-water pumping.

Soil heterogeneity typically reduces the effectiveness of vacuum extraction because of the formation of preferential flow paths during treatment. In such cases, air flows predominantly through the permeable soils, and the less permeable zones are left relatively untreated. The detrimental effects of some heterogeneities or anisotropies can be avoided, however, by inducing air flow across low-permeability layers. This technique is described in the Superfund Innovative Technology Evaluation of soil vapor extraction at Groveland, Massachusetts (U.S. EPA, 1989b).

The performance of a vacuum extraction system is monitored by both internal system parameters and external conditions. Internal parameters include strength of vacuum applied, air flow rate, and contaminant concentration. These parameters can be monitored at each individual extraction well or at the blower. External monitoring includes vapor monitoring wells, which are used to determine vapor flow paths from pressure distributions and to collect vapor samples for chemical analysis; and soil borings, which may be required to determine the actual residual concentration of contaminants in the soil. Based on monitoring data, system parameters such as flow rate and inlet gas temperature may be altered to optimize cleanup efficiency.

In order to control the system operation, valves are typically installed at each wellhead. These valves are then used to restrict flow from less contaminated areas and focus cleanup on the most contaminated soils. In addition, changing flow rates or selectively cycling wells on and off will alter the flow paths of air through the soil, preventing the formation of stagnant zones between wells where air flow velocities would otherwise be very small. Recharge wells can also be strategically placed within the contaminated area to counteract stagnation of air flow.

Several strategies have been used to determine when a system has satisfactorily cleaned a site and may be shut

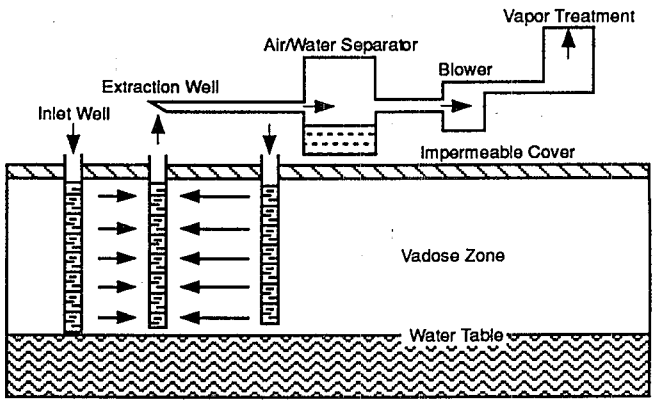


Figure 3-2. Schematic of a Vacuum Extraction System (Adapted from U.S. EPA, 1990d).

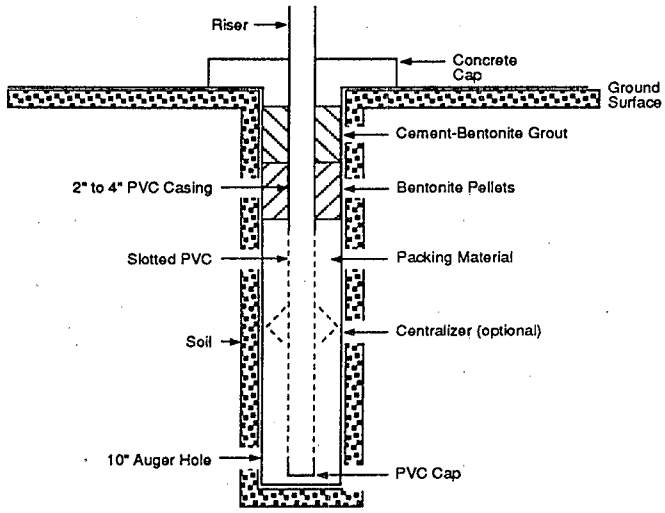


Figure 3-3. Typical Extraction/Air Inlet Well Construction (U.S. EPA, 1989c).

down. Since cleanup goals are typically expressed as permissible soil concentrations, the most direct and usually most reliable method is direct soil sampling. Vapor monitoring wells and pumped air sampling may also be useful in evaluating system performance. Comparisons of the amount of contaminant recovered with estimates of the contaminant mass in the soil have not proved to be reliable indicators of complete cleanup (U.S. EPA, 1989c).

The vacuum extraction equipment requires a power source, and may require equipment shelter, depending upon the anticipated duration of the remediation. For all components of the system, the potential to accumulate hazardous vapors should be considered. Equipment shelters should have adequate ventilation to ensure personnel safety. Systems for treatment of flammable vapors should use explosion-proof equipment as required.

3.5 REFERENCES

American Public Health Association (APHA). 1971. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, New York.

American Society of Testing and Materials (ASTM). 1973. Annual Book of ASTM Standards, Part II. Philadelphia, PA.

Conner, Jesse R. 1990. Chemical Fixation and Solidification of Hazardous Wastes. Van Nostrand Reinhold, New York, NY.

Dupont, R.R., W.J. Doucette, and R.E. Hinchee. 1991. Assessment of In Situ Bioremediation Potential and the Application of Bioventing at a Fuel-Contaminated Site. Presented in *Proceedings of the In Situ and On-Site Bioremclamation International Symposium* - San Diego, 3/19-3/21.

Ehlke, T.A., et al. Undated. Biotransformation of cis-1,2-Dichloroethylene in Aquifer Material from Picatinny Arsenal, Morris County, New Jersey.

Evans, D.D. 1965. Gas Movement. In: Methods of Soil Analysis: Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling (C.A. Black, editor-in-chief). American Society of Agronomy.

Fuller, E.N., P.D. Schettler, and J.C. Giddigs. 1966. A New Method for Prediction, of Binary Gas-Phase Diffusion Coefficients. *Indus. Engr. Chem.* 58, 19-27.

Gibson, S.A. and G. W. Sewell. Undated. Stimulation of Reductive Dechlorination of Tetrachloroethene (PCE) in Anaerobic Aquifer Microcosms by Addition of Short Chain Organic Fatty Acids, Alcohols, Sugars, or Aromatic Compounds. Robert S. Kerr Environmental Research Laboratory, Ada, OK.

Hazardous Waste Consultant. 1989. July/August.

Johnson, P.C., C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart. 1990. A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems. *Groundwater Monitoring Review,* Vol. 10, No. 2.

Sowers, C.B. and G.F. Sowers. 1970. Introductory Soil Mechanics and Foundations, 3rd ed. The MacMillan Co., London.

Stevens, D.K., W.J. Grenney, and Z. Yan. 1988. User's Manual: Vadose Zone Interactive Processes Model. Department of Civil and Environmental Engineering, Utah State University, Logan, UT.

Stroo, H. et al. 1989. Development of an In Situ Bioremediation System for a Creosote-Contaminated Site. International Conference on Physiochemical and Biological Detoxification of Hazardous Wastes, HMCRI.

Thomas, J.M. and C.H. Ward. 1989. In Situ Bioremediation of Organic Contaminants in the Subsurface. *Environmental Science and Technology,* Vol. 23, No. 7, pp. 760-766.

U.S. EPA. 1991. Draft Quick Reference Fact Sheet: Immobilization as Treatment. Office of Solid Waste and Emergency Response. Publication 9380.3-07F2.

U.S. EPA. 1990a. Assessing UST Corrective Action Technologies: Site Assessment and Selection of Unsaturated Zone Treatment Technologies. EPA/600/2-90/011. Risk Reduction Engineering Laboratory, Cincinnati, OH.

U.S. EPA. 1990b. Subsurface Contamination Reference Guide. EPA/540/2-90/011. Office of Remedial Response, Washington, D.C.

U.S. EPA. 1990c. Handbook on In Situ Treatment of Hazardous Waste-Contaminated Soils. EPA/540/2-90/002. Risk Reduction Engineering Laboratory, Cincinnati, OH.

U.S. EPA. 1990d. Ground-Water Handbook. Volume 1: Ground Water and Contamination. EPA/625/6-90/016a. Office of Research and Development, Cincinnati, OH.

U.S. EPA. 1989a. Stabilization/Solidification of CERCLA and RCRA Wastes. EPA/625/6-89/022.

U.S. EPA. 1989b. Technology Evaluation Report: SITE Program Demonstration Test, Terra Vac In Situ Vacuum Extraction System, Groveland, Massachusetts. Volume I. EPA/540/5-89/003a.

U.S. EPA. 1989c. State of Technology Review Soil Vapor Extraction Systems. EPA/600/2-89/024.

U.S. EPA. 1988a. Bioremediation of Contaminated Surface Soils. EPA/600/2-89-073.

U.S. EPA. 1988b. Determination of Aerobic Degradation Potential for Hazardous Organic Constituents in Soil - Interim Protocol. Risk Reduction Engineering Laboratory, Cincinnati, OH.

U.S. EPA. 1988c. Interactive Simulation of the Fate of Hazardous Chemicals during Land Treatment of Oily Wastes: RITZ User's Guide. EPA/600/8-88-001. Robert

S. Kerr Environmental Research Laboratory, U.S. EPA, Ada, OK.

U.S. EPA. 1988d. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA/540/2-88-004. NTIS.

U.S. EPA 1986a. Handbook for Stabilization/Solidification of Hazardous Waste. EPA/540/2-86/001.

U.S. EPA. 1986b. Prohibition of the Disposal of Bulk Liquid Hazardous Wastes in Landfills - Statutory Interpretive Guidance. EPA/530-SW-106. Office of Solid Waste and Emergency Response.

U.S. EPA. 1986c. Test Methods for Evaluating Solid Waste. SW-846.

U.S. EPA. 1986d. Systems to Accelerate In Situ Stabilization of Waste Deposits. EPA/540/2-86/002. Hazardous Waste Engineering Research Laboratory, Cincinnati, OH.

U.S. EPA. 1984. Review of In Place Treatment Technologies for Contaminated Surface Soils. Vol. 2: Background Information for In Situ Treatment. EPA/540/2-84-0032.

U.S. EPA. 1979. Manual of Methods for Chemical Analysis of Water and Wastes. EPA/600/4-79/020.

Verschueren. K. 1983. Handbook of Environmental Data on Organic Chemicals. 2nd edition. Van Nostrand Reinhold, New York, NY.

Vomocil, James A. 1965. Porosity. In: Methods of Soil Analysis: Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling (C.A. Black, editor-in-chief). American Society of Agronomy.

Wilson, B.H. Undated. Biotransformation of Chlorinated Hydrocarbons and Alkylbenzene in Aquifer Material from the Picatinny Arsenal, N.J. Environment and Groundwater Institute, University of Oklahoma.

Wilson, David J., Ann N. Clarke, and James H. Clarke. 1988. Soil Cleanup by In Situ Aeration. 1. Mathematical Modeling. *Separation Science and Technology,* Vol. 23, No. 10.

CHAPTER FOUR
Water Treatment Technologies

This section presents a thorough discussion of ground-water extraction required for the pump-and-treat method of ground-water remediation, and a screening matrix of some of the more commonly used, easily implemented treatment technologies. Due to the wealth of information available on the conventional treatment technologies traditionally used for industrial water or wastewater treatment, a thorough discussion was not deemed necessary.

4.1 PUMP-AND-TREAT

Pump-and-treat remediation technology refers to the extraction of contaminated ground water and subsequent treatment of the extracted ground water at the surface. Extraction of contaminated ground water is accomplished through the use of extraction wells or drains which are completed at specified locations and depths to optimize contaminant recovery. Determination of the location and depth of extraction wells or drains requires prior delineation of the contaminant plume and knowledge of the aquifer properties such as hydraulic conductivity (K), storage, stratigraphy, and depth to bedrock. Treated water may be discharged to injection wells or recharge basins that are positioned to enhance contaminant recovery by flushing contaminants toward extraction wells. Treated water may also be discharged directly to surface water (NPDES permit is normally required). Pump-and-treat with reinfiltration or reinjection can be combined with in situ soil treatment systems such as flushing and/or bioremediation to recover contaminants in both the vadose zone and ground water. Pump-and-treat systems may also be used with containment technologies such as slurry cutoff walls to limit the amount of clean water flowing to the extraction wells, thus reducing the volume of water to be treated.

Pump-and-treat systems are generally considered at sites where significant levels of ground-water contamination exist. In order for this technology to be effective, it must be possible for contaminants to readily flow to extraction wells, thus the subsurface must have sufficient hydraulic conductivity (i.e., $K>10^{-5}$ cm/s) and the chemicals must be transportable by the ground water (i.e., not strongly sorbed to soils). This technology is often desirable from an implementation standpoint because it can be designed to be versatile in operation and often can be modified or augmented during operation to enhance performance as data are collected. For example, if it is determined during operation that a system is not as effective in a certain contaminated area as originally expected, additional extraction wells could be installed to enhance recovery. However, it is often not as easy to modify treatment system designs during operation; consequently, total system flowrates should be known with certainty during design.

The main limitation of the pump-and-treat technology is the long time that may be required to achieve an acceptable level of cleanup (U.S. EPA, 1990a). The following factors contribute to this problem and therefore may limit the applicability of the pump-and-treat technology to certain sites: (1) the presence of chemicals with relatively low mobility (e.g., PCBs, dioxin); (2) aquifers with low hydraulic conductivities (i.e., $<10^{-7}$cm/sec); (3) highly heterogeneous hydrogeologic settings (e.g., highly stratified aquifers with multiple layers of coarse and fine textured material); and (4) the presence of a spatially discontinuous or inaccessible dense nonaqueous phase liquid (DNAPL).

NAPLs in general can complicate remediation because they can become trapped in pore spaces by capillary forces and are not readily pumped out. The residual saturation in the pore spaces can be a significant source of contamination, and pump-and-treat removal is therefore limited by how fast the NAPL components can dissolve.

For highly heterogeneous conditions pumped ground water will sweep through zones of higher hydraulic conductivity, recovering contaminants from those zones, but will be less effective in removing contaminants from low conductivity zones. Movement of contaminants from these zones is a much slower process and could increase cleanup times significantly; thus, pump-and-treat technologies may work in heterogeneous media, but cleanup times will be longer than in homogenous material. For higher sorbing compounds, cleanup times will be longer because more pore volumes must be removed in order for contaminants to be flushed away.

All of the above items contribute to a phenomenon called "tailing." Tailing is the asymptotic decrease of contaminant concentration in water that is removed in the cleanup process and is often observed during implementation of this technology (U.S. EPA, 1990a).

The surface treatment of extracted ground water will vary depending on the contaminants present. Treatment technologies to be used may include air stripping, activated carbon adsorption, and biological treatment. In some cases, treated ground water may be amended with nutrients and oxygen and reinjected into the subsurface to aid in stimulating biodegradation processes.

Variations in the operation of the extraction system can affect the recovery of the contaminants. The two basic modes of extraction are continuous and pulsed pumping. Continuous pumping refers to uninterrupted extraction of ground water to create a capture zone around the plume of contamination, thereby controlling migration while the contaminants are flushed from the aquifer. The pumping rate is limited by the yield of the aquifer. Pulsed pumping involves regular or periodic cessation of pumping activities to enhance the extraction of ground-water contaminants. Pulsed pumping may be necessary or more cost effective in cases where extraction wells cannot sustain even moderate yields (e.g., in bedrock and unconsolidated deposits of low permeability), where desorption and/or dissolution of contaminants in the subsurface is relatively slow, or where hydraulic conductivity heterogeneity is high. In the latter two cases, pulsed pumping would result in periodic low ground-water velocities, allowing contaminants to build up equilibrium concentrations locally and allow more efficient removal of contaminants. In general, pulsed pumping may be appropriate for (1) low-yield consolidated and unconsolidated deposits; (2) low-mobility contaminants; (3) heterogeneous formations consisting of alternating high- and low-permeability layers and containing contaminants; and (4) hydrogeological settings containing low to moderately soluble residual NAPLs. The instantaneous pumping rate may exceed the yield of the aquifer, but the long-term rate of withdrawal is limited by it.

Treatment system operation regimes include continuous flow, intermittent continuous flow, or batch operation. Selection of the treatment system operation is dependent upon both the ground-water extraction system operation as well as treatment technology limitations and economics.

Treated water may be discharged to the aquifer either to enhance contaminant containment or recovery or simply for disposal. Reinjection refers to injection of treated ground water into the subsurface via wells. Recharge refers to the use of trenches, basins, or infiltration galleries to reintroduce the treated water near the ground surface. Recharged ground water can be used for in situ soil treatment by flushing soils in the unsaturated zone. Recharge or reinjection also may be used to introduce nutrients and biological organisms to enhance biodegradation processes in the saturated zone. This has proven effective particularly in the case of most light nonaqueous phase liquids (LNAPLs) that are derivatives of petroleum products.

4.1.1 Data Collection Requirements

The data required to make decisions regarding pump-and-treat technologies are shown in Table 4-1. The first four items are minimum data requirements for determining applicability of pump-and-treat technology. The remaining items must be considered for implementation and are required to design a system and evaluate system effectiveness.

4.1.2 Evaluation

The data evaluation for the ground-water extraction component of a pump-and-treat system generally involves a quantitative analysis of ground-water flow and contaminant transport. The parameters and conditions listed in Table 4-1 are used as input into analytical equations or numerical models to quantify natural flow conditions and the impacts of pump-and-treat systems. In the initial stages of the decision process, when it must be determined whether pump-and-treat is applicable, simplified methods can be employed. Simplified methods are available for evaluating the following (U.S. EPA, 1985a): (1) well hydraulics, (2) drain hydraulics, (3) ground-water mounding, (4) seepage/infiltration, (5) effects of multiple wells (superposition), and (6) contaminant transport. These methods can be used to determine if adequate recovery or containment can be attained. For example, simplified equations for well hydraulics can be used to estimate flow rates and associated zones of capture for a well or series of wells within a contaminated area. Given these flow rates, simple equations for contaminant transport or pore volume removals can be used to estimate cleanup time. If the rate, capture zones, and cleanup times appear feasible, then it is likely that the technology is applicable. Once this has been determined, a more detailed analysis can be undertaken to evaluate system effectiveness using these equations or more sophisticated tools like semi-analytical or numerical models. These are also useful tools for designing systems with regard to system configuration, flow rates, operational considerations, and cleanup times. If time and funding are available, numerical modeling should be employed in the design process to lead to more accurate and confident decisions regarding implementation of this technology.

4.1.3 Engineering Considerations for Implementation

Limitation of the pump-and-treat technology in terms of complete and timely restoration of water quality to "clean" status has been the subject of much recent literature. An analysis of operational experience at a number of active remediation sites is presented in U.S. EPA, 1989. This document concludes that contaminant migration control is more easily achieved than cleanup, that stratigraphically simple sites are easier to clean up than complex ones, that predesign data collection and operational monitoring are typically inadequate, and that the system

Table 4-1. Data Requirements for Pump-and-Treat Systems

Data Description	Purpose(s)	Source(s)/Method(s)
Hydraulic conductivities and storativities of subsurface materials	Determine feasibility of extracting ground water; determine applicability of pump-and-treat technology	Pumping tests, slug tests, laboratory permeability tests
Contaminant concentrations and areal extent	Determine seriousness of problem; determine applicability and evaluate effectiveness	Water quality data
Contaminant/soil properties (density, aqueous solubility octanol water, carbon partitioning coefficient, organic carbon content of soil)	Determine mobility properties, existence of NAPL; determine applicability of pump-and-treat	Literature (Wyman et al., 1982); laboratory tests
Types, thicknesses, and extent of saturated and unsaturated sub-surface materials	Develop conceptual design; determine applicability/ considerations for implementation	Hydrogeologic maps, surficial geology maps/reports, boring logs, geophysics
Depth to aquifer/ water table	Select appropriate extraction system type; considerations for implementation	Hydrogeologic maps, observation wells, boring logs, piezometers
Ground-water flow direction and vertical/horizontal gradients	To determine proper well locations/spacing considerations for implementation	Water level data
Seasonal changes in ground-water elevation	Used in locating wells and screened intervals; considerations for implementation	Long-term water level monitoring
NAPL density/ viscosity/solubility	Predict vertical distribution of contamination; considerations for implementation and evaluating effectiveness	Literature
Ground-water/surface water connection	Determine impacts of surface water	Seepage measurements stream gaging

Table 4-1 (Continued)

Data Description	Purpose(s)	Source(s)/Method(s)
Locations, screen/ open interval depths, and pumping rates of wells influenced by site	Determine impacts/ interference; considerations for implementation and evaluate effectiveness	Well inventory, pumpage records
Precipitation/ recharge	Used in calculating water balance; considerations for implementation and evaluate effectiveness	NOAA reports, local weather bureaus

may have to be changed after a period of operation to compensate either for changing conditions or for original design misconceptions.

In designing and implementing pump-and-treat systems, consideration must be given to the goals and objectives of the system. Oftentimes these are defined by the governing agency and are based on risk and endangerment assessments. In other cases, a problem might be apparent but the risk to the environment may not have been ascertained. In any case, the severity of the problem must be considered in determining how to design and implement the system. If the goal of the system is to clean the site as quickly as possible, then a more active pump-and-treat system may be designed focusing on aggressive removal of contaminants. An example of aggressive removal would be a pump-and-treat system installed within a totally encapsulating slurry wall. Such a system has been installed at the Gilson Road Superfund Site in New Hampshire (Weston, 1989). If the goal is simply to prevent offsite migration of contamination, then a more passive system may be designed such as a system consisting of interceptor wells or trenches.

Site conditions, particularly, site hydrology and contaminant conditions, must be well defined in order to properly evaluate and implement the pump-and-treat technology. Limited information on contamination and site hydrogeology resulted in problems at several of the facilities visited during the preparation of this document. At one site, a soil-gas survey was performed to locate wells. It was found that soil-gas proved to be an excellent technique for establishing the areal extent of contamination in the shallow contaminated zone but did not distinguish between contamination in the vadose zone and ground water. It also did not detect contamination in areas where the depth to ground water exceeded 400 feet. As a result, TCE contamination that had migrated off site was not initially detected, and an interim measure that had been proposed to recover contaminated ground water had to be abandoned.

At other sites visited where this technology was implemented before sufficient site characterization data had been collected, it was found that significant changes in design and operation had to be made during implementation because adequate recovery of contaminated ground water did not occur. This resulted in increased costs and continued offsite migration of contaminants.

Site aspects other than those presented under data requirements that should be considered during design and implementation include the following:

- The location of surface water bodies and other ground-water bodies with respect to the contaminated aquifer
- Cleanup standards or standards of the receiving body that must be maintained (e.g., SDWA MCLs, drinking water standards, local classifications of ground water and surface bodies)
- The location of nearby wetlands
- The size of the site property and the availability of land for installing a pump-and-treat system
- Past experience in applying this technology in similar site conditions

There are definite drawbacks to implementing this technology without sufficient site characterization data. An attempt should be made to obtain enough information to understand the ground-water flow contaminant migration processes at the site to prevent the implementation of costly ineffective measures.

As with any stabilization technology, monitoring is required to ensure the effectiveness of the system. For the pump-and-treat technology, this may involve periodic measurement of the following:

- Water levels—to ensure adequate capture zones

- Water quality—measured at monitoring wells, soil-gas surveys, surface water
- Treatment system effluent—to ensure adequate contaminant removal

The results of monitoring should continuously be used to evaluate system operations and to possibly make changes or additions to the system. This is particularly true for systems that have been implemented with minimal site characterization data for design.

Monitoring results will be required to determine when a system should be shut off. Postclosure monitoring may be required to ensure that concentrations do not increase after system shut-off. This could occur if ground-water velocities are too high to remove sorbed contaminants of NAPL residual saturation or if contaminants existing above the cone of depression of extraction wells have not been removed.

The design process should begin with the development of a conceptual design based on the above considerations. The next step would then be the design of the physical aspects of the system assuming that the required data to define subsurface conditions have been collected.

The first design aspects that must be determined for a pump-and-treat system are horizontal and vertical spacing of wells, pumping rates, and possibly cleanup times. Once these have been determined, components such as wells, pumps, piping, and treatment facilities can be designed. The design of the latter features are based on standard practices.

Analytical and numerical modeling techniques are typically used to determine well spacings, rates, and cleanup times. A variety of techniques are available for this purpose (U.S. EPA, 1985a). Analytical models typically involve the application of the Theis equation or Darcy's law or a variation thereof in simulating the response of an aquifer to pumping. They are often referred to as capture zone or wellfield simulation models. These models are typically two-dimensional and usually involve many simplifying assumptions. Therefore, it is often difficult to simulate three-dimensional aspects of hydrogeologic settings. This is particularly troublesome in complex settings involving multiple layers, or where partially penetrating wells and cutoff walls are to be designed. Analytical models are best suited for use in more homogeneous settings. There are several commercially available analytical models. The more accurate models incorporate image-well theory, the principle of superposition, well hydraulics equations, and particle-tracking analyses.

Depending on the site-specific design requirements, analytical models can be used to provide sufficient information for screening and, sometimes, for design. They can be used to provide rough estimates of well spacings and pumping rates. This is often suitable for quick or interim cleanup measures or for long-term measures where flexibility to modify the design once the system has been in operation has been incorporated into the design. However, care should be taken in applying these models to complex hydrogeologic settings. The simulative capability of the model may not be adequate for incorporating all of the flow complexities and may result in gross errors in design.

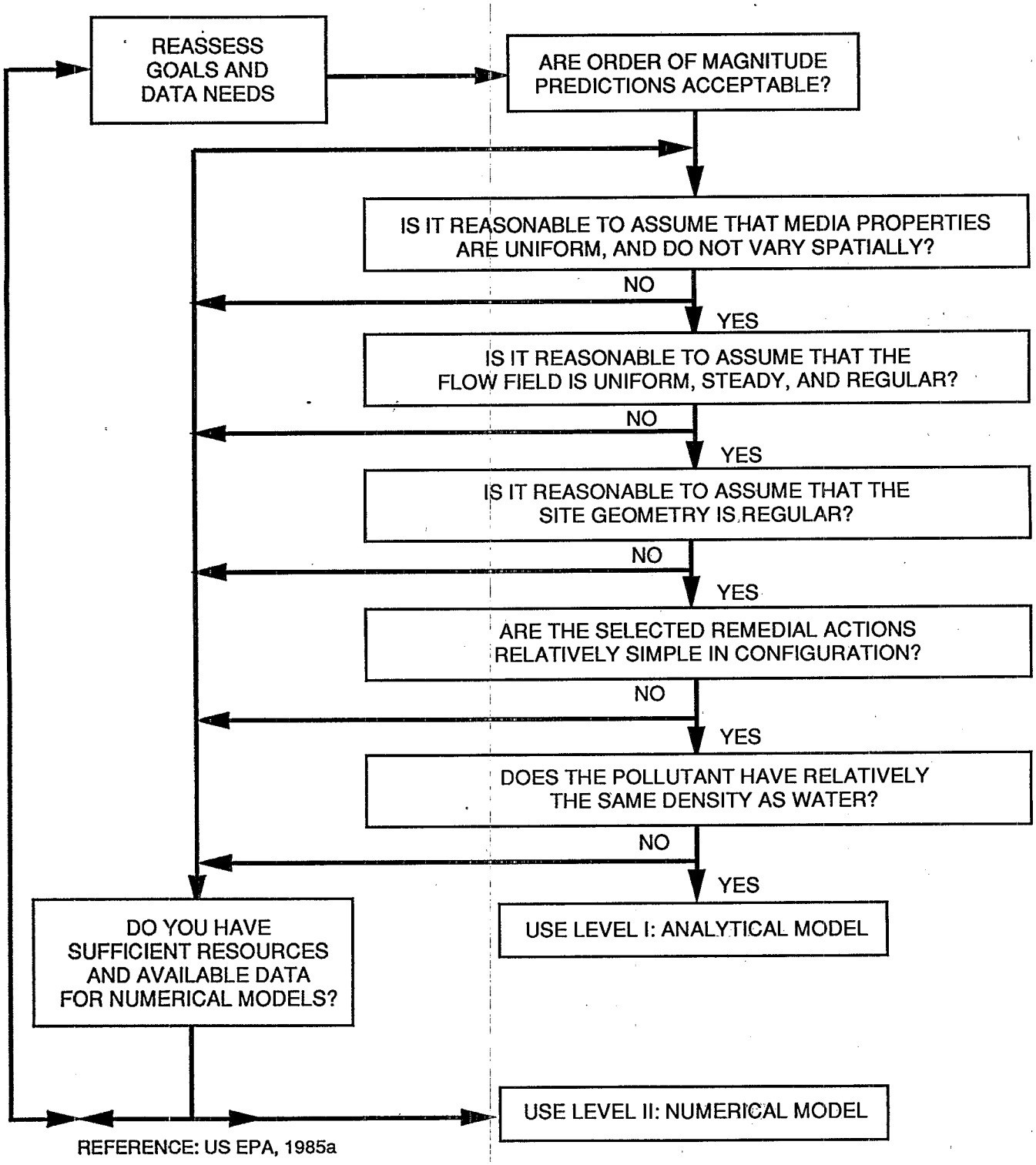
Numerical models typically offer more capability to simulate varying aspects of a hydrogeologic setting. These models have the capability to model features such as extraction wells, injection wells, impermeable boundaries, recharge from surface water or precipitation, and multiple aquifer systems. Both two-dimensional and three-dimensional numerical models are available. Three-dimensional models usually provide more representative results due to the capability of simulating vertical variations in flow properties. However, they are more complex and expensive to use. The predominant advantage of numerical models over other analysis techniques is the ability to incorporate vast amounts of data and complex hydrogeologic features into a framework that will provide realistic appraisals of how effective a pump-and-treat system may be. However, they are typically more expensive and time consuming and require detailed site characterization data to apply properly. Often, it is not feasible to apply numerical models to the design of short-term stabilization measures.

There are several questions to be answered when determining the required level of model. Figure 4-1 is a flow chart that illustrates the hierarchy of decisions to be made. Each question or decision must be answered in the affirmative for analytical (Level I) modeling to be chosen. A "no" answer at any decision point pushes the user towards the use of a numerical (Level II) model, whereupon data and resource availability should be examined. This hierarchy was developed to define the strict and limited conditions of analytical model use in remediation action assessment. The user is referred to U.S. EPA (1985a), for more information regarding model techniques and selection.

If sufficient information is available, numerical models should be utilized, particularly in the design of systems under complex hydrogeologic and contaminant conditions. The use of numerical modeling in designing pump-and-treat systems usually involves four steps:

1. Development
2. Calibration
3. Sensitivity analyses
4. Design and operational simulations

Model development involves the input of aquifer properties and site features. The following information is usually required as input:



REFERENCE: US EPA, 1985a

Figure 4-1. Flow Chart to Determine the Level of Modeling Required.

- Delineation of model boundaries
- Transmissivity
- Storativity
- Vertical hydraulic conductivity
- Aquifer thickness
- Surface water bodies
- Pumping or injection sources
- Precipitation recharge
- Potentiometric surface
- Porosity
- Dispersivity
- Retardation factors or adsorption coefficients
- Decay constants
- Source strength and location
- Initial concentrations

There are two basic formulations in numerical modeling: finite difference and finite element. In both cases, a grid system is developed. This involves discretizing the model area into individual cells. The cells are typically rectangular, triangular, or quadrilateral. Once the grid system is developed, the data are organized into arrays identifying a parameter value at each cell.

The accuracy and the credibility of model predictions are determined by the adequacy of calibration. This is particularly important in designing pump-and-treat systems, as the accuracy of predicted capture zones are dependent on how close the simulated response of the aquifer to pumping is to actual field behavior. This process may involve comparing field measured water levels, drawdowns, and concentrations to model predictions. Often, input parameters must be varied to provide a suitable match. Visual and statistical comparisons are typically used to describe the degree of calibration of the model.

Once a model is calibrated, it can be used to determine well spacings, pumping rates, cleanup times, and impacts of operational modifications. The actual use of the model is often a trial and error exercise in which different configurations of pumping and/or reinjection are simulated. If a flow model is used, the different configurations can be compared by comparing the resulting zones of capture. If a contaminant transport model is used, the effectiveness of the system can be evaluated through the prediction of cleanup times or the effectiveness of capture. The model can be used to optimize the system from a technical and cost standpoint. Once the system is operational, field monitoring data can be used to refine the model's predictive capability through additional calibration. The model can then be used to simulate operational changes and impacts of operational changes on cleanup.

4.2 GROUND-WATER TREATMENT OPTIONS

Numerous treatment technologies exist for the remediation of contaminated ground water. Generally, most conventional treatment technologies traditionally used for industrial wastewater treatment are applicable to treatment of contaminated ground water. The selection of the most appropriate technology or series of technologies requires careful consideration of the type and concentration of contaminant(s) in the ground water, and the discharge requirements for the treated water. Ambient water quality characteristics important to process design, such as iron and manganese occurrence, should not be overlooked. Often a treatment train consisting of several technologies in a series is needed.

A number of ground-water treatment technologies and their applications are presented in Figure 4-2. The intent of this figure is to provide a representative sampling of technologies that may be used for ground-water treatment during a stabilization action. It is not meant to imply that other technologies could not be used. The treatment technologies presented in Figure 4-2 can be applied whether treating surface water or ground water.

Due to the proven status of these treatment technologies and since an extensive amount of literature is available that describes the technologies and their uses, the reader is referred to several U.S. EPA guidance documents, among others. Recommended reference documents include the Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites (U.S. EPA, 1988a), and Technology Transfer Handbook—Remedial Action at Waste Disposal Sites (U.S. EPA, 1985a). Patterson (1985), is an excellent textbook for screening technologies since it is organized by contaminant rather than by technology. Information useful for designing ground-water treatment systems can be found in Eckenfielder (1989). Other recommended references are identified below.

4.3 REFERENCES

Eckenfielder, W.W. 1989. Industrial Water Pollution Control. 2nd edition. McGraw-Hill, New York.

Goveland, S.M. 1982. Optimal Dynamic Management of Groundwater Pollutant Sources. *Water Resources Research*. Vol. 18, No. 1, February.

Lyman, W.J., W.F. Reehl, and D.H. Rosenblatt. 1982, Handbook of Chemical Properties Estimation Methods. McGraw-Hill, New York, NY.

Ohneck, R.J. and G.L. Gardner. 1982. Restoration of an Aquifer Contaminated by an Accidental Spill or Organic Chemicals. Presented to 2nd National Symposium on Aquifer Restoration and Ground-Water Monitoring, May 26-28.

CONTAMINANTS	Neutralization	Precipitation	Coprecipitation/ Coagulation	UV/Ozone	Chemical Oxidation	Reduction	Distillation	Air Stripping	Steam Stripping	Activated Carbon	Evaporation	Gravity Separation	Flotation	Membrane Separation*	Ion Exchange	Filtration	Biological	Electrochemical
Metals																		
Heavy Metals	X	●	●	X	X	O	X	X	X	O	●	●	X	●	●	●	X	●
Hex Chromium	X	●	X	X	X	●	X	X	X	O	●	X	X	O	●	X	X	●
Arsenic	X	O	●	O	O	X	X	X	X	O	X	O	X	●	●	●	X	X
Mercury	X	●	●	X	X	●	X	X	X	●	X	O	X	O	●	●	X	X
Cyanide	X	X	X	●	●	X	X	X	X	X	●	X	X	●	●	X	O	O
Corrosives	●	●	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X	X
Volatile Organics	X	X	X	O	●	X	●	●	●	●	X	X	X	O	O	X	O	X
Ketones	X	X	X	O	●	X	●	●	●	X	X	X	X	X	X	X	●	X
Semivolatile Organics	X	O	O	●	●	X	●	X	●	●	O	O	O	●	●	X	●	X
Pesticides	X	O	O	●	●	X	●	X	O	●	O	O	O	●	●	●	O	X
PCBs	X	●	●	●	●	X	●	X	X	●	●	●	●	●	●	●	O	X
Dioxins	X	●	●	●	O	X	●	X	X	●	●	●	●	●	●	●	O	X
Oil & Grease/Floating Products	X	●	●	X	X	X	●	X	X	X	●	●	●	●	●	O	O	X

● Applicable
O Potentially Applicable
X Not Applicable
References: U.S. EPA, 1986; U.S. EPA, 1989; U.S. EPA; 1985, Patterson, 1985; U.S. EPA, 1990
Note: *Technology includes several processes; reverse osmosis and ultrafiltration among others.

Figure 4-2. Applicability of Treatment Technologies to Contaminated Ground Water.

Patterson, J.W. 1985. Industrial Wastewater Treatment Technology, 2nd edition. Butterworths Publisher.

Roberts, P.V., P.L. McCarty, and W.M. Roman. 1978. Direct Injection of Reclaimed Water Into an Aquifer. *Journal of the Environmental Engineering Division*, Proc. ASCE, October.

U.S. EPA. 1991. Remedial Action, Treatment, and Disposal of Hazardous Waste. EPA/600/9-91/002. Office of Research and Development.

U.S. EPA. 1990a. Basics of Pump-and-Treat Ground Water Remediation Technology. EPA/600/8-90/003.

U.S. EPA. 1990b. The Superfund Innovative Technology Evaluation Program: Technology Profiles. EPA/540/5-90/006. Office of Solid Waste and Emergency Response.

U.S. EPA, 1989. Performance Evaluations of Pump-and-Treat Remediations. EPA/540/4-89/005. Office of Research and Development.

U.S. EPA. 1988a. Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites. EPA/540/G-88/003. Office of Emergency and Remedial Response.

U.S. EPA. 1988b. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA 540-2-88-004.

U.S. EPA. 1986a. Mobile Treatment Technologies for Superfund Wastes. EPA 540/2-86/003(f). Office of Solid Waste and Emergency Response.

U.S. EPA. 1986b. Treatment Technology Briefs—Alternatives to Hazardous Waste Landfills. EPA/600/8-86/017. Hazardous Waste Engineering Research Laboratory.

U.S. EPA. 1985a. Technology Transfer Handbook—Remedial Action at Waste Disposal Sites.U.S. EPA/625/6-85/006. Office of Emergency and Remedial Response.

U.S. EPA. 1985b. Modeling Remedial Actions at Uncontrolled Hazardous Waste Sites. EPA/540-2-85/001.

U.S. EPA. 1983. Methods for Chemical Analysis of Water and Wastes. EPA-60/4-79-020.

U.S. EPA. 1982. Evaluation of Landfill Remedial Action Alternatives through Groundwater Modeling. EPA-600/9-82-002.

Weston, Inc. 1989. Remedial Program Evaluation—Gilson Road Site. Nashua, New Hampshire. Prepared for NHDES. February.

U.S.G.P.O.:1991-548-187:40613

Agency

Cincinnati OH 45268-1072

POSTAGE & FEES PAID
EPA
PERMIT No. G-35

Official Business
Penalty for Private Use, $300

EPA/625/6-91/026