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RCRA CORRECTIVE ACTION STABILIZATION TECHNOLOGIES

PROCEEDINGS

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PREFACE

The main body of this document was developed from technical presentations given at a series of seminars on the U.S. Environmental Protection Agency's (EPA's) Resource Conservation and Recovery Act (RCRA) Corrective Action Stabilization Technologies Program, sponsored by the Center for Environmental Research Information (CERI), Office of Research and Development (ORD). Seminars in the series were held in all 10 EPA regional offices during Fall 1991 and Winter 1992. This seminar series introduced several technologies that may have application to the RCRA stabilization concept; however, many other existing technologies also may be applicable.

Chapter 1 of this proceedings provides an introduction to the RCRA corrective action stabilization strategy. Chapter 2 presents a conceptual approach for characterizing problems, including the use of the chemical mass balance. Chapter 3 discusses field screening methods including gas chromatography, mass spectrometry, x-ray fluorescence spectrometry, chemical sensor systems, sampling and analysis for soil gases and air, and immunoassay methods. Chapter 4 describes construction methods and considerations for several technologies such as covers, slurry walls, and grouting for RCRA corrective actions. Chapter 5 discusses innovative in situ delivery and recovery of liquids to facilitate RCRA corrective actions. Chapter 6 covers vapor extraction and gas control and bioventing as technologies for RCRA corrective actions.

Appendix A is a compilation of case studies originally presented at the National Corrective Action Conference. The conference was held February 25 through 27, 1992, in Colorado Springs, Colorado. Conference participants included consultants and representatives from EPA, other federal agencies, states, and industry. The conference was organized to educate and demonstrate how and when stabilization would be an effective remedial approach in the corrective action process. The selected presentations are a sampling of all presentations that portrayed the effective implementation of this strategy.

For additional information on stabilization technologies for RCRA Corrective Actions, the reader can access the RCRA Corrective Action Bulletin on the ORD Bulletin Board System (BBS) at (513) 569-7610.

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CHAPTER 1
Stabilization: A Strategy for RCRA Corrective Action

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1.1 BACKGROUND

In 1992, EPA began implementing an aggressive program strategy to increase the number of cleanup activities and the pace of cleanup and to achieve positive environmental results at Resource Conservation and Recovery Act (RCRA) treatment, storage, and disposal facilities (TSDFs) requiring corrective action. While comprehensive facility cleanup is the long-term goal for the RCRA corrective action program, this new initiative emphasizes the importance and value of controlling releases and preventing the further spread of contaminants at RCRA facilities.

Stabilization of RCRA facilities entails EPA and owner/operators taking whatever action is necessary to address actual and potential exposures to hazardous waste and to control any further spread of contamination. Stabilization activities will utilize available remedial techniques, such as those in Table 1-1, at the earliest practicable time. Implementation of this strategy may require that the facility-wide RCRA Facility Investigation (RFI) be rescheduled or redirected so that the interim remedial measures can be carried out. The RCRA corrective action program will demonstrate a "bias" for stabilization actions in the way it manages corrective actions at RCRA facilities. The near-term goal of the corrective action program will be to direct investigations and remedial actions to address releases at high priority RCRA facilities.

The RCRA stabilization initiative is a new program philosophy; it should not be confused with corrective measures that historically relied on solidification/immobilization technologies. This new initiative stresses the use of existing corrective action vehicles (e.g., interim measures and conditional remedies) to effect environmental benefits through a coherent and coordinated program policy direction. Although technologies such as solidification, vitrification, and other immobilization techniques may be effective as stabilization measures in certain situations, EPA also is interested in other source control measures and measures that will stop or slow any further spread of contaminant migration. The measures to stabilize releases or other environmental problems could be quite extensive, including, for example, the installation of a large-scale pump-and-treat system combined with treatment and/or containment-based source control actions. In addition, physical and institutional exposure controls, such as fences, access controls, or provision of alternative water supplies, also may be required to mitigate actual or imminent health threats.

Implementing the stabilization initiative will yield substantial benefits for the corrective action program by focusing limited resources in the near-term on stabilizing environmental problems at more facilities, initially of high priority, rather than pursuing final, comprehensive remedies at a few facilities. This should enable the Agency and states to address the most serious environmental problems at a larger number of facilities more quickly. Furthermore, by imposing such expeditious actions, the extent and incidence of continued environmental degradation from existing releases should be significantly reduced. Conversely, the environmental benefit gained by taking this early action should impart greater efficiency in final remedies undertaken.

1.2 CORRECTIVE ACTION AND STABILIZATION

1.2.1 Objectives and Scope of the RCRA Corrective Action Program

The primary objective of the RCRA corrective action program is to clean up releases of hazardous waste or hazardous constituents that pose a threat to human health and the environment. The program applies to all operating, closed, or closing RCRA hazardous waste facilities acquiring a permit or under order. RCRA corrective action authority can be used to address releases to all media from all solid waste management units (SWMUs) at a RCRA facility.

To carry out this corrective action program objective, EPA developed a five-phased corrective action process, which

Table 1-1. Examples of Stabilization Measures

BY MEDIA

Ground Water
- Interceptor Trench/Sump/Subsurface Drain
- Pump-and-Treat System (Source Removal and Containment)
- Physical Barriers (Covers/Slurry Walls)

Soils
- Runoff/Runon Control (Diversion or Collection Devices)
- Cap/Cover
- Source Removal (Excavation)

Surface Water Release (Point and Nonpoint)
- Overflow/Underflow Dams
- Filter Fences
- Runoff/Runon Control (Diversion or Collection Devices)
- Regrading/Revegetation

Gas Migration Control
- Barriers/Collection/Treatment/Monitoring
- Evacuation (Buildings)

Particulate Emissions
- Truck Wash (Decontamination Unit)
- Revegetation
- Application of Dust Suppressant
- Cover/Cap

BY UNIT TYPE

Containers
- Overpack/Re-drum
- Construct Storage Area/Move to Storage Area
- Segregation
- Temporary Cover

Tanks
- Overflow/Secondary Containment
- Leak Detection/Repair/Partial or Complete Removal

Surface Impoundments
- Reduce Head
- Remove Free Liquids and/or Highly Mobile Wastes
- Stabilize/Repair Side Walls, Dikes, or Liner(s)
- Provide Temporary Cover
- Runoff/Runon Control (Diversion or Collection Devices)

Landfills
- Runoff/Runon Control (Diversion or Collection Devices)
- Reduce Head on Liner and/or in Leachate Collection System
- Repair Leachate Collection/Removal System or French Drain
- Cap/Cover
- Waste Removal

Waste Piles
- Runoff/Runon Control (Diversion or Collection Devices)
- Cap/Cover
- Waste Removal

OTHER TYPES OF ACTIONS
- Fencing to Prevent Direct Contact
- Alternate Water Supply to Replace Contaminated Drinking Water
- Temporary Relocation of Exposed Population
- Institutional Restrictions

it described first in the October 1986 National Corrective Action Strategy (51 FR 37608) and more recently in the Subpart S proposed rule (55 FR 30798; July 27, 1990). The first phase is the RCRA Facility Assessment (RFA). During the RFA, EPA or the state visits the facility, characterizes the solid waste management units, and identifies releases or potential releases requiring further investigation. The second phase of the process, if required, is the RFI. During the RFI, the facility's owner/operator fully characterizes the nature and extent of the releases. Based on the results of the RFI, a facility owner/operator may be required to conduct a Corrective Measures Study (CMS) to evaluate the potential alternatives for cleanup. In the fourth step, EPA or the state selects the final remedy, which is then carried out by the owner/operator during Corrective Measures Implementation (CMI). The process can take 5 to 8 years from the start of the RFA to the implementation of the final corrective measures. The stabilization initiative is intended to shorten the time before cleanup can start by encouraging appropriate interim remedial actions to be identified and implemented on a short-term basis.

Such interim measures are generally defined as remedial measures that are undertaken following the RFA and prior to completion of the CMS. They are usually designed to address a specific aspect of the overall contamination at a facility that can be readily isolated. Interim measures may encompass a broad range of possible actions. In some cases, interim measures will involve the control of the source of the release, while in other cases, they will involve cleanup of contaminated media (i.e., soil, ground water, surface water, or air), whereas in still other cases, they may involve limiting exposure to the contamination. For example, a facility responsible for contaminating a public drinking water supply may be required to initiate

cleanup of the water supply, as well as to make an alternative water supply available until the original water supply is remediated. Other examples of interim measures might include initiating ground-water pump-and-treat systems to contain the flow of contaminated ground water, fencing an area of contaminated soils to prevent public access, or overpacking damaged or corroded drums to prevent possible leakage.

1.2.2 Objectives and Scope of the Stabilization Initiative

Approximately 4,600 RCRA facilities may be subject to corrective action requirements. Based on current program data, EPA estimates that approximately 80 percent, or 3,600, of these facilities, will require varying degrees of cleanup. Because resources available to address these facilities are limited, EPA plans to maximize the near-term environmental benefits of the RCRA corrective action program by focusing resources on those facilities and SWMUs where accelerated cleanup activities can produce the greatest environmental benefit. One aspect of this strategy is to stabilize known releases of hazardous constituents at "high priority" corrective action facilities. Stabilization means taking whatever action is necessary to address exposures to hazardous waste releases and to control or prevent any further migration of contamination. After actions have been taken to stabilize releases at high priority facilities, the Agency will focus its attention on stabilizing and remediating lower priority facilities.

By implementing this strategy, EPA will be able to concentrate its efforts at high priority sites where there are the greatest threats to human health and the environment, and eliminate or minimize these threats through either stabilization or remediation, thus achieving the greatest environmental benefit. Stabilization of a contaminant release at a facility will require less time than full remediation, thereby allowing a greater number of releases to be addressed, at least partially, in a shorter period of time. Those sites that are stabilized will continue through the corrective action process toward final remediation, albeit the continued corrective action is projected to occur at a slower pace and with the potential for a reduced level of EPA/state oversight.

Stabilization activities at appropriate facilities could provide a number of benefits to regulatory agencies, the regulated community, and the general public. As indicated above, once a facility has entered the stabilization process, EPA/state attention and oversight can be refocused on other facilities, thus maximizing Agency resources. Facility owners and operators may benefit from stabilization by potentially reducing future liability by limiting the spread of contamination. They also may benefit from reduced overall costs and shorter remediation time due to early installation of the stabilization measure. The public also benefits from stabilization because environmental protection measures, where appropriate, are being implemented earlier at more facilities, thereby reducing the potential threat of exposures to contaminants and degradation of resources.

By implementing stabilization measures at a facility, the Agency may be able to lessen active oversight. In other circumstances, stabilization could simply be a milestone within a continuous remediation process. There may be cases where a stabilization measure could be adequate to serve as a final remedy for a particular release. Consideration of the stabilization measure as a final remedy would be based upon an evaluation of performance monitoring data collected after the measure was implemented. When selecting a stabilization interim measure, compatibility and assimilation with final corrective actions should be incorporated.

1.2.3 Stabilization as Part of the Corrective Action Process

It should be understood that to a large extent, the stabilization initiative builds on vehicles already existing/available in EPA Regions and States. Although stabilization is a new RCRA initiative, it was not designed to create a new regulatory or administrative process. Stabilization measures will be implemented through the existing process described above. The corrective action activity most relevant to this initiative is interim measures. However, conditional remedies and voluntary corrective action by the owner/operator also may be helpful in implementing this initiative.

Regions have already required a large number of facility owner/operators to undertake interim measures to address obvious environmental problems, particularly where actual or imminent exposure of human or environmental populations has been identified. Interim measures, as described in the proposed Subpart S corrective action rule, may be conducted at a facility whenever the Agency determines that a release, or potential release, poses a threat to human health or the environment. Examples of releases that may be candidates for stabilization include those that pose threats to human populations, ecosystems, and/or drinking water sources.

Along with interim measures, conditional remedies and voluntary actions by owner/operators also may be used under the stabilization initiative. Conditional remedies are intended to phase in remedies over time and, therefore, may include stabilization activities to control the future migration of wastes on site and to expedite cleanup of releases that have migrated beyond the facility boundary. Voluntary corrective actions may be conducted by facility owner/operators who wish to initiate stabilization activities rather than wait for EPA to begin actively pursuing corrective action at the facility. In addition, owner/operators may wish to proceed with corrective action in an attempt to reduce their liability.

Thus, this stabilization initiative will adopt and institutionalize existing techniques (e.g., interim measures) and management approaches (e.g., voluntary cleanups) to implement the corrective action program. While this stabilization initiative builds upon ongoing activities, the national program is adopting the philosophy that, in the near term, there are increased environmental benefits associated with taking stabilization actions at more facilities compared to pursuing final, comprehensive remedies at fewer facilities. This philosophy, however, does not remove the goal of final cleanup of the facility. It does bias remediation to the earliest possible phases of corrective action.

Procedurally, stabilization will typically involve an initial evaluation of RFA information to establish the need for stabilization. Subsequent information gathering during the RFI should be focused on supporting technical decisions regarding the stabilization approach chosen, and implementing the stabilization response, typically under an "interim measure" authority. In addition, information gleaned from stabilization actions is envisioned to supplement the ongoing RFI and support additional corrective actions. Stabilization measures for any media of concern may be undertaken separately from the final corrective action or as an incremental step toward a final remedy. However, all stabilization projects should be designed to be compatible with any anticipated long-term corrective action.

1.3 IMPLEMENTING STABILIZATION

1.3.1 Overview

A stabilization strategy may be considered or implemented for either a specific SWMU, a group of SWMUs, or an entire facility. Stabilization activities, while addressing releases from one or more SWMUs, are likely to concentrate on a specific environmental medium, such as ground water or soil.

If stabilization is imposed by EPA or the authorized state, it will be implemented through a six-step process. The first step is the assignment of a priority level for corrective action and stabilization based on the National Corrective Action Prioritization System (NCAPS). The second step is the evaluation of the facility and its contaminant releases to determine whether they can be addressed through stabilization activities. Third, the Agency may have to amend a compliance schedule in either an enforcement order or permit to include clauses requiring stabilization. If a permit or order has not yet been issued, the Agency may have to issue one to provide an enforceable agreement outlining the upcoming stabilization activities. The fourth step is the collection of data needed to select and design the stabilization measures that will be used. This data collection will normally be carried out as part of the early phases of the RFI. The fifth step is the selection and design of the stabilization measures. In most cases, the owner/operator will propose technologies or techniques for approval by EPA or the state. The final step is the implementation of the stabilization measure. An overview of this six-step process is shown in Figure 1-1 and described in greater detail below. It should be noted that in the case of a voluntary stabilization action (i.e., one that is initiated by the owner/operator without being required by EPA or the state), several of the steps do not apply.

Step 1: Priority Setting

NCAPS was developed to assist in prioritizing TSDFs for corrective action activities. NCAPS is designed to receive and manipulate data for four migration pathways, each of which is scored separately: ground-water releases, surface water releases, air releases, and onsite (e.g., soil) contamination. A total facility score is calculated and facilities are ranked as high, medium, or low priorities based on their total and media-specific scores.

NCAPS is simpler and less data intensive than the Superfund Hazard Ranking System (HRS). However, NCAPS and the HRS consider many of the same ranking factors, including the history of hazardous waste releases, area hydrogeology, risks of continuing and sudden releases, waste types and quantities handled, and likelihood of human and environmental exposure to hazardous waste and hazardous constituents through direct contact, air, surface water, and ground water. The data needed to perform the priority setting should be available after the RFA or its equivalent (e.g., a Preliminary Assessment [PA] conducted at storage and treatment facilities under the Environmental Priorities Initiative) is completed.

Step 2: Evaluation

Stabilization should be implemented at a particular facility if it offers clear advantages in terms of protecting human health and the environment in a timely manner. Identifying these advantages involves a series of policy and technical decisions, the most important of which are outlined in Table 1-2. These judgments are difficult to quantify and, therefore, must be based on the professional judgment of the federal and state officials responsible for implementing the RCRA corrective action program. The sum of these judgments, as a group, should form a basis upon which the relative benefits to be gained through stabilization at a particular facility are evaluated. The types of benefits envisioned from facility stabilization include limited contaminant migration, reduced volume of contaminated media, lowered risk to human health and the environment, opportunity to pretest remediation technologies, reduced remediation costs, and a lower level of EPA/state oversight of owner/operator's corrective action activities.

Table 1-2. Key Decisions for Determining the Need for Stabilization

Have interim measures, if required or completed, been successful in preventing the further spread of contamination at the facility?
To what media have contaminant releases from the facility occurred or been suspected of occurring?
Are contaminant releases migrating off site?
Are humans currently being exposed to contaminants released from the facility?
Is there a potential for human exposure to the contaminants released from the facility over the next 5 to 10 years?
Are environmental receptors currently being exposed to contaminants released from the facility?
Is there a potential that environmental receptors could be exposed to the contaminants released from the facility over the next 5 to 10 years?
If already identified or planned, would final corrective measures be able to be implemented in time to adequately address any existing or short-term threat to human health and the environment?
Could a stabilization initiative at this facility reduce the present or near-term (e.g., less than 2 years) risks to human health and the environment?
If a stabilization activity were not begun, would the threat to human health and the environment significantly increase before final corrective measures could be implemented?
Are appropriate stabilization technologies available to prevent the further spread of contamination, based on contaminant characteristics and the facility's environmental setting?
Has the RFI, or another environmental investigation, provided the site characterization and waste release data needed to design and implement a stabilization activity?
Can stabilization activities be implemented more quickly than the final corrective measures?
Can stabilization activities be incorporated into the final corrective measures at some point in the future?

Stabilization should be considered an option at a facility up until the point where it becomes more expedient and cost effective to implement the final corrective measures. Generally, the immediate implementation of final corrective measures, rather than stabilization measures, becomes more efficient after the RCRA CMS is completed, because the effort and resources that might be used to plan, design, and construct stabilization structures may be more effectively spent implementing the corrective measures. Furthermore, if final corrective measures are just about to be constructed, it is unlikely that short-term stabilization measures could be implemented fast enough to be more effective in reducing threats to human health and the environment.

If interim measures have been implemented at a facility and they have been successful in preventing the further spread of contamination from all known *releases, stabilization* may, in effect, already be completed.

The implementation of stabilization measures is, of course, dependent on the availability of appropriate technologies and techniques. If there are no identified technologies appropriate for stabilizing contamination at a facility, stabilization is not a real option and the facility should continue toward final corrective measures.

Step 3: Developing Enforceable Agreements

When it is determined that stabilization measures can and should be required, Regions and states should use enforceable agreements to document the responsibilities of all parties involved. Stabilization can be initiated either through enforcement actions or through permitting procedures. Generally, an order will be used if the facility is not yet permitted and the permit issuance date is not in the near future (i.e., within the next 6 months). A RCRA Section 3008(h) order is the enforcement authority most likely to be used, but a Section 7003 order could be used to require stabilization if there is an imminent and substantial endangerment. If the Region or state is in the process of drafting a permit, the permit would be the most appropriate vehicle for stabilization. If a permit has already been issued, a permit modification to insert stabilization requirements may be necessary.

Step 4: Data Collection for Stabilization

The data required to determine the need for stabilization should be available after the RFA has been completed. However, in many situations, data regarding the nature and extent of the hazardous constituents that have been released will not be available until the RFI is under way or completed. Given that the selection of an appropriate stabilization measure may depend on the collection of sufficient site/unit characterization data, EPA encourages the Regions and states to require owner/operators to develop RFI workplans that gather such data during the early stages of the RFI. This subject is discussed more fully in Section 1.4.

Step 5: Selection and Design of Stabilization Measures

After all of the data needed to design stabilization measures have been collected and evaluated, the owner/operator should propose the technologies and techniques he or she feels will be most appropriate to contain the spread of contamination and/or possibly begin remediating the facility. In most instances where stabilization is being carried out under a RCRA permit or enforcement

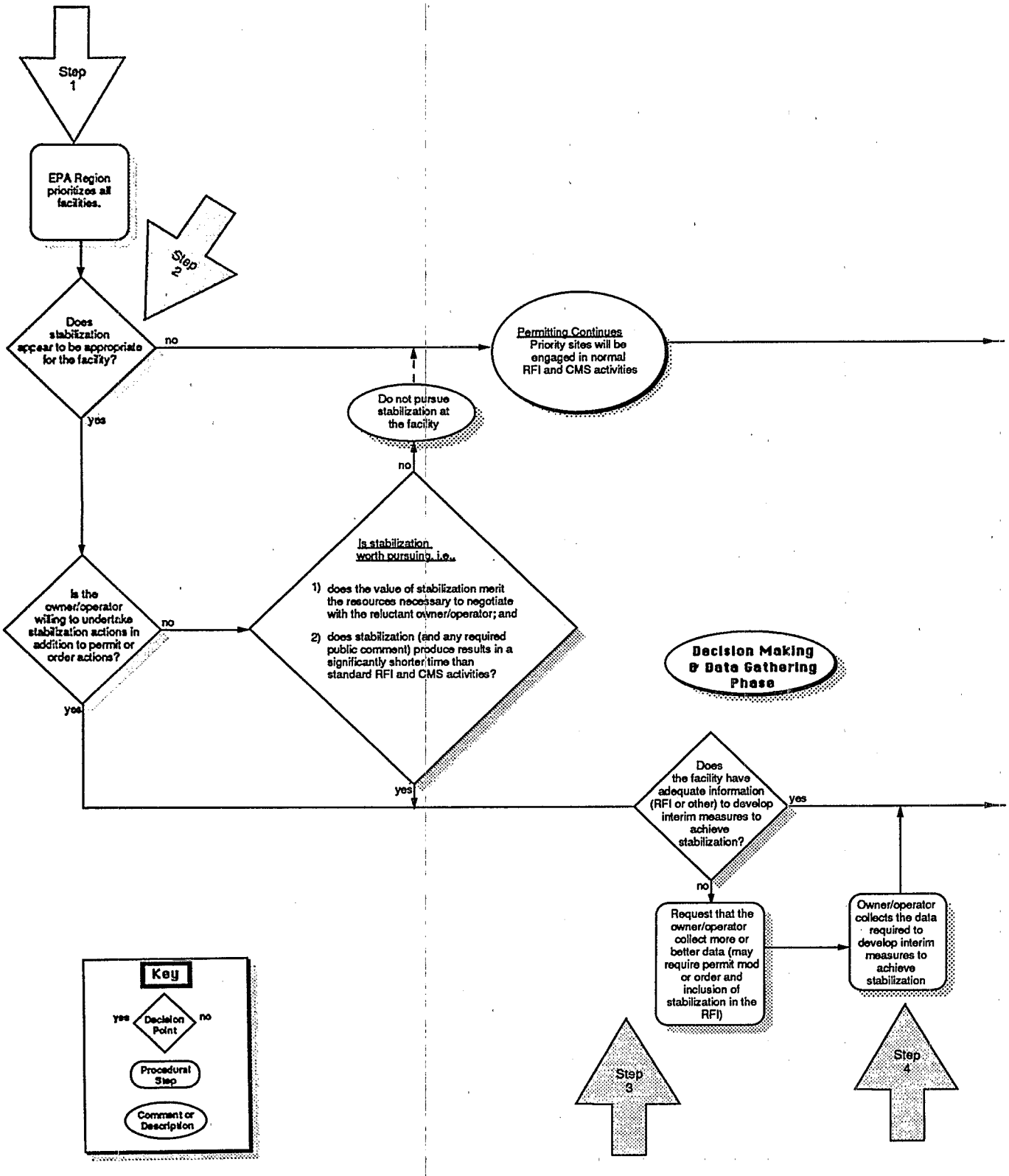

Figure 1-1. Stabilization strategy flowchart.

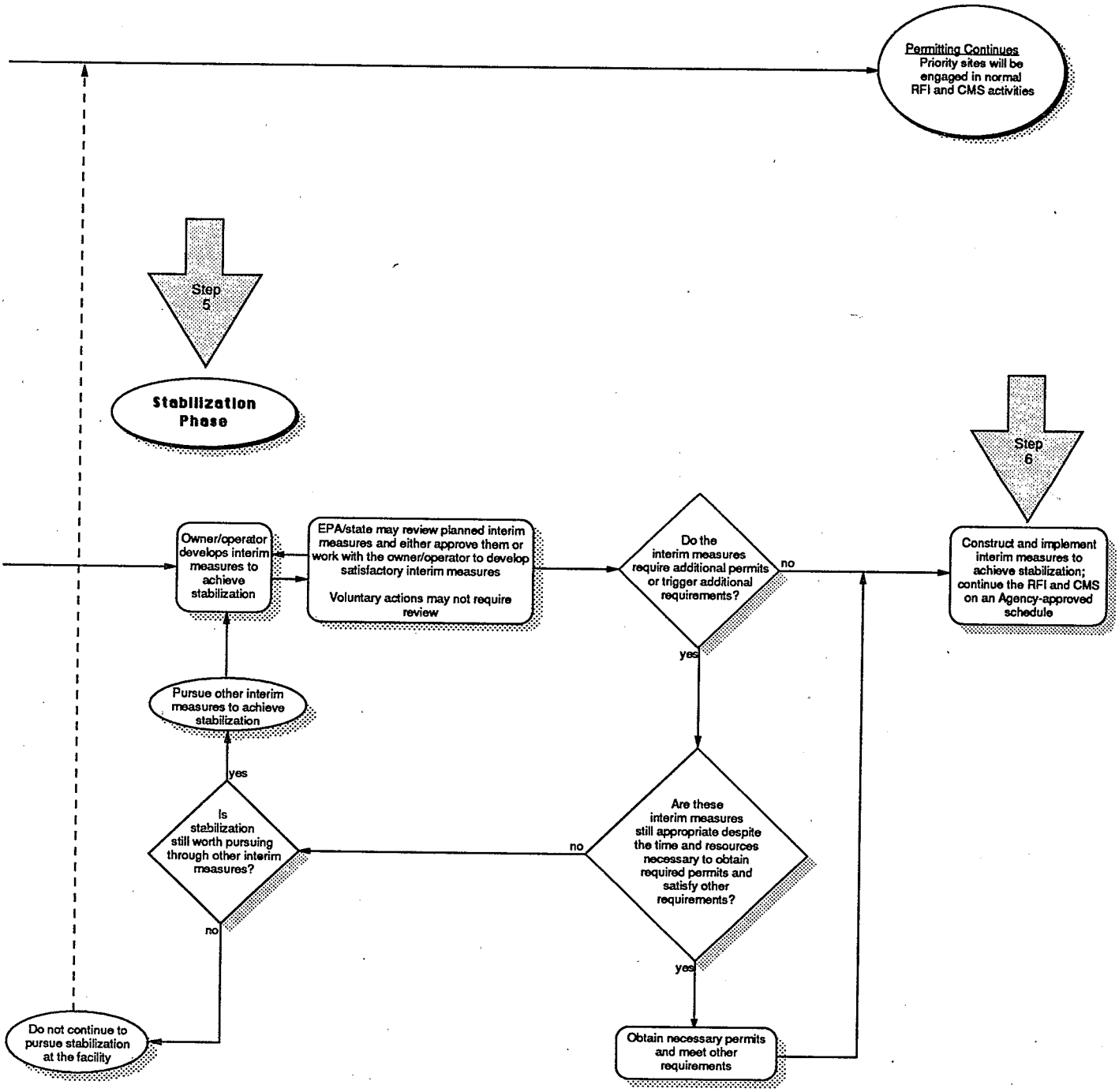

Figure 1-1. Stabilization strategy flowchart (continued).

order, the owner/operator will be required to obtain either EPA's or the state's approval for the proposed stabilization measures. After approval has been granted, final specifications and design drawings should be prepared and any required permits should be secured.

Step 6: Implementation

After stabilization measures have been designed and approved, they should be carried out in a timely manner so that contaminant migration can be limited to the extent possible. When stabilization measures are in place, a monitoring program should be used to ensure that the measures are effective in controlling the contaminant movement. This monitoring program will vary in sophistication depending on the nature of the stabilization measure. For example, in some instances, removal of drums and contaminated soil may only require that surficial soil samples be collected and analyzed to show that the contaminant source has been removed. However, in some instances of widespread ground-water contamination, monitoring wells and regularly collected samples may be required to show that contaminated ground water is not bypassing whatever system has been built to contain it.

1.4 DATA CONSIDERATIONS FOR STABILIZATION

1.4.1 Overview

The amount of information needed to support technical decisions for stabilization will vary greatly. Obvious waste removal situations might often be addressed more or less immediately, without extensive studies, whereas ground-water contamination in a complex hydrogeologic setting could require extensive investigations before an effective stabilization remedy is chosen. Table 1-3 depicts some of the key data elements that may be helpful in designing some of the more common stabilization actions. Factors that come into play when identifying data needs include:

- Immediacy of exposure threats.
- Types of contaminants and volumes of releases.
- Technical complexity of remediation.
- Media-specific characteristics, such as site hydrogeology or prevailing wind direction.

1.4.2 Phased Investigations

The broad spectrum of situations that may exist at the beginning of the RFI process, along with the need to focus on releases that can be stabilized, calls for a flexible, phased approach to site investigations. A phased approach begins with an evaluation of existing data, the development of a conceptual model of the extent of contamination, and identification of possible stabilization technologies to remedy the situation. This is followed by the collection of additional data, as necessary, to characterize releases and environmental settings, and to narrow down the possible stabilization alternatives. From such data, the conceptual model of the releases can be refined and used to design an appropriate stabilization program.

In a phased investigation for stabilization, the initial phases should focus on the SWMUs presenting the most imminent threat to human health and the environment. After stabilization for the high priority units has been implemented, the focus of the RFI should shift to characterizing any lower priority units and releases at the site.

1.4.3 Integrating Stabilization into RFI Workplans

In some cases, existing RFI work schedules and requirements may have to be revised to accommodate data collection for stabilization. This is not likely to pose a problem at facilities where an RFI workplan is currently being negotiated through either a permit or an enforcement order. Ideas and strategies for stabilization can be readily incorporated before the workplan becomes final. Where existing RFI workplans and schedules of compliance are not sufficiently flexible to accommodate stabilization needs prior to completion of the RFI, the potential benefits of stabilization should be weighed against the time and effort needed to make the modifications to the agreement.

The RFI workplan should provide flexibility for data collection and a phased approach for completing the facility-wide RFI. For some facilities, this may mean altering the speed of the facility-wide RFI so activities can be focused on the SWMU(s) undergoing stabilization. Although facility-wide RFIs are necessary, they should be the last step in data gathering for a facility and should occur after stabilization actions for the worst SWMU releases have been assessed and imposed.

After stabilization measures are taken and imminent releases are contained successfully, the RFI can continue to address additional releases. Because the worst releases will be stabilized, more time will be available to work toward appropriate corrective measures to address less environmentally significant releases.

1.5 REFERENCE

U.S. EPA. 1992. U.S. Environmental Protection Agency. Focusing RCRA facility investigation (RFI) data collection for RCRA stabilization. Draft. July.

Table 1-3. Stabilization Data Needs

	Drains and Trenches	Cap-ping	Slurry Wall	Runoff/ Runon Control	Gas Vent-ing	Solidifi-cation	In Situ Soil Flush-ing	Bioreme-diation	Vacuum Extrac-tion	Pump and Treat
Depth to Water Table	■	❑	■	—	❑	■	❑	❑	■	■
Surface Water/Ground Water Relationship	■	—	❑	—	—	—	❑	—	—	■
Ground-Water Flow Rates and Direction	■	—	■	—	—	—	❑	—	—	■
Seasonal Changes in Ground-Water Elevation	■	❑	—	—	❑	❑	❑	❑	❑	■
Hydraulic Conductivity/Permeability	■	■	■	—	■	—	■	■	■	■
Climate/Precipitation	■	■	—	■	—	■	—	■	■	—
Contaminant Characteristics	■	❑	■	—	■	■	■	■	■	■
Contaminant Concentration	■	—	■	—	■	■	■	■	■	■
Extent of Contamination	■	■	■	—	■	■	■	■	■	■
Types, Thicknesses, and Extents of Saturated and Unsaturated Subsurface Materials	■	—	■	—	❑	❑	■	■	■	■
Soil Characteristics	❑	—	■	■	■	—	■	■	■	■
Soil Water Content	—	—	—	—	■	■	—	■	■	—
Depth of Air Permeable Zone	—	—	—	—	■	—	—	■	■	—
Topography	—	■	■	■	—	—	—	—	—	—
Depth of Aquitard	❑	—	■	—	—	—	❑	—	—	■

■ High Priority; ❑ Medium Priority; — Low Priority

CHAPTER 2
Conceptual Approach for Characterizing RCRA Contaminated Facilities

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2.1 BACKGROUND

The conceptual approach to characterizing a contaminated site refers to the method by which site information is generated and interpreted. Many times under both the Resource Conservation and Recovery Act (RCRA), including stabilization, and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) programs, the scope of information gathered will determine the solution to the problem. In contrast, stabilization goals are used to direct the extent of information gathering and remedial action. In the past, one major conceptual approach has been the inherent faith that enough information will inevitably lead to a problem's solution. The experiences of more than 10 years of the CERCLA (Superfund) program, and several years of RCRA, however, have often shown that more information leads to additional confusion. This approach has in many cases led to the investigative phase lasting longer than 4 to 6 years, delaying actual remediation of the facility to even later in the process (more than 8 years). Without understanding interactions among soil, contaminants, and ground water, however, it is not always clear what information to ask for and what to do with it.

Collecting large amounts of information is an approach also found in case studies. The investigators will sometimes gather empirical evidence until a solution is found through trial and error. The final conclusions reached can be very useful, especially in providing a starting point for an investigation of a similar site. If the study found that a combination of pumping and treating and bioremediation cleaned up ground water in one situation, investigators might try the same thing at another site. The idea behind the conceptual approach proposed in this chapter, however, is to tie the problem identification and the remedy selection/implementation phases together based on the most scientifically appropriate stabilization strategy.

The following proposed conceptual approach offers a "tool" to characterize a problem in two stages:

- Ask questions that will direct the investigation toward obtaining the types of information necessary to characterize the problem at a site.
- Select stabilization technologies that will address the problem as it has been defined.

The mass balance conceptual approach is a way to ask these questions. To arrive at an appropriate stabilization solution, investigators and remediators need to be able to talk across disciplines, for example, chemist to hydrogeologist, in the context of the qualitative mass balance.

The next section, Section 2.2, describes the chemical mass balance concept. Section 2.3 presents a methodology for applying the mass balance approach.

2.2 THE CHEMICAL MASS BALANCE

The chemical mass balance approach attempts to characterize the chemicals at a site and the site itself, and to define the problem in terms of where the contamination actually occurs in the subsurface and in what phase. After the removal of surface sources such as drums, rockpiles, or tanks, the source of contamination to ground water is often the subsurface. This subsurface might contain the contaminant in a number of different forms coating the soil, in the air, or in the water.

It is very important to match the treatment technology to the appropriate phase. Pump and treat, for example, is effective for the removal of dissolved contaminants, but it is less effective for removing chemicals that are sorbed or chemicals present as a nonaqueous phase held by capillary tension or other physical phenomena in the geology matrix. Scientists and engineers often make the mistake of claiming that a particular technology failed, whether it is bioremediation, vacuum extraction, vitrifica-

tion, or some other method, when, in fact, they were using the technology in a situation where it was not applicable.

2.2.1 A Hydraulic Mass Balance Model

Hydraulic mass balance for site remediation is based on the movement of water onto and off of a site. Figure 2-1

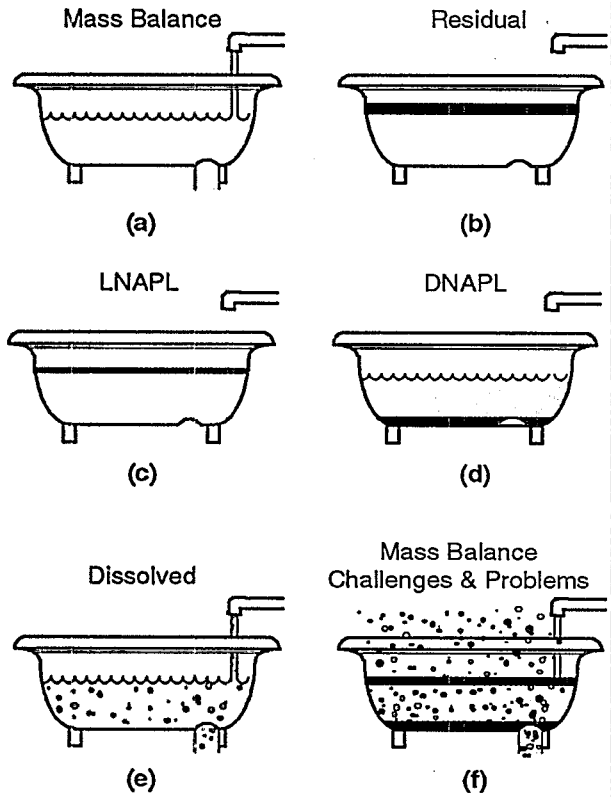

Figure 2-1. A bathtub model of a mass balance showing water and various chemicals entering a site and their phase transformations.

represents a mass balance by showing water and various chemicals entering a site (using a bathtub model) and their phase transformations. If oil is added to the water, it floats on top of the ground water. This floating product is known as a light nonaqueous phase liquid (LNAPL), because it is less dense than water. In this example, 95 percent of the chemical associated with the LNAPL is on top of the water (Figure 2-1c). As the chemical constituents slowly dissolve from this LNAPL in very minor amounts into the water, the contaminant may eventually exceed the maximum contaminant level (MCL). Thus, even though 95 percent of the mass is LNAPL, the ground water still is contaminated. The same scenario applies for dense nonaqueous phase liquid (DNAPL) that migrates downward because of its gravity-driven flow properties (Figure 2-1d). If the contaminant can be addressed at the subsurface source, it might be the best possible strategy to stabilize the site, thus preventing the further spread of contamination into the ground water. Physically containing the LNAPL or DNAPL, or hydraulically containing the LNAPL or extracting the free phase through product recovery, may serve as a stabilization measure to further prevent or minimize dissolved phase ground-water contamination and migration.

If the chemical of concern, such as nitrate, methanol, ethanol, or acetone, completely dissociates in water (Figure 2-1e), then removing the water is going to effectively remove the chemical. For a chemical predominantly in the water phase, it is appropriate to stabilize the water keeping in mind that some portion will still be adsorbed to the geologic matrix. If, however, chemicals exhibit a greater propensity to sorb to soil and form a residual, as in Figure 2-1b, this material will be trapped or sorbed in the surfaces of the sand, silt, and clay. Cleaning out the water, or "flailing the water phase" (a term used by sanitary engineers to describe measures that appear to address a symptom but fail to alleviate the problem), will not stabilize the site. When the tub is refilled, the chemicals will desorb or migrate from that residual soil just enough to exceed the MCLs again (Figure 2-1e). In this case, the residual as well as the water phase needs to be stabilized.

An important step in choosing a technology to stabilize a site is to determine which phase(s) needs stabilization or can effectively be stabilized. Once this has been established, the best technology or combination of technologies can be selected to stabilize the residual, water, LNAPL, DNAPL, or various combinations of phases that might occur.

A real-life example of the situation demonstrated in Figure 2-1d occurs at sites with creosote contamination. Contamination sinks to the bottom of the aquifer, and water is contaminated with chemicals such that the concentrations exceed the MCLs, because the source, which is a DNAPL, dissolves into the water phase. The water phase contamination is a symptom at most sites of the presence of other phases that hold, in many cases, more than 90 percent of the chemical mass.

On the other hand, volatile chemicals such as trichloroethylene (TCE) at a site might, to some extent, move out of the water into the air or gas phase (as in Figure 2-1f). If they move and are stopped by a horizontal layer, either manmade or natural, they may condense and dissolve into the water phase at another location not previously contaminated, thereby spreading the contamination further.

The goal of stabilizing sites is to control, minimize, or abate threats to human health or the environment from chemical releases. This approach aims to minimize the further spread of contamination by addressing the phases of the contaminant. Thus, in characterizing a site, it is important to ask in what phases the contaminant may be

present in the subsurface which may act as sources for ground-water contamination.

2.2.2 Transformation Potential

Another question to ask during the initial characterization stage is whether the phases that currently exist in the subsurface have the potential to be transformed. If transformation does occur, the remedial engineer must determine into what phase the product would be transformed. Figure 2-2 shows another way to draw a mass balance. Chemicals get into both unsaturated and saturated soil

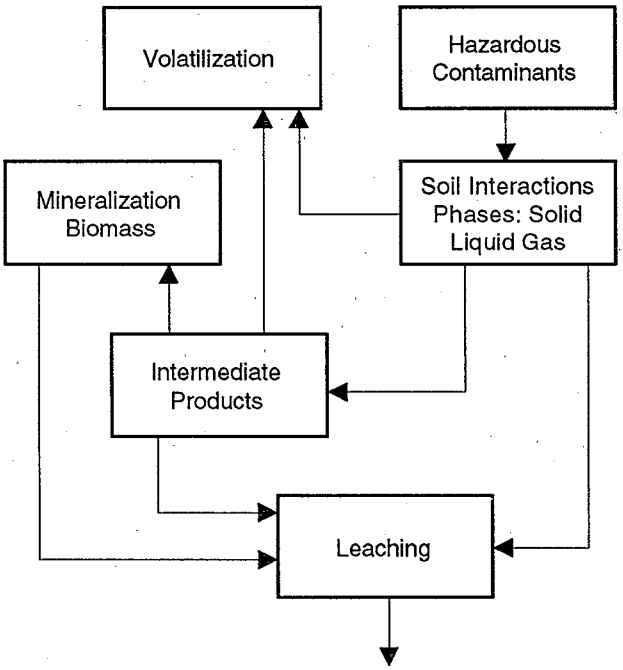

Figure 2-2. Fate of hazardous contaminants in the subsurface (Sims et al., 1989).

zones, and may be water soluble and leach to the ground dissolved in water or as free product. Once the chemicals reach the ground water, they will move through the aquifer in the dissolved water phase or as free product. Sometimes those chemicals will transform into intermediate products, such as in the familiar example of TCE degrading to vinyl chloride under anaerobic conditions. Therefore, the investigation must determine where this transformed product, the vinyl chloride, will go in the subsurface. Vinyl chloride has a higher tendency to be a gas than does its parent compound, TCE, and will tend to volatilize. Vinyl chloride and TCE also are soluble in water and therefore will be in the leachate phase.

2.2.3 Subsurface Mass Balance and Phases

Figure 2-3 illustrates the mass balance conceptual approach for the subsurface. In this diagram, the subsurface is divided into two phases: the solid phase and the fluid phase. The solid phase has an organic matter compo-

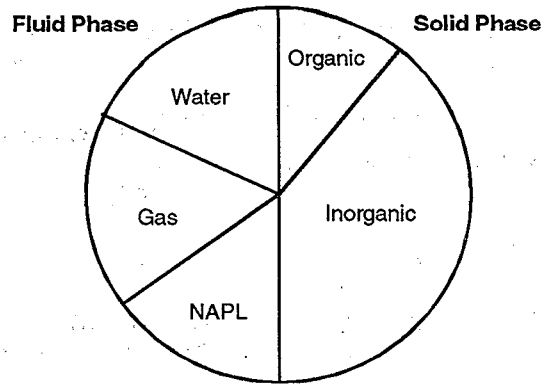

Figure 2-3. Mass balance conceptual approach (U.S. EPA, 1991).

nent, naturally occurring humus in the soil, and inorganic matter composed of sand, silt, and clay. The solid phase generally does not move relative to the fluid phase. Fluid phases, including aqueous and nonaqueous gases, will move under some type of pressure, suction, or force in the subsurface.

Often, with regard to sources of drinking water, the water compartment is contaminated because the solid and gas compartments are contaminated. Stabilizing the site, or preventing the further spread of contamination, may mean addressing one or more of the other phases in order to clean up the water phase. This brings into play a whole different way of looking at cleanup technologies, in terms of their ability to clean up not just the phase of immediate concern, but the other phases, such as the organic, the inorganic, the nonaqueous, or the gas phases, that may be contributing to the problem.

In this regard, the mass balance approach offers a way to ask questions, not an answer. A mass balance approach still will not allow the identification of 100 percent of the chemicals in different phases in the subsurface but can be used to characterize which chemicals will tend to be in which phases. The cleanup technology then can be evaluated based upon its ability to control whatever phase is responsible for the contamination. The mass balance conceptual approach attempts to link the subsurface and surface systems.

2.2.3.1 Solid Phase

Organic Matter (Humic Material)

The organic matter content can be useful for defining the problem at a site with regard to transport, and thus for evaluating treatment options. Figure 2-4 illustrates a theoretical composition of generic organic matter: benzene rings, aromatic structure, and many straight chain carbon compounds. Organic matter is chemically complex and serves as a solvent for organic chemicals. The more a chemical added to the soil structurally looks like this organic material, the more it tends to act as a solvent for

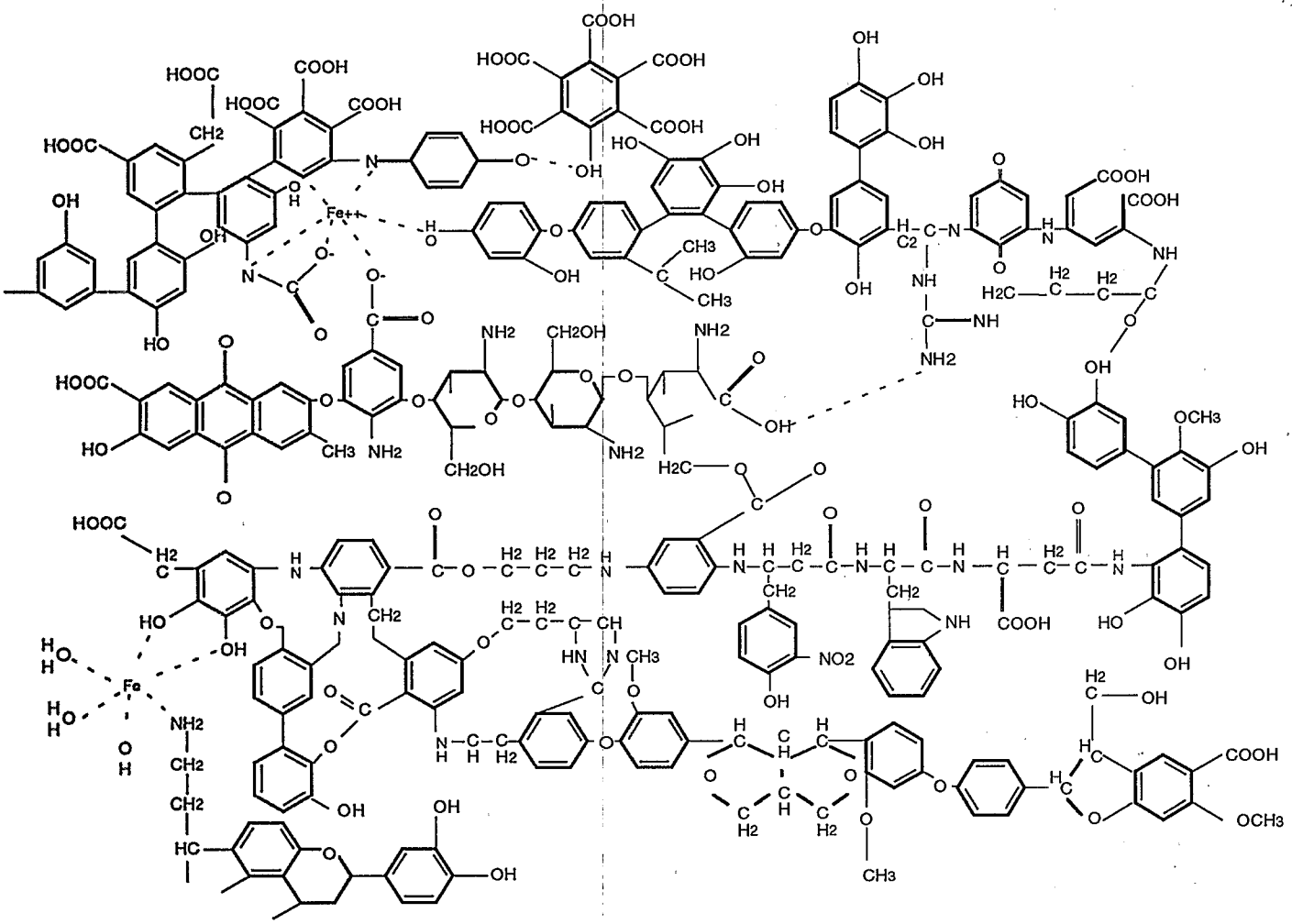

Figure 2-4. Composition of organic matter.

the contaminant. A rule in organic chemistry is "like dissolves like." For example, if one tries to pour gasoline into a styrofoam cup, the cup dissolves in one's hand, because both materials are structurally similar. In a simple system, such as soil material surrounded by water, the more the chemical resembles organic matter, the less it will tend to be in the water phase, and the more difficult it will be to clean up the site with pump and treat. Therefore, knowledge of the organic matter compartment can relate directly to the efficacy of a treatment technology.

Inorganic Matter (Texture)

The texture of soils (inorganic material) can be an important consideration in selecting a treatment technology. Texture influences permeability to fluids, and influences the storage and sorption of contaminants. Figure 2-5 is a standard soil classification texture triangle. Gravel is made up of relatively large pieces of material; sand, silt, and clay are composed of increasingly smaller particles. As the size of the particles shrinks, the interstices between the particles shrink as well, and surface to volume ratio increases; this is accompanied by an increase in the capillary pressure, called capillary rise, and an increase in porosity. In clay environments, this can result in the storage of large amounts of water in the vadose zone. Figure 2-6a shows the values for capillary rise in various soils. If a chemical in the water phase is stored in the vadose zone, the vadose zone can become a source of contamination to the saturated zone.

Texture also can indicate the porosity of a material, or the extent of internal pores. Figure 2-6b illustrates the percentage porosity of different textures (clays, sands, gravels, and silts) ranging from 10 to 60. Clay has a very high porosity, and because of its internal pores can store a lot of pollutants. Also, because clay has a low saturated conductivity, it is difficult to push any fluid, or nonaqueous phase liquid (NAPL), through it to recover product. Permeability, or hydraulic conductivity, indicates the relative ease with which fluids move, including water with nutrients (Figure 2-6c). Bioremediation, vacuum extraction, and pump and treat have limited success when remediat-

Using materials less than 2.0 mm in size. If approximately 20% or more of the soil material is larger than 2.0 mm, the texture term includes a modifier. **Example:** gravelly sandy loam.

Example of use: A soil material with 35% clay, 30% silt, and 35% sand is a clay loam.

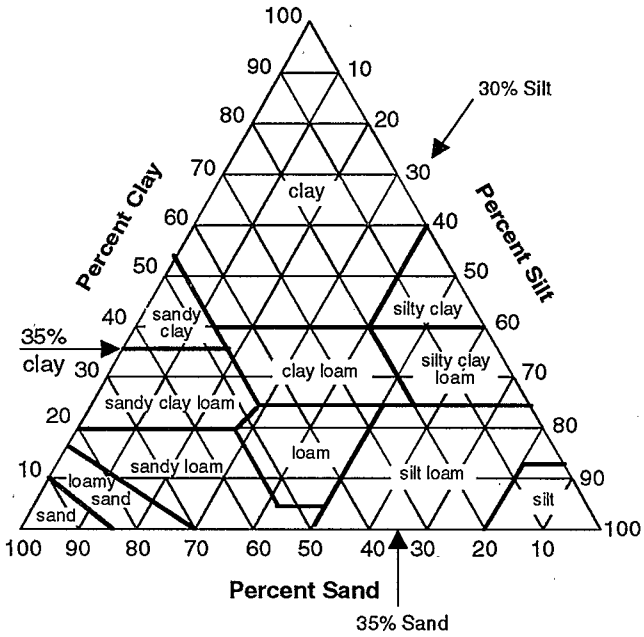

Figure 2-5. U.S. Department of Agriculture soil textural classification (texture triangle) (Soil Conservation Service, 1971).

ing clay, because clay has a much lower hydraulic conductivity than gravel, sand, or silt. Because clays have a higher storage capacity and lower ability to transmit fluids, their presence in the subsurface at a site will provide a challenge for site stabilization or site cleanup.

2.2.3.2 Fluid Phase

Nonaqueous Phase Liquids

The characteristics of NAPLs include their free phase flow, residual saturation, and ability to retain chemicals that contaminate air, water, and soil through distribution among compartments in the subsurface. Some examples of LNAPLs are oil and pentachlorophenol (PCP) in oil; PCP alone (without an oil carrier) is a DNAPL, as are creosote, methylene chloride, and many other chlorinated solvents. Knowing whether a chemical is a DNAPL or an LNAPL gives an indication of where to look for it in the subsurface.

Gas

The gas compartment is an essential part of site characterization and can be useful in characterizing transport from a site. Depending on their density relative to air, chemicals in the gas compartment may move upward toward the atmosphere or downward toward ground water

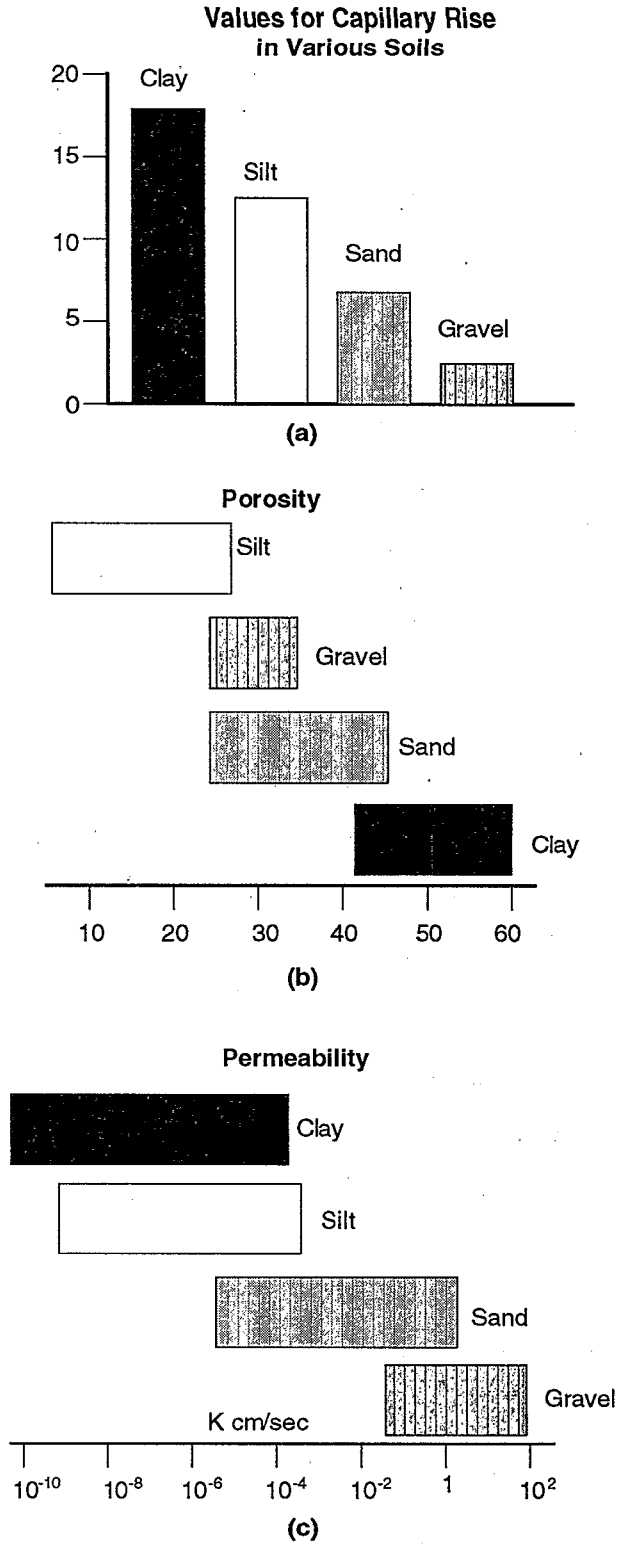

Figure 2-6. Values for capillary rise (a), porosity (b), and permeability (c) in various soils (Dragun, 1988).

in the subsurface. If the chemicals move upward and horizontally, they can increase the threat to human health and the environment. If they move downward, they can

further the spread of contamination into the ground water and beyond a site. Understanding the gas compartment is useful for evaluating an approach to treatment. For example, vacuum extraction is effective for controlling or minimizing the gas phase, whereas many other treatment systems are not. Treatment of the gas phase with bioremediation, for example, can be deceptive because volatilization is sometimes mistaken for biodegradation, since the contaminant seems to have disappeared.

Water

Capillary forces, as a function of texture, facilitate the ability of soil to store water, contaminate it, and then return the water back to the ground-water source through precipitation. The metric potential or suction in the soil influences the movement of water and chemicals dissolved in the water. It also can indicate storage of contaminants and sources of contamination to ground water.

2.2.4 Distribution Coefficients

The distribution coefficient (K_d) is the concentration of a chemical adsorbed onto the organic and inorganic solid phase, compared to the concentration of the chemical in the water phase:

$$C_s/C_w = K_d$$

The higher the K_d, the more the chemical tends to be adsorbed on the solid phase; therefore, the less efficient pumping and treating the water will be. If a contaminant has a high K_d, it is going to associate with the soil phase. The problem then remains whether to destroy the chemical in the soil phase or move it from the soil phase into the water phase using a solvent or surfactant. The lower the K_d, the more the chemical tends to be in the water phase, and the better pumping and treating will work to stabilize contamination. This, however, should not preclude the use of pump-and-treat systems in lower K_d systems to stabilize the facility by mitigating contaminant migration.

For a NAPL, this equation reads:

$$C_o/C_w = K_o$$

with C_o being the concentration of the chemical in the nonaqueous phase, compared to its concentration in the water phase. The higher the K_o the more likely the chemical is to be found in the nonaqueous phase. Remediation technologies for a chemical with a high K_o should focus on recovery of the product NAPL.

Finally, the concentration of the contaminant in air versus water is represented by:

$$C_a/C_w = K_h$$

If a chemical has a high K_h, it has a greater affinity to partitioning into the air phase. A chemical that has a low K_h tends toward being in the water phase. Vacuum extraction or venting would be a technology to consider for a chemical with a high K_h.

Distribution coefficients indicate the tendency of a system to move towards equilibrium by showing in what phase the chemicals tend to be. This tendency toward equilibrium is, conceptually, the reciprocal of fugacity, a term that implies the tendency of a chemical to escape from a particular phase.

2.2.5 Migration/Transport

Figure 2-7 shows a flow diagram of the methodology for integrating site characterization with subsurface remediation. Investigators need to determine how the waste and soil interact, whether there is partitioning to the soil in the gas phase or in the nonaqueous phase, and what type

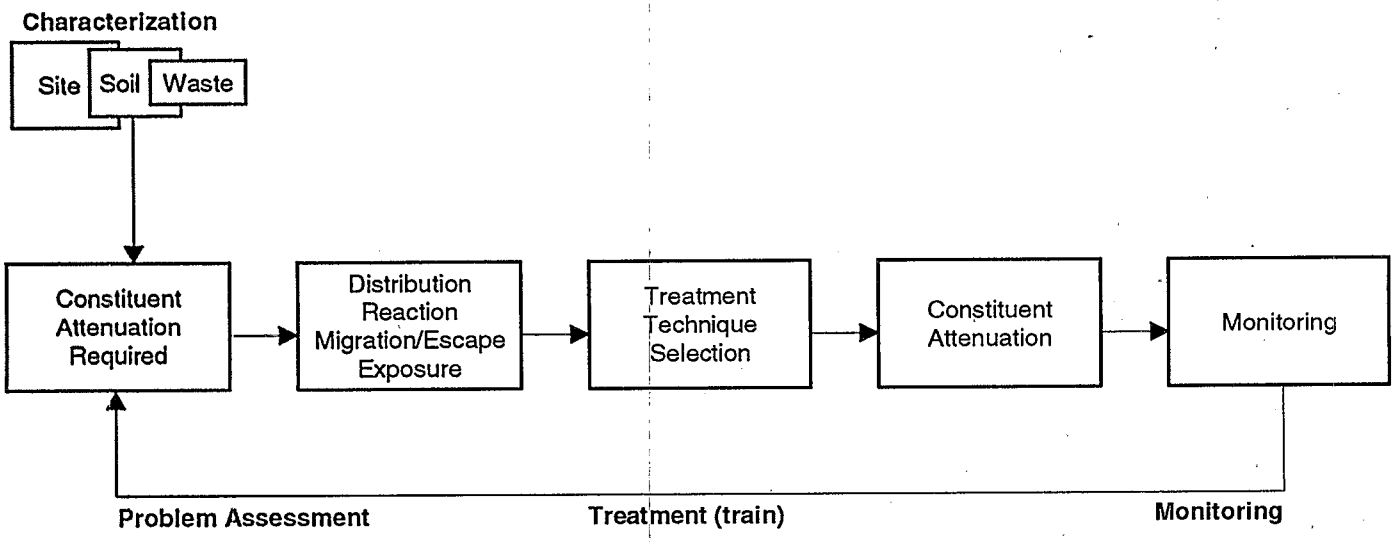

Figure 2-7. Methodology for integrating site characterization with subsurface remediation (U.S. EPA, 1990).

of climate and precipitation are present at the site. This information will help investigators determine the migration and transport potential of contaminants in different phases.

Table 2-1 presents some of the most important properties and parameters needed to perform a soil-based waste characterization. Most of this information is contained in the Corrective Action Plan (CAP). Using this information, a chemist will be able to determine whether a given chemical oxidizes or reduces, and in what phases and where the chemical is likely to be found. PCP, for example, is an acid with a maximum dissociation at a pH of 4.7. If there is PCP in a soil, the pH will indicate in what form (salt or free acid) the PCP will be found. If it is in the ionized form, pH above 4.7, it is going to be more water soluble. In the western part of this country, where soil tends to have a higher pH, the PCP is going to be more ionized, and thus more water soluble. In the eastern part of the country, however, the soil pH may be as low as 4 or 5. In that case, the PCP is going to be sorbed to soil and/or occur in the nonaqueous phase, i.e., in the oil, if it is present.

Table 2-1. Important Properties and Parameters Needed to Perform a Soil-Based Waste Characterization

Physical Properties	**Soil Degradation Parameters**
Density	Half-life ($t_{1/2}$)
Viscosity	Rate Constant
	Loss of Parent Cpd
Chemical Properties	Mineralization
Molecular Weight	Intermediates
Melting Point	
Specific Gravity	**Volatilization Parameters**
Structure	Air/Water (K_h)
Water Solubility	Vapor Pressure
Vapor Pressure	
Chemical Class	**Soil Sorption Parameters**
Acid	Cation Exchange Capacity
Base	Anion Exchange Capacity
Polar Neutral	Soil/Water (K_d)
Nonpolar Neutral	Octanol/Water (K_o)
Inorganic	
Photodegradation	**Soil Contamination Parameters**
Chemical Reactivity	Concentration in Soil
Oxidation	Soil Horizonation
Reduction	Depth of Contamination
Hydrolysis	
Polymerization	
Precipitation	
Biotic/Abiotic	

Adapted from: U.S. EPA (1984).

2.2.6 Management

Using a knowledge of chemistry, the remedial manager first can predict in what phases the different chemicals will occur, and then select a treatment train based on those phases. All treatment technologies can be simplified into three categories:

- Containment technologies
- Extraction technologies
- Destruction technologies

Figure 2-8 offers a basic scheme to describe these basic

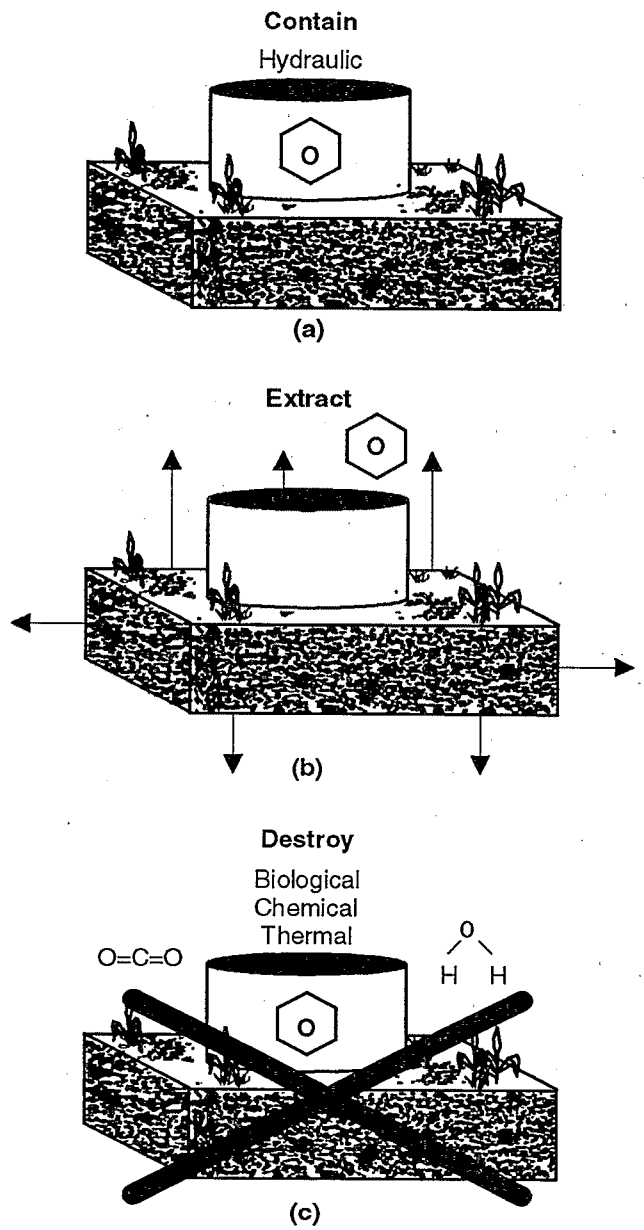

Figure 2-8. Treatment train approach.

categories. Within these categories, however, are hundreds of individual processes.

2.2.6.1 Containment

Containment might be the first step to consider in a stabilization action (Figure 2-8a). Pumping and treating is being studied both as an effective method for containing the aqueous and the nonaqueous plumes and as a method for cleaning up a site. Containment could be hydraulic as well as physical, such as constructing a slurry wall or using a temporary clay or synthetic cap. Chapter 4 will discuss capping and clay liners in more detail. Temporary containment is also an option, especially if the remediation team is examining longer term corrective action remedies for eventual site cleanup and restoration.

Containment systems can get very large, such as the slurry wall in Laramie, Wyoming, which is 30 to 70 feet deep and 10,000 feet long. Systems also are available for combining hydraulic with physical containment, which can be followed up with an additional longer term remedial technology.

2.2.6.2 Extraction

Figure 2-8b shows extraction technologies, including vacuum extraction (pulling material out of the soil through the air phase) and product recovery. The vertically downward arrows could represent leaching, soil flushing, or pumping and treating where the material is used to move the water-soluble phase through the soil.

2.2.6.3 Destruction

Many technologies attempt to destroy contaminants by biological, chemical, and thermal techniques (Figure 2-8c). Following the extraction phase in Figure 2-8b, the contaminants extracted could be destroyed above ground or destroyed in situ.

2.3 METHODOLOGY

Figure 2-9 shows a schematic of a particular site that has an unsaturated zone and a saturated zone. To characterize for a stabilization action, it is necessary to put all of this information together for the CAP. The key questions to ask are:

- What chemicals, and at what volumes, are at the site?
- What phases of contaminants are present at the site (aqueous, nonaqueous, gaseous, sorbed)?
- Where are those phases found in the subsurface, both in the unsaturated and saturated zone?
- Where are the LNAPL and the DNAPL? (Both may be caught in the unsaturated zone.)

The investigation must determine how to stabilize the particular phases present for preventing the further spread of contamination for particular chemicals.

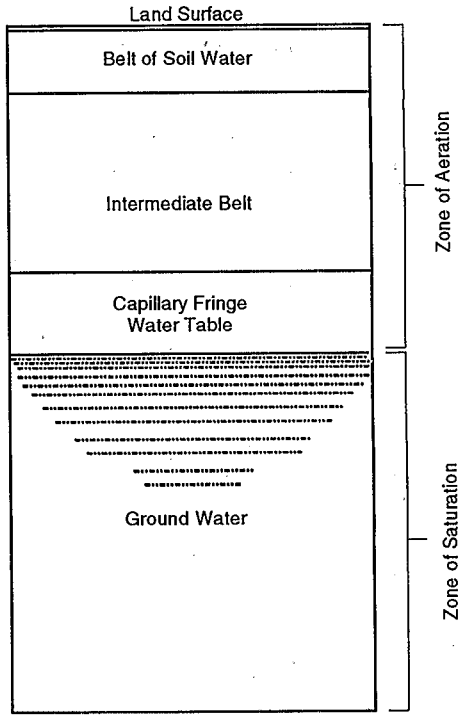

Figure 2-9. Contaminated site with an unsaturated and saturated zone.

The four steps in the conceptual approach to stabilization are:

- Characterization of chemical and site information
- Problem definition with regard to risk, risk assessment, and exposure to populations and the environment
- Treatment train selection using both chemical and site data to determine which combination of containment, extraction, and destruction technologies will be most effective at the site
- Monitoring the stabilization technology for each phase of the chemical

2.3.1 Characterization

The two main types of data needed to select treatment are chemical characteristics and site characteristics. Both of these must work together; often a technology that would work based on chemical characteristics might be rejected because of conditions at the site and vice versa. In terms of chemical characteristics, for example, the investigation needs to determine whether a contaminant is an LNAPL or a DNAPL, in the gas or dissolved water phase, or sorbed to soil. The site investigation should reveal information about conductivity of the subsurface, i.e., how the site allows fluids to move in and out.

2.3.2 Problem Assessment

The next major stage is problem assessment, in which

remediators determine which chemicals are in what phases, and how those phases will move. In addition, they need to assess how these chemicals in their various phases pose risks to human health and the environment (i.e., an exposure assessment). Once the remedial team determines whether the population is being exposed through the air, through pure product, through the leachate, or through some other medium, they can select a treatment train, the next stage of the process. The cleanup goals at a site also are part of the problem definition.

2.3.3 Treatment Train Selection

Generally, more than one phase at a site requires treatment, so a train instead of a single treatment technique is usually necessary. If a site has only one contaminant in only one phase, treatment is much less complex. For example, at one industrial site, formic acid was the only contaminant. The partition coefficient for formic acid revealed that it tended to occur only in one phase, the water phase, so treatment was relatively simple.

As mentioned above, three approaches—containment, extraction, destruction—form the basis of the treatment train. Technologies are selected that perform one or more of these functions. An example of a stabilization train might combine a slurry wall and hydraulic containment, vacuum extraction, soil flushing, and bioremediation in a configuration based upon the phases present at the site. Figure 2-10 shows a treatment train that begins with product removal, then uses pump and treat and soil flushing, and finishes with bioremediation. Hydraulic and physical containment might be established first to stabilize the site, followed by product recovery. Pump and treat could be used to pull the chemicals out of the site that are in the water phase. Soil flushing, with or without water, would help remove chemicals in the unsaturated zone that are soluble in the solution used, but are partitioned to soil. A surfactant or solvent could be used to decrease the partition coefficient (K_d), thus increasing the tendency of a particular chemical to go into the solution phase so it can be pumped out. Flushing moves the chemical from the solid phase to the solution phase. Bioremediation is the last stage of the treatment train, the "caboose," and not generally considered as a front-line stabilization technique. Bioremediation might be best applied to remediate whatever cannot be extracted from the soil.

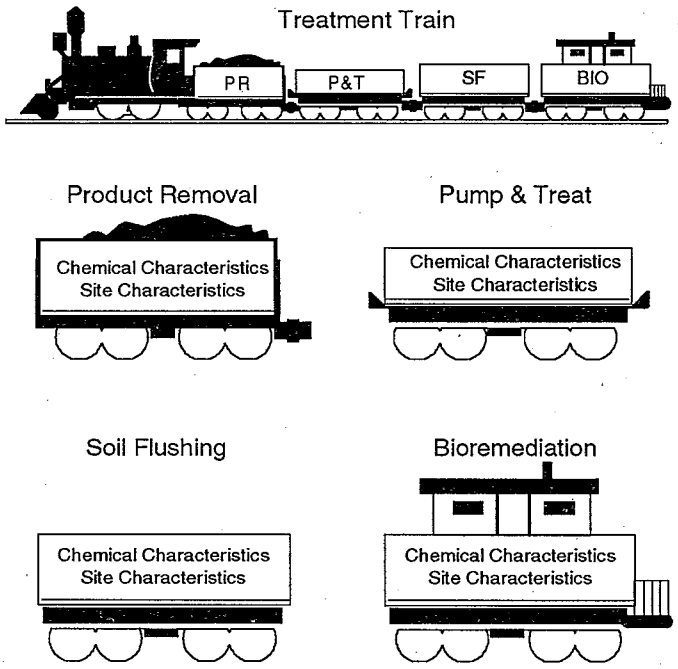

Figure 2-10. Treatment train from product removal to pump and treat, soil flushing, and bioremediation.

2.3.3.1 Pump and Treat

When considering pumping and treating for stabilizing plume migration and for source (hot spot) removal, the investigator needs to know the characteristics of the chemicals present that tend toward being in the water phase. Site information would be used to determine whether the site will allow water to be pushed or pulled through the material. Based on chemical characteristics, some contaminants are amenable to pump and treat, but if the site is largely clay, or has a lot of clay stringers, this technology may be less effective. The reader is referred to EPA (1990) on pump and treat technologies.

2.3.3.2 Soil Flushing

Those chemicals that are more tightly bound to or trapped in the soil might yield better remediation results with soil flushing. An important consideration is the extent that solvents and surfactants partition the chemical out of the solid phase or trap residual saturation into the solution phase. The site characteristics again relate to the ease with which water solvent or surfactants move in and out of the site.

2.3.3.3 Bioremediation

The relative recalcitrance of a chemical to degrade is important in bioremediation. Dioxins and PCBs, for example, are more difficult to degrade than methanol, ethanol, and some hydrocarbons. Chemical characteristics provide information concerning the tendency of the chemical to degrade under aerobic or anaerobic conditions. Relevant site characteristics relate to the feasibility of transporting nutrients and oxygen to the site. Bioremediation is usually limited by the supply of nutrients, the presence of toxic chemicals, and the supply of oxygen.

2.3.4 Monitoring Treatment Performance

After investigators determine the particular treatment technologies that will be effective for specific phases and begin implementation, then the investigation must monitor particular phases for particular chemicals in an attempt to optimize the technology application.

For any stabilization measure, delivery and recovery are going to influence the success of application. The impact of stabilization will be restricted or limited if fluids are unable to be moved into and out of the subsurface through methods such as nonaqueous phase product recovery, vacuum extraction in the air phase, or pump and treat in the water phase.

2.4 REFERENCES

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U.S. EPA. 1990. U.S. Environmental Protection Agency. Basics of pump and treat groundwater remediation technology. Laboratory RSKERL Ada, OK. EPA 600/80-90/003.

CHAPTER 3
Field Screening Methods

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3.1 FIELD SCREENING REQUIREMENTS: SCOPE AND EXPECTATIONS

Field screening refers to the use of rapid, low-cost test methods to determine whether a contaminant of interest at a given site is present or absent, above or below a predetermined threshold, or in a concentration within a predetermined range. The goal is to develop simple and inexpensive field screening methods for organic and inorganic analyses to support onsite monitoring and characterization activities. Rapid, low-cost methods are projected to be the mainstream techniques in stabilization for characterization and monitoring. The rapid and real-time capabilities of many of these methods allow for stabilization to be implemented in the short term, at a reasonable cost, and at an appropriate analytical level. Figure 3-1 shows the chemical classes of 200 hazardous substances that can occur at a site and be detected by field screening methods.

Field screening methods would support stabilization by helping to accelerate cleanup, instill confidence in cleanup, save money, allow collection of real-time data, achieve higher sample density, and effectively detect "hot spots." Field screening aids site characterization by providing legally admissible quality data and rapid sample analysis. It also can direct ongoing stabilization and corrective action remedial field investigations (RFIs), help assign priorities to sampling surveys and excavations, and reduce the need for more expensive offsite analysis.

When performing field screening exercises, the investigator should 1) ensure the objectives of the study are clear and 2) use the right tools to accomplish the stated objectives. Before initiating field screening at a site scheduled for stabilization, it is important to consider some basic issues. The first decision the investigator must make is where to sample, taking into account the representativeness of samples and sample integrity. The investigation then must define a sampling strategy.

To provide guidance and standardize procedures for field screening, a Monitoring and Measurement Technologies Program has been established. Its purpose is to identify new or existing technologies; evaluate, demonstrate, and report on performance; transfer technology; and develop and distribute standard methods when required. The types of technical support available include field studies, data interpretation, and technical oversight including on-site audits, analytical support, and technical review. A Field Assessment Program also complements Agency programs by providing quality field data with a minimum of analytical waste. The EPA Environmental Response Team (ERT) offers sampling quality assurance (QA) programs through Bill Coakley, who has developed Representative Field Sampling Guidelines for various media and techniques.

Field screening can provide data for several levels of analysis depending on the required quality of the data. Table 3-1 presents the data quality necessary for each analytical level.

Table 3-1. Analytical Levels Relative to Data Quality

Analytical Level	Data Quality
Level I	• If instruments are calibrated and data are interpreted correctly, it can provide indication of contamination
Level II	• Dependent on QA/QC steps employed • Data typically reported in concentration ranges
Level III	• Similar detection limits to CLP • Less rigorous QA/QC
Level IV	• Goal is data of known quality • Rigorous QA/QC
Level V	• Method specific

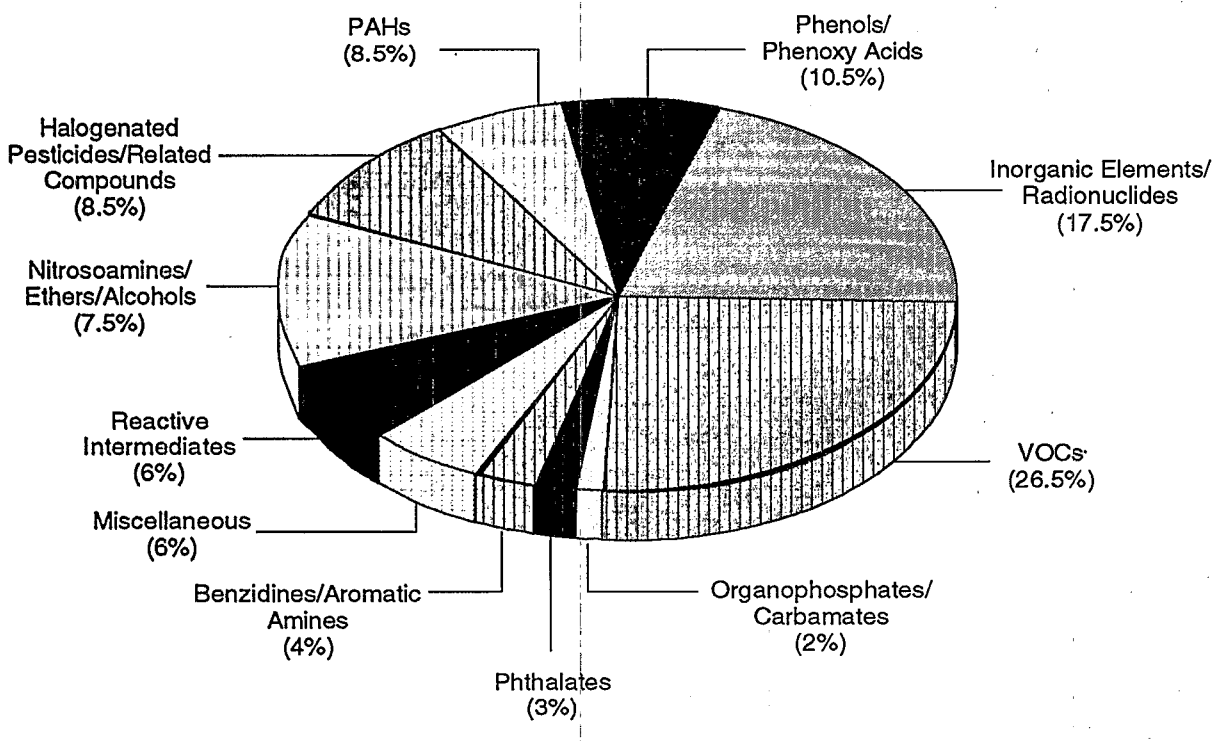

Figure 3-1. Chemical classes of 200 hazardous substances.

Finally, QA is essential for effective field screening. At a minimum, the following QA activities should be performed when conducting field screening:

- Analyze blanks frequently.
- Monitor retention time or detector response to identify and/or compensate for instrument drift.
- Adapt data quality objectives as well as QA/quality control (QC) procedures to site-specific conditions. These cannot be standardized for field and laboratory.
- Incorporate blind spiked samples into the analytical sequence for precision, accuracy, and comparability.
- Consider system and site-specific characteristics, along with personnel experience, in setting study objectives.
- Send a percentage of the field analysis samples to an offsite lab for independent verification of results.

The following sections describe actual field techniques and instruments, and future needs and directions in field screening. Section 3.2 presents analytical equipment amenable to stabilization investigations, such as gas chromatographs, gas chromatographs/mass spectrometers, chemical sensor systems, and x-ray fluorescence spectrometers; sampling methods for soil-gases and air; and immunoassay methods. Section 3.3 outlines future needs and directions and Section 3.4 is a bibliography.

3.2 FIELD TECHNIQUES AND INSTRUMENTATION

The Hach® kit is one of the oldest utilized field screening techniques. The advantages of Hach® kits are that they have a large library of analytes, are easy to use, and are quick and relatively inexpensive. When using Hach® kits, however, there may be interferences from other compounds present. While Hach® kits are used largely and designed for water samples, they have been adapted for use with soils. Any chemical or laboratory instrument supply may have a Hach® catalog.

Other types of field screening devices useful for providing site information for the implementation of site stabilization include:

- Gas chromatographs
- Gas chromatographs/mass spectrometers
- Chemical sensor systems
- X-ray fluorescence spectrometers
- Sampling and analysis equipment for soil-gases and air
- Immunoassay methods

Each of these types of devices is described in the pages that follow.

3.2.1 Gas Chromatographs

Portable gas chromatographs (GCs) are very useful in the field for analyzing concentrations of known contami-

nants in soil and water. They are more complex and expensive than some other equipment that will be discussed, but are useful for surveying for extensive contamination. GCs have internal gas supplies, detectors, and integration systems. Integration systems are important for evaluating the concentrations of compounds in soils or water. GCs provide very low detection limits, but have a limited library of compounds that they can detect. Many GCs have routine field applications and numerous vendors; some units have been specifically designed for the field, and are proving to be more accurate in field analyses than are offsite lab analyses. There is, however, a need for improved sensitivity and selectivity of appropriate equipment and for instituting standardized field methods and QA procedures.

Two types of GCs—the purge and trap and the headspace—are discussed below.

The **purge and trap** GC can analyze volatile organic compounds (VOCs) in soil and water, with low Henry's Law constants (Henry's Law constants are discussed in detail in Chapter 6). Two examples of purge and trap GCs are the argon ionization detector (AID) and the thermal conductivity detector (TCD). The AID has an electron capture detector (ECD), and is very useful for halogenated compounds, such as trichloroethylene (TCE) and especially for the chlorinated alkanes, which cannot be seen by a photoionization detector (PID). A PID is an instrument that detects and measures airborne, ionizable gases and vapors. The AID also can detect benzene, toluene, and other compounds that a PID can detect, and it can perform analysis on water and soil samples. A Scentograph® has a library of 16 compounds. The Micromonitor®, a very quick field screening method, uses a thermal conductivity detector (TCD). It is easily portable, but unfortunately requires a concentrator. It has a large library of compounds.

The Viking gas chromatograph/mass spectrometer (GC/MS) is another purge and trap device (not in Table 3-2), which is portable but more expensive than those discussed above. It detects nonpolar organics in the air, and provides the highest level of certainty for identification of different compounds.

The **headspace** GC has a higher detection limit than does the purge and trap GC, unless a sensitive or selective detector is used. The Photovac®, a popular type, has a high detection limit, and is used only for compounds with high Henry's Law constants. The Photovac® has a library of 25 compounds. EPA's ERT uses the Photovac® in much of its field screening, soil gas, water, and soil headspace work.

The Photovac® has a PID, which is sensitive to aromatics and unsaturated aliphatic compounds, such as benzene and styrenes. PIDs do not, however, detect methane or alkanes. A PID will detect only substances that are ionizable at or below the lamp intensity for the instrument, and its built-in integrator can provide the relative concentration.

Table 3-2 summarizes advantages and disadvantages of two categories and three types of gas chromatograph detectors.

When using GC analytical methods, it is helpful to determine the target compounds first, in order to select the appropriate analytical tools and procedures. Choosing the proper gas chromatograph for a specific situation involves consideration of the following selection criteria:

- **Detector Type**—Sensitivity requirements and compound class
- **Injection System**—Sample matrix
- **Column Type**—Sample components
- **Oven Temperature**—Sample components
- **Data System**—QA/QC and archiving requirements

Figure 3-2 provides some guidance on selecting a GC detector based on volatile target compounds. A TCD has two columns, and identifies a compound based on studying the resolution times on the two columns. It has a very short retention time in the columns, and can provide results in 3 minutes. (Other GCs take 15 to 60 minutes, depending on the number of blanks run between each hot sample.) In addition to its unique retention time, the thermal conductivity detector has a library of 100 compounds. It works primarily in parts per million (ppm) levels, but a concentrator can drive the detection limit down to parts per billion (ppb) levels, which can be useful when dealing with unknown contaminants. The disadvantage of

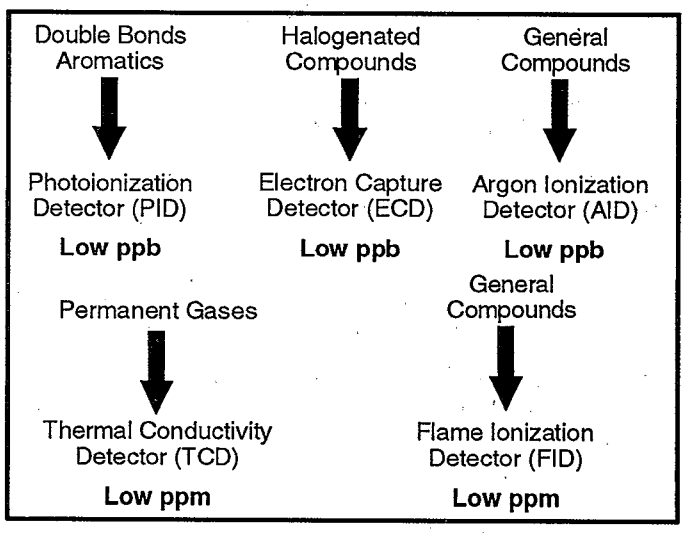

Figure 3-2. Selection of portable gas chromatograph detectors based on volatile target compounds.

Table 3-2. Summary of Three Gas Chromatograph Devices

	Advantages	Disadvantages
PURGE AND TRAP		
AID	• Data archiving via internal personal computer • Responds to aromatics and chlorinated alkanes and alkenes • Rugged; easily decontaminated • Internal adsorption trap allows sample preconcentration to enhance sensitivity	• Limited linear range (10^2 to 10^3) • Limited capillary column capabilities
TCD	• Fast run times • Detects broad range of compounds • Best detector for permanent gases (O_2, N_2, CO, CO_2, and CH_4) • Isothermal heated column (30° to 180°C) • Large compound library (100+) for screening unknowns • Dual column for compound identification/combination	• Poor sensitivity (>1 ppm) • Sophisticated external data system required • External concentrator required if ppb levels required
HEADSPACE		
PID	• High sensitivity (low ppb range) • Self-contained and rugged • Precolumn with backflush • Capillary column capability • Widespread use, well-developed methods • Ideal for aromatics (BTXs), double bonds (PCE, TCE, DCE)	• Limited temperature control of columns • Complicated external plumbing • Prone to electronic interference • High ambient temperature breakdowns

this device is that it is very expensive and, because it requires a high vacuum, has the potential for a long downtime.

Selection of the oven temperature is determined by the boiling points of the target compound. For compounds with a stabilized ambient boiling point, within 20°C of the ambient temperature, the Photovac® is the most appropriate tool. Isothermal compounds, those with constant, elevated temperatures of up to 300°C (boiling point is less than that of chlorobenzene) work best with the Scentograph®. For situations in which there is a wide variation in target compound boiling points (temperature programmed), a laboratory or advanced transportable instrument is recommended.

3.2.2 Gas Chromatography/Mass Spectrometry

Gas chromatography/mass spectrometry is particularly useful for its ability to measure concentrations of a broad range of unknown contaminants. This equipment is miniaturized and rugged. Much research and development has been done on these devices for the defense and aerospace industries. EPA has conducted a demonstration of one available unit, and other instruments show promise. Quality assurance and standardized field methods, as well as a standard data reporting format, are still needed for this technique.

3.2.3 Chemical Sensor Systems

Chemical sensor systems are an emerging technology that offers much promise in compound identification and quantification. Current types of systems include surface acoustic wave devices, fiber optics, spectroelectrochemical devices, solid phase sorption/spectroscopic devices, and porous polymer and glass fibers. Some of these available technologies, however, have limited environmental application.

A few remote or stand-off sensor systems are available commercially, two of which EPA is examining under the

Superfund Innovative Technology Evaluation (SITE) program. Two technologies are long path Fourier transform infrared (FTIR) spectrometry for air and long path ultraviolet (UV) spectrometry. Spectrometry uses the energy source of a particular wavelength to activate the molecules of a substance, thereby producing a spectrum. FTIR spectrometry identifies unknown contaminants by using infrared light to determine bonding between atoms, and thus the molecular structures, of all contaminants present. FTIR spectrometry evaluates and identifies volatile compounds that pass through a beam stretching from the device to a mirror and back. It can be operated at any height, the important parameter being the distance between the source and the mirrors, which can range from one to several hundred meters, the length of a substantial fence line. This spectrometer also gathers virtual real-time data. Because it provides results in minutes, FTIR spectrometry provides more valuable information than do discrete fence-line monitors like SUMA canisters or XAD tubes, which have to be left in a location for a period of time, and then sent to a laboratory for analysis. UV spectrometry uses ultraviolet light to determine molecular bonding to ascertain if specific known contaminants are present. Much research is still needed on these systems, including a definition of their use in air pathway analysis, standard methods and QA procedures, and comparability to point samples.

Spectroscopic techniques using fiber optics are another emerging technology that is the focus of much research and development. Studies have been done on luminescence, fluorescence, and absorption. Optical fibers have the potential to be used for in situ monitoring. Prototype units now exist, and the technology is beginning to be commercialized.

An infrared temperature indicator, which can be in the form of a gun-like device, can be used to estimate the liquid volume in above ground tanks by taking a vertical profile down the side of the tank. The change in temperature indicates the air-aqueous interface, from which the volume estimate of product or liquid in the tank can be estimated.

3.2.4 X-Ray Fluorescence Spectrometers

X-ray fluorescence (XRF) spectrometry works on the basis of a photoelectric effect, activating atoms of materials in dry soil and counting the X-rays that are energized. This device is in widespread use for determining the extent of soil contamination, selecting samples for offsite analysis, guiding cleanup activities, and analyzing air monitoring filters. An XRF spectrometer also can be used for determining hot spots in "extent of contamination" surveys.

The XRF spectrometer can detect as many as 23 different metal compounds. The detection of matrix effects using this device is almost more important than the detection of the compound of interest. A lot of sample preparation is necessary to get a valid reading on the XRF spectrometer. It is much more effective if it can be calibrated using 6 to 10 site samples of the same relative concentrations analyzed by a standard method such as an atomic absorption (AA) or inductively coupled plasma (ICP) detector. After calibration, the XRF spectrometer can provide reliable data. Newly released models provide better internal calibration via different ion excitation, thereby allowing for elimination of site-specific sample calibration.

This device is easy to use, can be easily transported in a backpack, and provides nondestructive analysis. It is also reliable and quick. The XRF spectrometer has a relatively low sensitivity, reading primarily in ppms, which is adequate for most metals, especially lead. If there is a mix of metals at the site, however, there may be some interference overlaps. At a site with cadmium or where concentrations are about 3 ppm, an XRF spectrometer probably would not be appropriate. For most sites, however, such as lead battery sites, it works quite well.

Data comparability, standards and performance evaluation methods, standard field methods, and improved sensitivity for portable units are still needed, but new and improved instrumentation is continually being introduced.

3.2.5 Sampling and Analysis Equipment for Soil-Gas and Air

3.2.5.1 Soil-Gas Survey

The soil-gas survey can be useful for finding either contaminated ground water or soil contaminated with volatile organics. Figure 3-3 shows a simple schematic of a soil-gas sampling device. A slam bar creates a hole into which a collection tube may be slid. The flux gate magnetometer ensures the slam bar will not punch through any water or electrical lines. Other important features are the vacuum pump, Gillian®, and a simple desiccator that creates a vacuum to collect the soil pore-space sample. The PID detector is used to measure relative concentrations of different volatile organics in the pore space and may be used to help locate "hot spots" and subsurface extent for well placement locations.

The soil-gas survey is a quick and easy way to locate contaminated spots over a very large area. The contaminants, however, should be relatively insoluble, highly volatile, and have a specific gravity of less than 1. Contaminants floating on top of the ground-water table will volatilize into the porous space in the soil-gas survey equipment so the survey can be performed. The class of halogenated compounds, such as TCE, which sink, do not partition as well into that pore space above the ground water. In addition, the presence of a perched water table above the contaminant plume can present an obstacle with this method because the vapor phase could solubilize into the perched water phase. An overlying clay

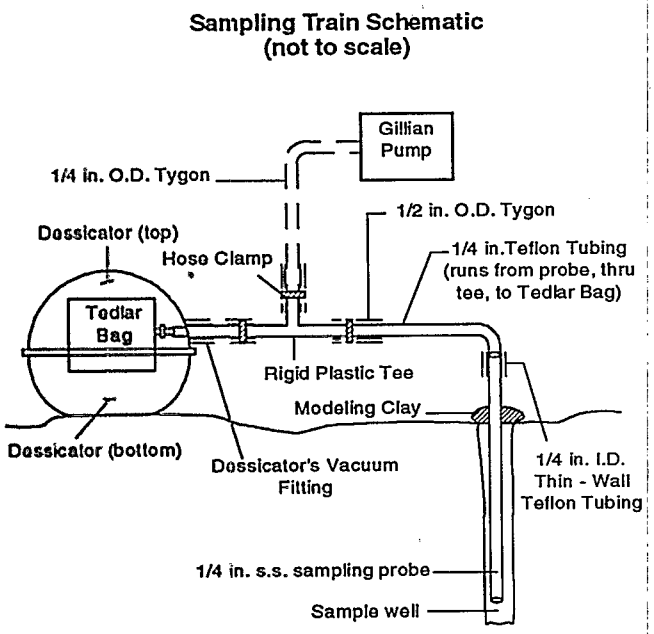

Figure 3-3. Sampling train schematic for soil-gas survey.

zone above the contaminated ground water or soil makes detection difficult by restricting vapor mobility.

3.2.5.2 Geoprobe

The geoprobe, the next step up from the soil-gas survey in sophistication, is a hydraulically operated sampling tool that punches down into the soil. It is a rapid site assessment tool, very effective for collecting soil, soil-gas, and ground-water samples. It is a rugged system, which can collect samples at discrete depths to about 40 feet, whereas most soil-gas surveys can collect only from 4 to 10 feet.

The geoprobe can work in three different media types: pore space, soil, or ground water. It does not perform well in competent clays or cobble. It may, however, be useful in weathered bedrock if the overburden is well fractured. It punches the hole much more quickly than does the slam bar of a soil-gas survey. This feature is especially useful with soils that have been compacted by heavy equipment. The geoprobe is also easier to use than the slam bar, and can be manipulated like a drill rig by pushing different levers. Because it is truck mounted, however, a truck must be able to get in and out of the area. One disadvantage of this method is that, because of the diameter of the device, the sample volume is small. It also provides screening only for ground-water samples and will not penetrate cobble or hard rock.

3.2.5.3 Flux Measurements

Flux measurements determine mass emission rates using the concentration and flow rate of gases through a chamber and the surface area isolated by the chamber. Flux measurements are used primarily for landfill emissions, treatability studies, and contaminated aquifers, and less for underground storage tank work. Flux chambers are becoming popular for studying overall mass emission rates from excavated soil piles and landfills. Because landfills have passive emission rates, flux measurements are used when residents living near a landfill complain about odors at active or inactive sites. They also are used for large-scale excavation where the soil is contaminated and the potential for offsite contamination or migration is not known. Recently, EPA's ERT used flux measurements on a treatability study looking at degradation rates of polyaromatic hydrocarbons (PAHs) in soil to assess contaminant volatilization versus biodegradation in a creosote composting project.

Some limitations to this method are that condensation or moist soil hampers its effectiveness, cross contamination sometimes occurs, and careful representative sampling is required.

3.2.5.4 Other Methods

A number of other methods can be used for field screening sampling and analyses, including colorimetric tubes, combustible gas indicators, organic vapor analyzers (OVA), soil texture kits, hydrolabs, and RAMs. These methods are described below.

The ***colorimetric tube*** is a quick chemical-specific indicator. It can detect inorganics as well as organics, and cyanides and chlorines in the air. The colorimetric tube is usually used to detect threshold limit value (TLV) levels for site entry. The personal protective gear then can be adapted to the exposure levels that might be indicated by the Draeger® tubes. This method is very quick but temperature dependent.

A ***combustible gas indicator*** detects oxygen as well as the lower explosive limit for combustible gases, reading in ppm levels for the combustible gases. This reading is very important when entering an enclosed space with drums or any area that might have a low oxygen content. It has been used to determine the safety of entering excavation pits, storm drains, and basements that may have heavily contaminated atmospheres and where there might be some negatively buoyant gases that can displace ambient oxygen.

An ***organic vapor analyzer*** can be used in situations involving lagoon sludge in drums. This device is particularly useful for detecting methane, and hydrogen sulfide. A flame ionization detector (FID) uses a hydrogen flame, and can be used in a GC or scan mode. FIDs detect methane and hydrocarbons, especially important at wood treating sites where naphthalene may be present. An FID is a little more sensitive to naphthalene than PIDs in a rough screening. FIDs detect the alkanes, including the carbon-carbon and hydrogen-carbon bonds.

A ***mercury organic vapor analyzer,*** which is an elemental indicator for mercury vapors, is very useful for a variety

of mercury-contaminated sites. It is a gold film detector and measures the higher resistance, as it accumulates more mercury on the gold film. The elemental mercury indicator has been useful at mercury wood treating sites and in soil-gas surveys. It also is useful in the laboratory where there may have been broken thermometers or at mercury spill sites.

A basic ***soil texture kit*** is useful for doing soil borings, working with hand augers, or doing attenuation or profiles of soil depth. It can be used to determine percent sand, silt, and clay, and is very simple to use. An organic matter test kit measures from 0 to 16 percent organic matter when evaluating adsorption or attenuation of organics and soil.

A ***hydrolab*** is used quite a bit in streams and down wells, as well as other water bodies, that are not too contaminated. In a hydrolab, numerous functions are built into one tool. It can perform all the various tests for temperature, pH, dissolved oxygen, conductivity, redox potential, and salinity. A drawback is that because a hydrolab works as a function of temperature, the temperature must be stabilized. A hydrolab is very simple to use, however, and can be backmounted and transported easily.

A ***RAM***, or an aerosol monitor with a data logger attachment, can be used for evaluating offsite migrations while evaluating test pits or excavations on soil at different sites. This instrument measures and evaluates airborne particulates, such as those from a wood treating site. A RAM is not ion specific, but it can relate the amount of dust migrating off site from an excavation with real-time monitors to the amount measured by XAD or filter cassette tubes. (XAD tubes and filter cassettes are commonly used in tandem to measure particulate laden with contaminant versus semi-volatile organic compounds.)

3.2.5.5 Geophysical Methods

Some geophysical methods that can be used for analyses include EM31s, magnetometry, well logging devices, open path infrared spectrometers, and Scanex Juniors.

An ***EM31***, an ***electrical conductivity device***, can be used to evaluate ground water or to detect metals and different geology in soils. It also is helpful for finding utility lines and buried transformers. This device is usually used in tandem with a magnetometer to detect ferric metal as well as electrical conductivity, or changes in conductivity, of the soil. It can be useful in detecting discontinuities, such as a buried lagoon or impoundment, and is useful for examining differences in porosity and permeability in fluids.

EPA's ERT used sophisticated ***magnetometry*** at a site in Aberdeen Proving Ground to look for a white phosphorus munitions burial area in a wetland to which there was no access, either by boat or land. Investigators suspected that there was a large dump site of white phosphorus contained in metal drums on the site. The survey was performed with a helicopter towing a helium magnetometer. This method is very effective for covering a large area in a short period of time, but can be quite expensive. That 1½-day survey, for example, cost about $35,000, which included the cost of 150 survey lines over an area approximately ¼-mile square as well as data interpretation.

At the Aberdeen Proving Ground, ERT also used magnetometers attached to a frame on a zodiac boat. When the survey team located spikes which could be indicative of metallic explosives, investigators deployed a buoy to pinpoint these areas. With real-time magnetometers, it is possible to collect and map information about potential magnetic anomalies and their locations that may be suggestive of buried containers, tanks, or at Aberdeen, projectiles.

Well logging devices use electrical conductivity, resistivity, or gamma logs. These devices can supply information about well construction, water bearing zones, and rock type. A geophysical well logging device called a downhole well logger, an EM39, can be used in wells with different diameters. It is very adaptable and relatively inexpensive.

The ***Scanex Junior*** has been used predominantly at Department of Defense (DOD) sites. It is useful for evaluating nitrocellulose compounds and explosives in air, but it cannot detect phosphorus compounds. It also operates real-time and has an electronic capture detector.

3.2.6 Immunoassay Methods

Immunoassay field screening kits are becoming increasingly popular, because they can detect compounds, like PAHs and total petroleum hydrocarbons (TPHs), in a short turn-around time. They also are very useful for cost control on treatability studies. Field immunoassay techniques are semi-quantitative, limited to numbers in ranges of concentrations, and work on antibody mechanisms.

There are many vendors for these kits, and most methods have undergone preliminary field testing. Currently, EPA is actively looking at immunoassay techniques for PCBs, PCP, pesticides, nitroaromatics, and metals in soils and water. Under the SITE program, EPA has already demonstrated one kit and a plate assay. All methods show promise as field screening or analytical methods.

The advantage of the field immunoassay for PCP is the ease of handling methods and low cost use for untrained personnel. This method provides real-time performance at slightly higher values than gas chromatography or mass spectrometry. The test for PCP takes about 30 minutes and has a detection limit of 2 ppm in soil. The cost of performing the test on a single sample is $30 to $50. The disadvantage of an immunoassay is the potential for false positives. The ERT has experienced an accuracy of greater than 50 percent with this method.

3.3 FUTURE NEEDS AND DIRECTIONS

There are many areas of development open in field screening methods. Some immediate needs include improvements in the following technologies:

- In situ or standoff chemical sensors
- Soil and ground-water sampling devices
- Soil-gas sampling devices
- Fluid sampling devices for the vadose zone
- In situ and field portable analytical methods for the analysis of contaminants in all types of environmental media
- Geophysical methods
- Data analysis and interpretation tools
- Sampling network design (e.g., expert systems)
- New or refined chemical or compound-specific analytical methods

Many other tools are being evaluated by the Environmental Response Branch and may soon be available for performing field screening surveys but it is difficult to present them all. For more information on field screening devices in general please contact the Chief of the Site Investigation Section, Environmental Response Branch, (908) 321-6740, U.S. EPA.

In addition, the future of the field might include such technologies as toxicity devices to mimic human responses, remote sensors to detect surface hot spots, light pipes to determine concentration gradients below ground, disposable microsamples and sensors, expert systems and robotics, and continued miniaturization.

With existing technologies it is possible to achieve rapid, analytic appropriate, and cost-effective site characterizations. Field screening and analytical methods still have to gain acceptance by the chemists and the courts, however, and recognized field methods and quality control procedures do not exist for most emerging and alternative technologies. The usability of data also needs to be clearly defined.

3.4 REFERENCE

Kaelin, L. 1992. Senior Field Chemist, Roy F. Weston/Response Emergency and Analytical Contract, Edison, N.J.

CHAPTER 4
Covers, Slurry Walls, Grouting, and Dynamic Compaction for RCRA Corrective Action Stabilization

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Stabilization activities carried out under RCRA corrective action involve clear engineering designs and some type of actual field construction, using common construction equipment and proven operational technologies. The designs for a short-term stabilization cover may be modified from standard textbook and guidance manual models, and, in general, the equipment used will be whatever is locally available. The theories, concepts, approaches, and schematics in guidance documents often are modified significantly for actual practice.

The RCRA Corrective Action Stabilization Program is young, and few case studies are available. This chapter will examine several structures and processes that are well documented in published technical literature. These technologies can be and are being effectively applied as corrective actions to physically stabilize sites. The structures and processes discussed include:

- Cover systems and caps (Section 4.1)
- Slurry walls (Section 4.2)
- Grouting (Section 4.3)
- Dynamic compaction (Section 4.4)

Figure 4-1 is a commonly seen drawing that includes many features and structures associated with stabilization of a contaminated site.

Section 4.5 discusses quality assurance and Section 4.6 is a bibliography.

4.1 COVER SYSTEMS

4.1.1 Considerations

A cover system includes not merely a single concrete pad, clay cap, or geomembrane, but a combination of materials of varying complexity that are constructed in a logical order, each to perform a particular function. In designing a cover system, one needs to consider the characteristics of the waste, the site geology, any accessory structures, extraction wells, monitoring wells, and other types of "plumbing" associated with biological, chemical, or hydraulic technologies.

Both the type of waste and the type of site must be carefully considered. Municipal solid waste is frequently found at corrective action sites, with industrial waste products buried throughout the site. Industrial wastewater ponds are also common.

At one example site, an entire pond, used for industrial process wastewater, was excavated, including the synthetic membrane liner and the underlying compacted clay liner. It was discovered that the foundation under the compacted clay consisted of fly ash from an old power plant on the site. Remedial engineering designers had to rebuild this foundation to reconstruct the pond according to modern standards. This example shows the importance of not only the specific remedial structure, but also the surrounding soil material. The new pond was built with a composite liner of both newly compacted soil and a new geomembrane.

Also to be considered as an aspect of design is the impact on construction, timing, and cost of having operational people in confining protective clothing. The severe impact of having to work under the constraints of health protection has been well documented in the Superfund program.

4.1.2 Recommended Design

There are recommended standards for covers as interim protective measures at corrective action sites. The scenario of the beautiful grass cover with carefully designed runoff control drainage structures and a fence around the perimeter, however, is probably the exception rather than the rule. In fact, even a cover system that looks fairly close to the ideal may not be meeting the regulatory requirements for minimum erosional soil loss.

Environmental engineering technologies continue to develop rapidly. Thus, it is essential for both design engi-

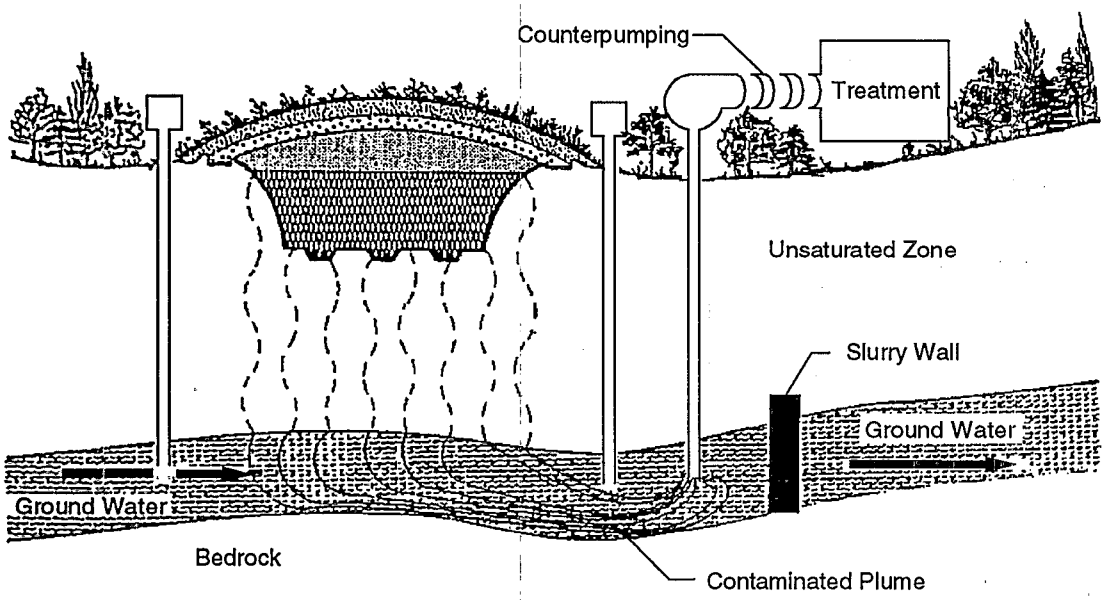

Figure 4-1. Corrective action stabilization site.

neers and regulatory staffs to continually look at the various guidance documents available from EPA and state agencies to ensure that they are up to date. The Soil Conservation Service, for example, no longer recommends the universal soil loss equation (USLE), so guidance documents that recommend using USLE may have been written several years ago. Any local Soil Conservation Service office should be able to provide the new or modified soil loss equation.

Many Agency-published guidance documents have a number of standardized line drawings showing the ideal structure for a cover system. Figure 4-2 shows the recommended RCRA multi-layer design with vegetational topsoil, drainage layer, filter layer, and composite infiltration barrier system. This design has been modified slightly for use or application in more arid and other regions where this precise design may not be the most effective. Figure 4-3, for example, includes a biotic barrier, originally designed to combat penetration by small mammals such as gophers. How important it is to use a biotic barrier and under what particular site conditions is still under debate. This figure also shows a gravel armor surface instead of a vegetative surface; an adaptation of this type of design may be more desirable and more effective than the vegetative cap in many areas. Engineers may want to look at variations of these designs, depending upon the degree of stabilization necessary. The drainage layer, for example, may be unnecessary in areas of 5 inches or less of annual precipitation.

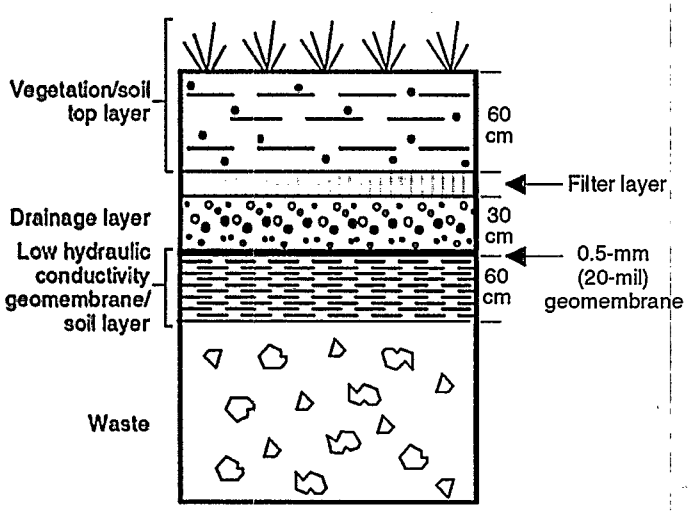

Figure 4-2. Recommended landfill cover design (U.S. EPA, 1991).

A number of standardized test methods for foundation preparation have been used by the civil engineering community for many years. EPA guidance documents contain recommendations for the minimum frequency of testing for foundations and other structures related to a cover system that must restrict rainfall infiltration. Many of the tests carried out during actual construction involve simple observation by the onsite engineer. The construction quality assurance plan for a corrective action cover is likely to place more emphasis on the field inspection aspect than on rigorous laboratory testing. This then places an increased emphasis on the training and experience of the field inspection and construction staff.

4.1.3 Soil Components

The barrier layer is the 2 to 3 foot thickness of compacted soil used as either a liner or an infiltration barrier. EPA has refined and published criteria for barrier layers in the last year. These criteria ensure that a contractor will con-

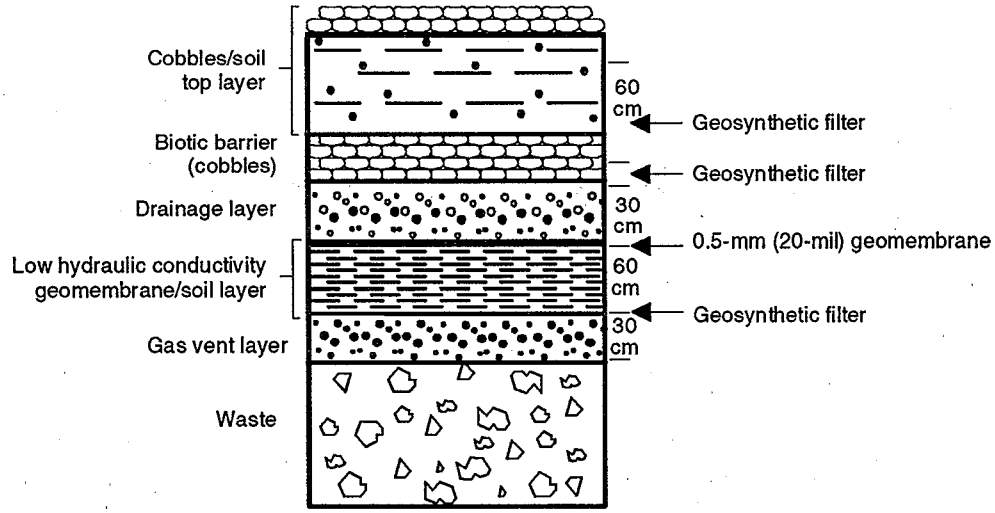

Figure 4-3. Recommended landfill cover with options (U.S. EPA, 1991).

struct a low permeability soil layer after performing the specified Proctor density tests, various permeability studies, and other tests to obtain the required less than 10^{-7} centimeters per second permeability for a soil liner or infiltration barrier. This procedure involves performing a fairly complex set of laboratory studies using different compaction energies, developing moisture density curves, correlating those data with hydraulic conductivity measured in the laboratory at different holding water contents, and then developing an Acceptable Zone of combinations of density and moisture that will result in low permeabilities (see Figure 4-4). This Acceptable Zone then must be adapted to a region and presented in a curve so that the contractor can ensure that all lifts of the soil-based infiltration barrier will have a moisture content and/or density inside the shaded region shown in Figure 4-4. The frequency of sampling and testing is largely determined by the characteristics of individual job sites, although ASTM testing methods are available as a resource. Some states, however, have specified these details of construction quality verification for waste sites. A number of the guidance documents now available present specific details aimed at increasing the probability and assurance that the final structure will meet the required

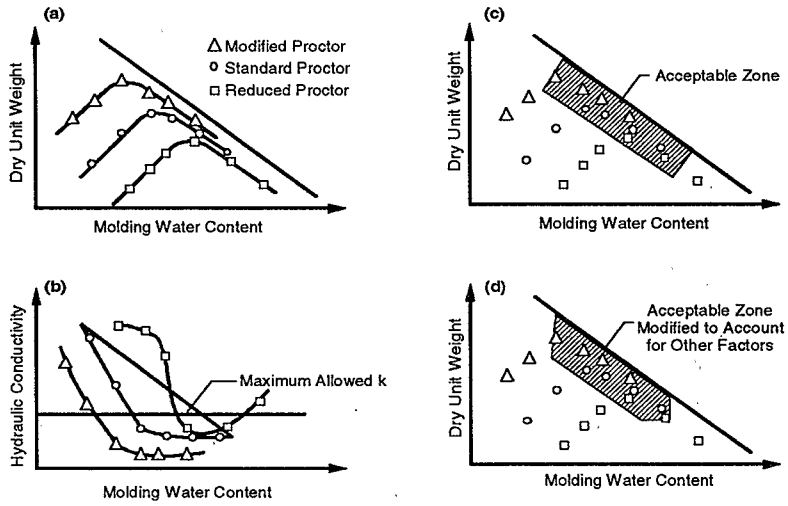

Figure 4-4. Recommended procedure (U.S. EPA, 1991).
(a) Determine compaction curves with three compactive efforts.
(b) Determine hydraulic conductivity of compacted specimens.
(c) Replot compaction curves using solid symbols for samples with adequately low hydraulic conductivity and open symbols for samples with a hydraulic conductivity that is too large.
(d) Modify Acceptable Zone based on other considerations such as shear strength or local construction practices.

design specifications. Tables 4-1 and 4-2 show recommended tests and observations for subgrade preparation and recommended materials tests for barrier layers.

4.1.4 Geosynthetic Components

A major component of modern waste site construction includes geosynthetic materials, such as geomembranes, drainage materials, support, and strengthening products. (The term flexible membrane liner is used interchangeably with geomembrane by many people in the industry.) Table 4-3, developed for EPA by the Geosynthetic Research Institute at Drexel University, shows the various uses in waste containment systems of these materials. Since this table was developed a new category, the geosynthetic clay liner (GCL), has been added. This category is an additional type of geosynthetic material used primarily for the barrier and to some extent for the separation and reinforcement functions.

A GCL is a prefabricated composite sheet material, composed of one or more layers of a synthetic polymeric membrane or textile and a uniform layer of very low permeability bentonite clay. This product swells when hydrated and forms a layer with a permeability much lower than can be achieved by compaction of soil. The GCL offers the advantages of quality-controlled manufacturing, and it can be easily transported in rolls and installed with minimal field equipment.

Table 4-1. Recommended Tests and Observations on Subgrade Preparation

Parameter	Test Method	Minimum Testing Frequency
Percent Compaction	ASTM D2922 or ASTM D1556 or ASTM D2937 or ASTM D2167	1 per acre
Compaction Curve	ASTM D698	1 per 5 acres
Preparation of Previously Compacted Lift	Observation	Full coverage

Table 4-2. Recommended Materials Tests for Barrier Layers

Parameter	Test Method	Minimum Testing Frequency
Percent Fines	ASTM D1140	1 per 1,000 yd^3
Percent Gravel	ASTM D422	1 per 1,000 yd^3
Liquid & Plastic Limits	ASTM D4318	1 per 1,000 yd^3
Water Content	ASTM D4643	1 per 200 yd^3
Water Content	ASTM D2216	1 per 1,000 yd^3
Construction Oversight	Observation	Continuous in barrier pit on major projects; continuous in placement area on smaller projects.

Table 4-3. Customary Primary Functions of Geosynthetics Used in Waste Containment Systems

	Primary Function				
Type of Geosynthetic	Separate	Reinforce	Filter	Drain	Barrier
Geomembrane					■
Geotextile	■	■	■	■	
Geonet				■	
(Geo) pipe				■	
Geocomposite				■	
Geogrid		■			

Source: Adapted from U.S. EPA (1991).

EPA (1991) provides significant details about site preparation, testing of soil materials, and inspection criteria for the compacted soil component of a cover. In corrective action designs that may not be planned for long-term performance, but must serve as effective interim precipitation barriers, the engineered soil is a preferred choice. It is difficult to achieve a tightly compacted soil liner. Desiccation cracks, the definition of which is still open to interpretation, indicate that the compacted soil or the clay liner underneath the geomembrane may not be properly built. A smooth roll subgrade is very important, especially for some of the heavier or stiffer geomembrane materials that may not be particularly flexible.

The disadvantages of the simple "clay cap," and the real problems involved in ensuring that it meets a 10^{-7} cm/sec permeability specification, must be realized in cover design and construction. Conversely, a site may have no current infiltration protection, so that even a poorly constructed "clay cap" may have significant short-term value. The regulatory authority should make sure that a rapidly constructed "clay cap" is not relied upon for long-term protection.

When employing a geomembrane as a primary cover component in a RCRA corrective action cover system, there are several considerations. If such an interim measure has a useful lifetime of 5 to 10 years, and it is uncertain whether it will be part of the final closure cover system, the remedial engineer must balance the need for intensive seam quality control and geomembrane quality with a cost-benefit or risk analysis of gains. Intensive seaming and quality control covering with carefully designed soil can be quite expensive. A final closure cover system, for example, requires very careful cleaning of the seam area followed by immediate covering with soil. A

significant concern may be the removal or replacement of a geomembrane when the final site remedy is implemented. The possibility of completely removing and rebuilding a site cover at final site closure should be considered during interim cover design.

The "composite action" of a geomembrane and compacted soil seepage barrier has recently been an area of technical discussion and construction concern. Texas A&M University studies have shown that without intimate contact between the geomembrane and the underlying compacted soil, any leachate or infiltration from precipitation coming through a fault in the geomembrane will spread laterally and across the top of the compacted soil liner. As it spreads, it will find a fault, fracture, or desiccation crack, and will go down through the liner (see Figure 4-5). A number of studies have verified that interface lateral flow and flow times through compacted clay liners are much faster than predicted by time of travel models. These studies confirm the importance of intimate contact between the geomembrane and underlying soil liner. Achieving this type of contact begins with construction. Ideally, the top of the soil liner should be graded smooth as a pool table top, although that is difficult to achieve in actual field construction situations.

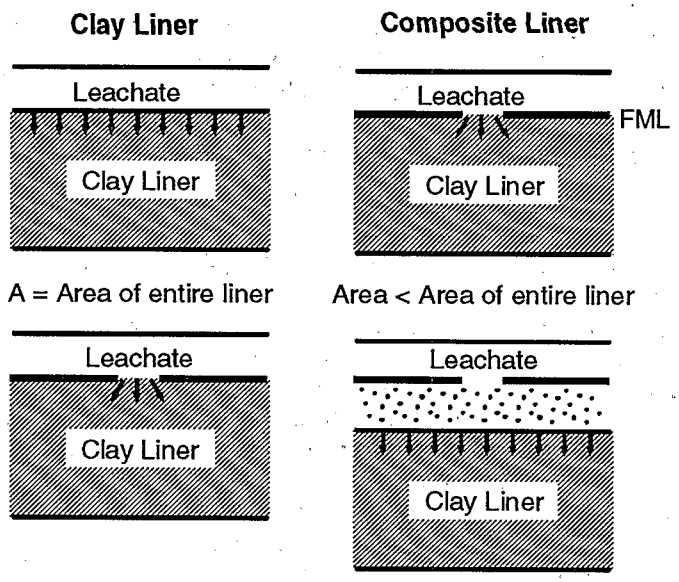

Figure 4-5. Leachate or precipitation infiltration with a soil (clay) liner and composite liner (U.S. EPA, 1991).

4.1.5 Accessory Structures

Pipe penetrations or other accessory structures need to be designed as parts of corrective action covers. Figure 4-6 is a simplified view of an ideal multi-layer cover with a gas vent (it omits the various collars that would prevent piping or short circuiting along the sides of the pipe). The remedial manager needs to assess what structures, such as collars or graded slopes, are necessary at a particular site, keeping in mind the interim nature of the action. The RCRA corrective action program provides a good opportunity to try alternative designs. Figure 4-7 shows one example of a novel design to conduct infiltration away from underlying wastes. Installing interim covers presents a good opportunity to evaluate promising new ideas, since a final closure can still be implemented in the future if the design is not adequate. If the design is successful, however, real advances in economics or performance may be achieved.

4.1.6 Subsidence

Subsidence is an aspect of cover design that comes up in almost every discussion of cover systems. The problem

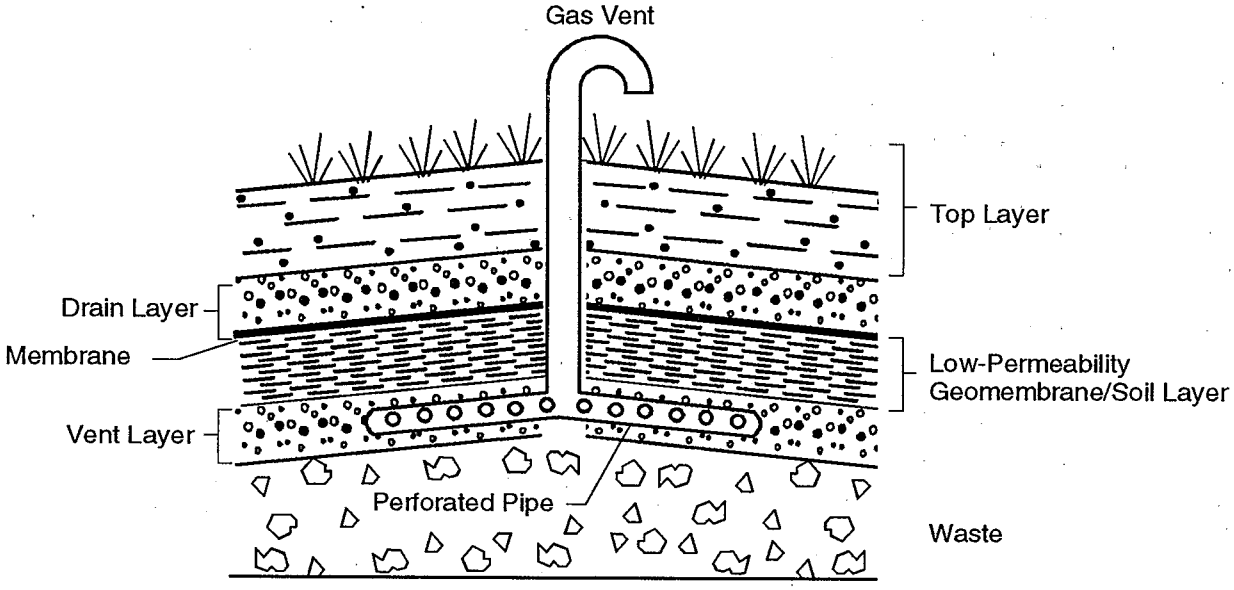

Figure 4-6. Cover with gas vent outlet and vent layer (U.S. EPA, 1991).

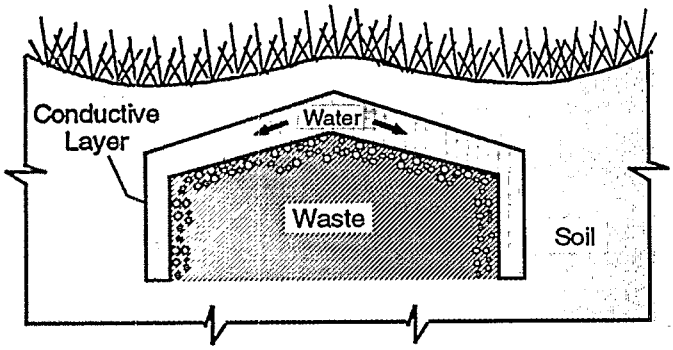

Figure 4-7. Conductive layer barrier with graded slopes.

is how to design a cover that will accommodate the various depressions and peaks that evolve in the buried waste. Figure 4-8 shows the effects of cumulative subsidence. Very few sites have been intensively mapped, investigated, and documented in terms of the various degrees of subsidence that occur. As with accessory structures, the RCRA corrective action program offers an opportunity to research the effects of waste composition and density using benchmarks or elevation markers to chart movement. As early as is practical, remedial managers should take baseline measurements upon which to base future elevation measurements. This step will allow the manager to document whether subsidence is a real defect that can be addressed in designing the cover system.

EPA's Office of Research and Development (ORD) has developed approaches to predicting the strength of geosynthetic materials required to bridge specific subsidence voids. Figure 4-9 shows the derivation of geomembrane tensile stress due to subsidence of material beneath the geomembrane.

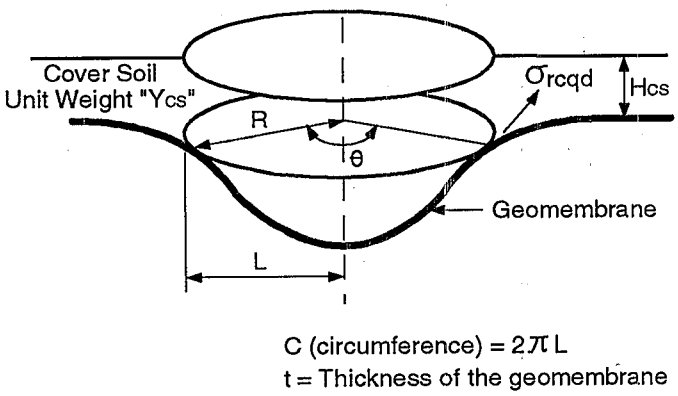

Figure 4-9. Derivation of geomembrane tensile stress due to subsidence of material beneath the geomembrane.

Most engineers involved in waste site cover design are familiar with the hydrologic evaluation landfill performance (HELP) model developed over 10 years ago by ORD. This model has gone through several iterations, updates, and modernizations, and is used worldwide to predict the effectiveness of different cover systems. Both a computer diskette and support documentation for this model are available from the EPA's Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive, Cincinnati, Ohio 45268. Figure 4-10 shows the simulation process in the HELP model.

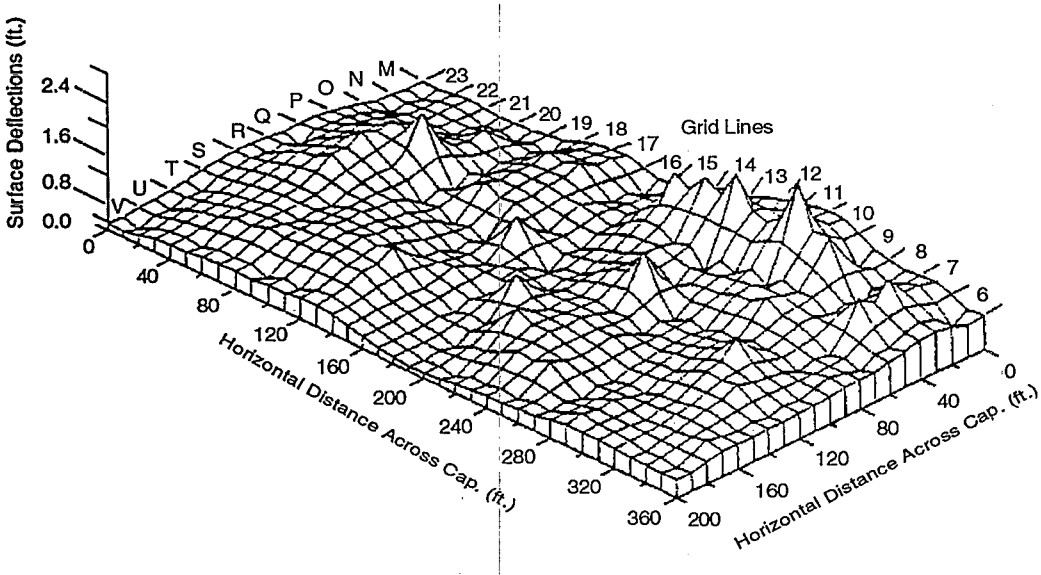

Figure 4-8. Cumulative subsidence (U.S. EPA, 1991).

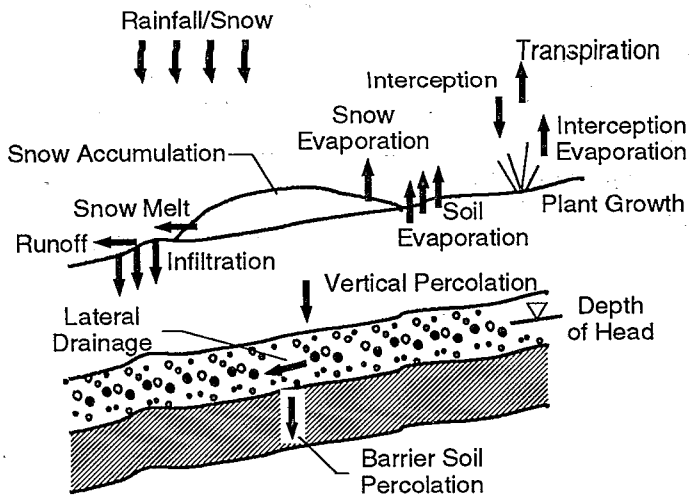

Figure 4-10. Simulation processes in the HELP model (U.S. EPA, 1991).

4.1.7 Materials Handling

Materials handling, like scheduling and logistics, are the kinds of features that the permit writer and the designer frequently leave up to people in the field. Materials handling issues to be considered when capping a site include the amount and types of soil material to be moved and the logistics and machinery required for distribution. Again, a decision needs to be made about the minimum that should be implemented in a corrective action.

Usual cover designs include a variety of different materials — topsoil, sand or gravel drainage materials, clayey soil for infiltration barrier compaction, geosynthetic materials for various applications, and pipes or other conduits. Installation of each of these materials may be greatly hindered or eased by weather conditions, previously installed structures, availability of trained installers, and other site-specific characteristics. The experience or advice of a construction contractor may significantly affect the speed of installation of some of these materials.

4.2 SLURRY WALLS

The slurry trench cutoff wall, or slurry wall as it is commonly called, is a vertical barrier surrounding a site, designed to control the water quality, flow, and level. The slurry wall is, in its simplest form, a discontinuity in a porous geologic formation. The slurry wall should be differentiated into its two distinct components — the slurry trench and the cutoff wall backfill material. The slurry trench is a mechanism that holds a ditch open in a sandy or porous geological material, so that plywood or steel sheets are not necessary. A colloidal bentonite clay suspension provides structural support during excavation. Filling the trench with backfill material provides a ground-water cutoff or a lower permeability zone. The engineering design and construction of the slurry trench requires different practice and testing than does that of the cutoff wall. The cutoff wall consists of the material put back into the trench to provide a ground-water control barrier. Trench backfill is often a soil enriched with fine or bentonite clay but may also be a cement-bentonite mixture, or even a geomembrane sheet. Numerous engineering reports and ASTM special publications are readily available to describe the state-of-the-art of slurry wall backfill design, construction, and testing. The slurry wall should be tied into the low conductivity base material, if possible, or water can be withdrawn from the enclosed material to form an inward gradient.

4.2.1 Equipment

Several different types of common construction equipment are used to construct a slurry wall. Backhoes, usually equipped with a long-reach arm, clamshell on a cable, and various specially modified excavation buckets are used, based on site-specific geology and depth. The excavating equipment opens a trench, usually 2 to 3 feet in width. The trench is continuously filled with a colloidal clay suspension designed to hold the trench open without requiring other mechanical devices. The construction procedure involves digging the trench, filling it with slurry, and then as a follow-up activity, adding the backfill that provides the actual barrier or retarding structure to ground-water flow (see Figure 4-11).

Figure 4-12 depicts several of the different equipment and excavation approaches applied, depending on depth and type of site geology.

One of the better primers describing pollution migration control cutoff walls is an ORD publication (EPA, 1984b). This guide provides engineering theory, historic applications, geologic and other studies needed to characterize a site, elements of design and construction, information on monitoring and maintaining a slurry wall, various cost elements (e.g., cost of a slurry trench cutoff wall in dollars per face, with a vertical face square foot ranging from $5 to $15), and evaluation guidelines. More current case histories may be found in civil engineering publications and in some Superfund conference and symposia proceedings.

4.2.2 Slurry Wall Performance Testing

Testing of slurry wall performance largely involves very simple laboratory determination of permeability and the use of permeability as a measure of compatibility with solvent, leachate, and nonaqueous phase liquids (NAPLs). The existence or occurrence of NAPLs, either light or dense, is a significant site feature affecting slurry wall performance. A number of NAPLs exist as fairly pure product, either sinking or floating, and have a detrimental effect in dehydrating soil and clay materials. Their presence may result in pods or floating layers of various NAPLs, which can significantly increase the permeability of backfill material.

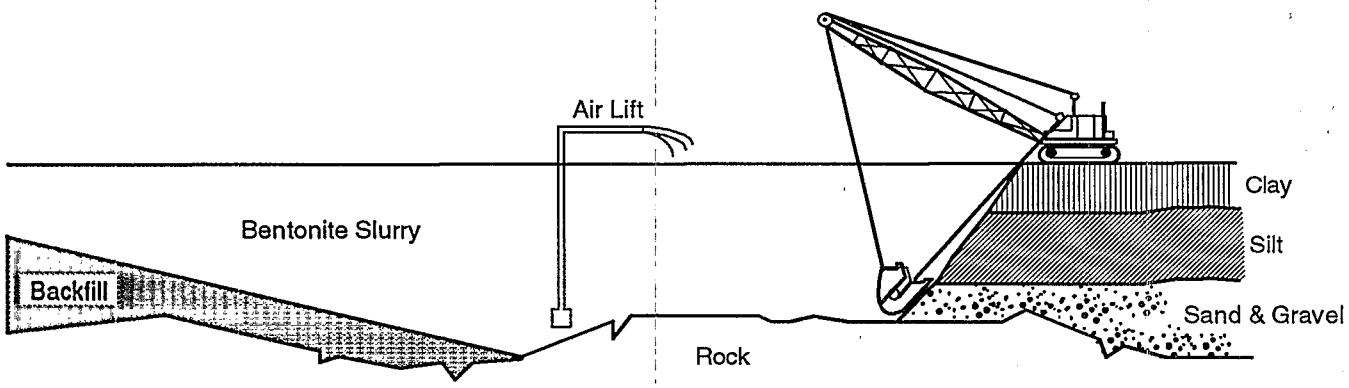

Figure 4-11. Slurry wall excavation and backfill.

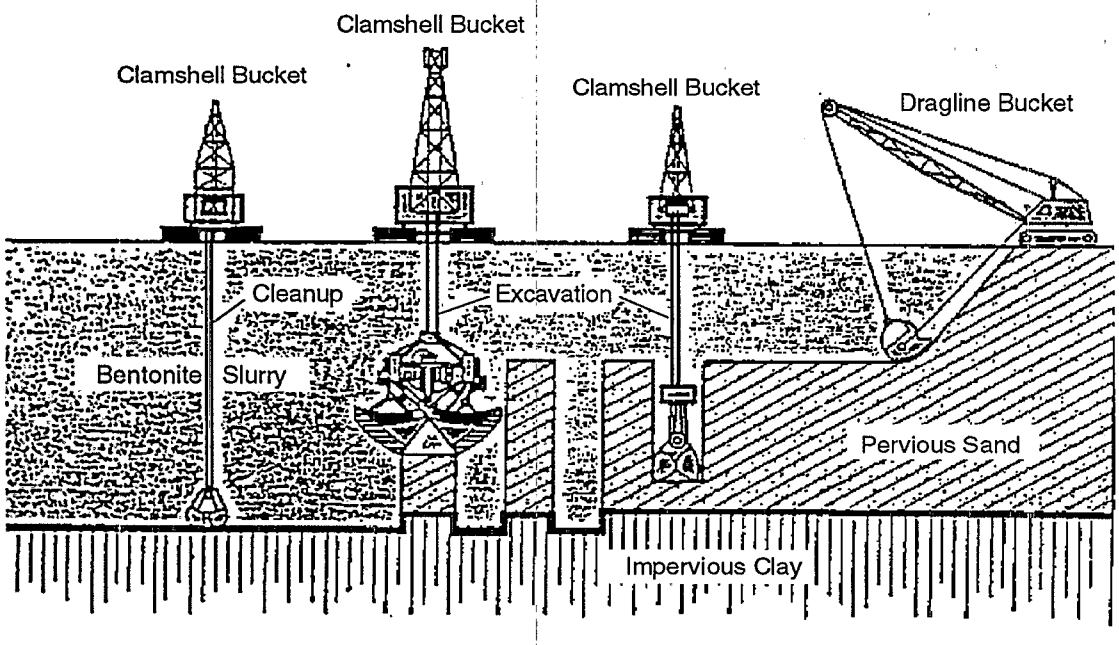

Figure 4-12. Methods of construction for a slurry wall.

The compatibility test of the backfill must rely on investigations that provide information concerning light or dense NAPLs on the site. The containment structure may need to be moved outside the zone of contamination to completely avoid NAPLs, or all NAPLs may need to be removed to reduce the possibility of attack and degradation of the slurry wall backfill.

In a RCRA corrective action, the site manager may wish to determine whether a slurry wall is going to be an effective structure that can be part of the total corrective action program. Two common tests are box tests and pump tests. The box test approach consists of excavation and construction of a small-scale cutoff wall fully enclosing an area approximately 50 to 100 ft square, to the depth of a low permeability geologic formation on site. This approach requires mobilization of nearly all the equipment required for construction of a full-scale ground-water barrier. Following construction, the ground water inside the box can be pumped, and ground-water elevation data from inside and outside the box applied to measure the permeability of the barrier. This method has been used by both governmental agency and private site owners to verify effectiveness before a slurry wall thousands of feet in length has been constructed.

A pump test consists of a series of wells installed on either side of the cutoff wall. The wells on one side are drawn down to a predetermined elevation, and the water levels in wells on the unpumped side of the wall are measured to determine the extent of lowering. From these data, wall permeability may be calculated.

Thin tube samplers from a setup wall have been largely experimental, and there have been a number of studies with ground-water monitoring wells on either side of the

barrier. Backfill retrieved by thin-tube samplers is normally tested for permeability by laboratory methods. Groundwater well arrays and the approach to data analysis from well water levels has not been standardized. This approach remains a site-specific and company-specific method.

4.2.3 Advances in Slurry Walls

The geomembrane industry has made continuing advances in providing lower permeability barriers for the backfill in a slurry wall. The current geomembrane technology involves a channel lock structure along the vertical edges of each sheet, to provide a tongue-and-groove type of slip joint between the two sheets. High density polyethylene (HDPE) barriers, however, are not commonly installed in the United States; they seem to be more widely accepted in Europe.

4.3 GROUTING

Grouting is a different type of containment or site stabilization structure. Classically, the grouting industry includes several different approaches:

- Top sealing, or stabilization of a soil area.
- Bottom sealing, or construction of a barrier underneath a waste site.
- Waste solidification and immobilization, which uses different chemicals to permeate and bond with the soil or the geologic material.
- Excavation of subsurface material followed by filling the void with a formulated grout to reduce the void space through which water can infiltrate and leach the waste.
- Grout curtain.

Figure 4-13 shows four of these types of grouting.

Waste solidification and immobilization, the historic interpretation of stabilization, can be used as a corrective action on a portion of a site to determine its effectiveness. The remedial manager can then decide whether it will be useful in stabilizing the whole site. There are a large number of industries involved and many case studies are available throughout the United States and a number of foreign countries that document the effectiveness of solidification and immobilization on different types of waste. EPA's research laboratory in Cincinnati has performed much research in solidification, studying the effectiveness of various types of leaching tests in evaluating the solidification processes. A number of different tests are being evaluated beyond the Toxicity Characteristic Leaching Procedure (TCLP), the EP Toxicity Leaching Procedure, and some long-term, large-scale exposure tests.

Grouting is considered to be predominantly a subsurface operation. Figure 4-14 shows small pods of grout underlying a site and isolating it from the surrounding environ-

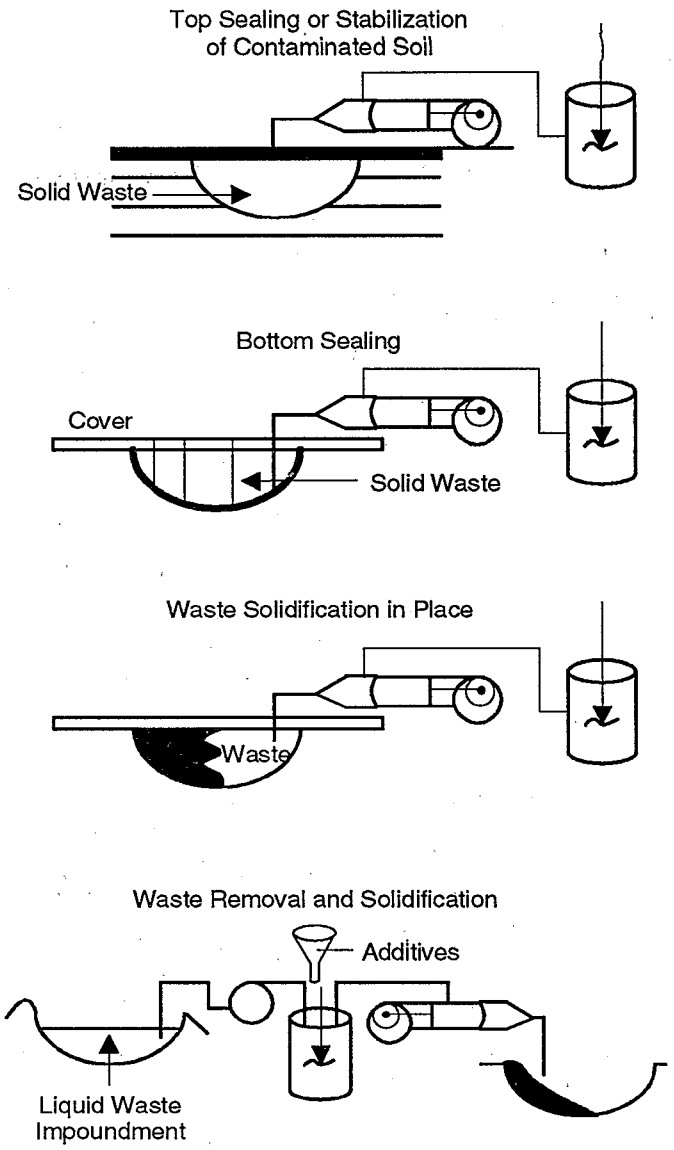

Figure 4-13. Uses of grouting to contain hazardous wastes.

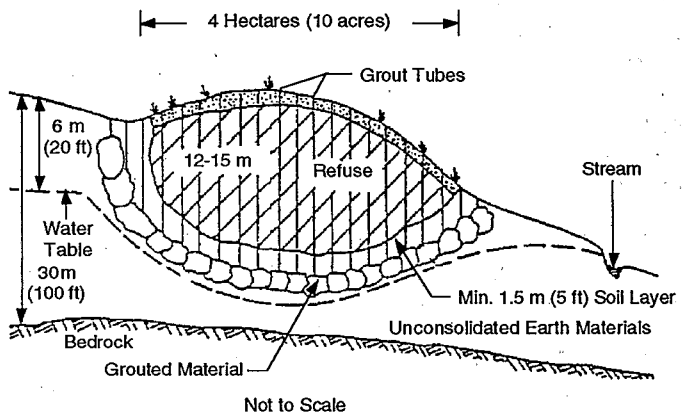

Figure 4-14. Cross-section of grouted bottom seal beneath a landfill (U.S. EPA, 1986).

ment. The degree of bonding and the possibility of seepage between adjacent grout pods are questions that require further research about this technology. Even geophysical methods have not yet been successful in verifying the degree of hydraulic integrity needed in environmental isolation applications of grouting. Grouting methods accepted for structural improvement still need refinement to assure environmental customers and approving agencies that adequate containment is achieved.

Figure 4-15 shows a schematic of the basic equipment needed for a grout injection system. (Chapter 5 will describe the different types of hardware and operations involved in placing grout in the subsurface.) One of the problems with grouting, which again can be examined carefully in a corrective action application, is how to determine where the grout goes beneath the ground and how effective it will be. If possible, the construction engineer should place some grout and then excavate it to examine its continuity and texture visually and with measurement devices.

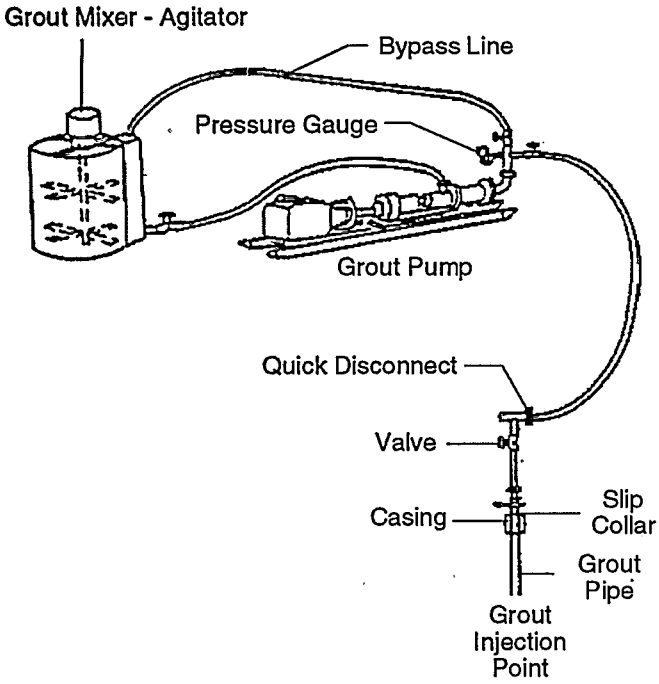

Figure 4-15. Schematic of grout injection system (U.S. EPA, 1986).

Figure 4-16 shows the injectibility of particulate and chemical grout in fine and coarse soils. This graph comes from standard engineering documents, and clearly shows that grout formulation must be developed specifically for each type of site geology. An additional reason for developing site-specific grouts is that many promising new grout formulas include organic components. If these components do not react with the soil or other grout components, they may form an undesirable presence in the ground water. Laboratory verification is needed of both the grout's effectiveness and of the absence of additional contaminants to a site.

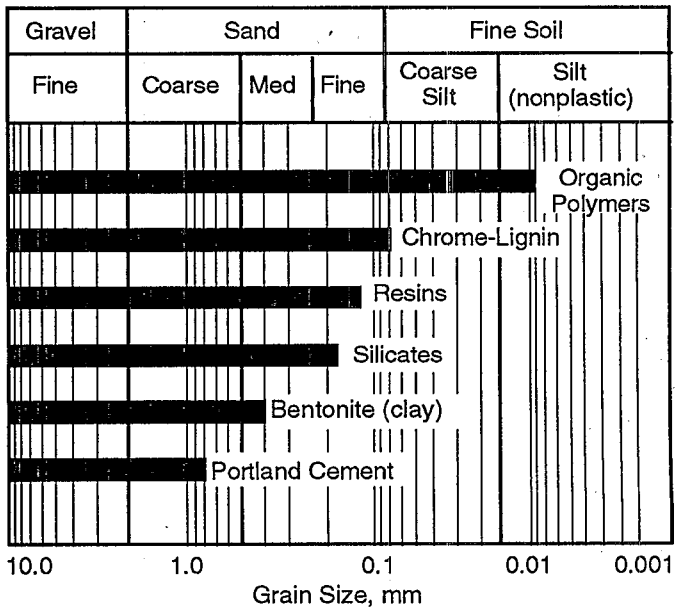

Figure 4-16. Injectibility of particulate and chemical grout in fine and coarse soils (U.S. EPA, 1986).

Another important consideration is the effect of the grouting process or construction on the surrounding area. In one example, the soil surface was raised almost a foot as a result of injecting a grout material into the subsurface. In this case, the area was situated away from habitation and adjacent to a Superfund remedial action site, since it was a test program to evaluate this particular subsurface placement project. When grouting in an urban area or with structures that could be affected by ground movement, the remedial manager must consider this type of surface shifting.

4.4 DYNAMIC COMPACTION TECHNOLOGY

The goals of dynamic compaction are to increase bearing capacity and decrease total and differential settlement. Dynamic compaction has seen limited use and has only limited documentation. Over the last 10 years, there have been about six examples of applying dynamic compaction to increase the density of wastes prior to capping or final closure of a site. The most recent application was at the Savannah River Plant in South Carolina. It is expected that several studies will be presented at the ASCE Specialty Conference in New Orleans. These proceedings will be the most recent update on dynamic compaction, its implementation, effectiveness, and performance in densifying waste sites as a stabilization technology.

In dynamic compaction, large weights of from 5 to 20 tons free fall from heights of up to 100 feet. The cumulative applied energies of this process typically range from 30 to 150 ft-ton/sq ft, and may succeed in densifying soil or waste down to 50 feet. The spatial distribution and the time sequence of dropping the weights are critical, and have been established by the industry. A few additional factors need to be taken into account, however, such as the effects on structures in the neighborhood, soil conditions, and soil characteristics in transmitting vibration effects. Seismic studies done many years ago with explosives can be applied to determine a safe distance from structures. Other problems requiring the designer's attention include present waste density, the geologic foundation underneath the waste site, impact of local or seasonal weather conditions on equipment operation, proof of effectiveness on a test section, and methods to be used to evaluate degree of success.

The effectiveness of densifying the underlying material is determined by measuring the volume and area of the various craters created by dropping the weight in a preplanned sequence. The data can be used to calculate the increase in density of the underlying soil or waste. The density, or the maximum depth of effectiveness of dynamic compaction, is calculated by a simplified equation proven to be quite accurate for field use. Depth of influence is found using the equation from Mayne et al. (1984). Some of the historic applications to waste sites have shown that induced subsidence, or compaction, is slower in wetter soil, because water is incompressible.

Evaluating the effectiveness of dynamic compaction primarily requires topographic volumetric methods (i.e., topographic surveys, including crater measurement) generally supported by some of the standard penetration tests, pressure meters, and geophysical approaches to confirm the calculations from the topographic measurements. Some of these tests include:

- Standard penetration tests (SPT)
- Cone penetration tests (CPT)
- Pressuremeter tests (PMT)

The economic advantages of dynamic compaction include reduction of differential settlement and subsidence and increased waste disposal volume. Stabilization of the site against settlement increases the reliability of a cover system in preventing water infiltration. Increases in waste disposal volume have been reported to offset the cost of dynamic compaction operations.

4.5 QUALITY ASSURANCE

Quality assurance (QA), credibility of data, and quality control are essential to the engineering construction in a corrective action. Ground-water monitoring wells are most commonly used to determine whether a structure, slurry wall, or cap is working effectively. If a cap is reducing infiltration, there will be less infiltration down through the waste and less offsite migration detected by the offsite well. Figure 4-17 shows a typical configuration for monitoring wells. EPA handbooks and guidance documents present standardized well arrays (see Section 4.6). Hydrologic guidance documents and the geologic, geohydrological, and hydrogeological literature contain a wealth of information about constructing and drilling monitoring wells.

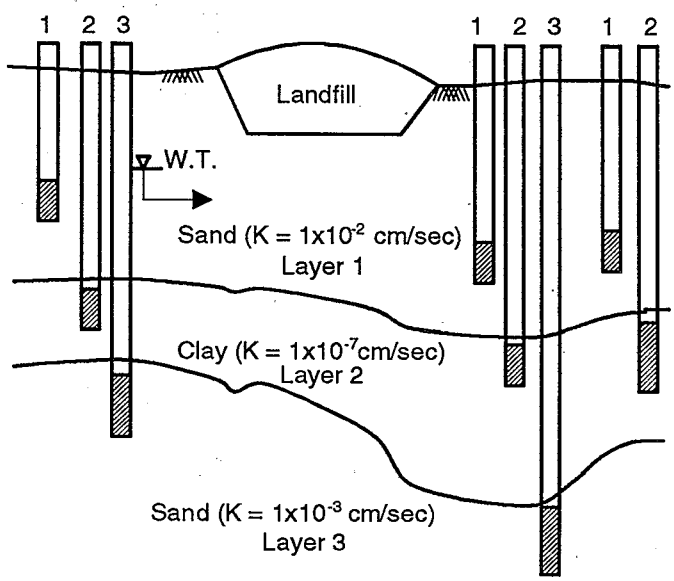

Figure 4-17. Monitoring well configuration.

Collecting and measuring what seeps through a site is the surest method to determine whether there is seepage or the amount of seepage or leaching. The leachate collection lysimeter is a structure that is readily placed under newly constructed covers. The environmental engineering literature adequately discusses the effectiveness of leachate collection lysimeters and includes actual field data. Chapter 5 provides more detailed discussion on structures such as horizontal drilling and other new technologies applied to waste sites to improve data credibility.

Construction quality documentation, in addition to collection of data that show ground-water or seepage quantity and quality, must begin early in the materials characterization phase of a corrective action. EPA (1986) details the various aspects of construction QA that should be addressed. These guidelines cover not only data gathering, but also data handling after collection, which should be according to a preplanned design. Qualified individuals at all levels and a continuous dedication to quality data from upper corporate management to field technicians are essential. Construction quality begins at the design stage and is continuous through actual field equipment

operation and sample collection, at times long after visible field work has ceased.

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CHAPTER 5
In Situ Delivery and Recovery of Liquids to Facilitate RCRA Corrective Actions

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This chapter reviews some conventional methods and introduces some innovative methods for in situ delivery and recovery of liquids that lend themselves to stabilization activities. The first sections examine the performance of delivery and recovery (Section 5.1) and review some processes of liquid flow through porous material (Section 5.2). The majority of the chapter (Section 5.3) focuses on field implementation, including conventional vertical wells and interceptor trenches, and some of the newer techniques, such as hydraulic fracturing, directional drilling, and soil flushing. It is projected that these techniques, still regarded as innovative, may increase the efficiency of subsurface remediation in the corrective action-stabilization areas. The use of these techniques in stabilization actions is likely to effect greater contaminant mass removal, and in less time, thus supporting two of the mass stabilization goals. Section 5.4 presents a list of references used as sources and for additional information.

5.1 PERFORMANCE

There are two types of performance: hydrologic performance, which includes local and field-scale processes, and economic performance, which includes fixed and operating costs. Local processes refer to the performance of equipment—pump pressures and flows, and power consumption. Field processes, however, refer to what is happening on a larger scale within the aquifer, including gradient control and remediation. The elements of interest here are the flow directions of the fluids, flow through porous material, the distribution of hydraulic head, and the transport of contaminants. During remediation, other elements of interest include the zones of contaminant capture, the paths contaminants take to these wells, travel time along those paths, and a variety of processes that occur along the way, such as adsorption, degradation, and biotransformation.

A remedial system's design is based on hydrologic performance, but economic performance is also critical, because cost can be an important decision-making criterion. Capital costs for constructing the system and operating and maintenance costs often dictate whether a remedial design can be implemented. Thus, reducing costs is often the impetus to improve design methods and seek innovative techniques.

5.2 LIQUID FLOW

Figure 5-1 shows what happens when a nonaqueous phase liquid (NAPL), such as oil, is displaced from soil. The cross-hatched areas represent soil grains, the white area oil, and the black area water. The flow is driven from left to right by a pressure gradient, the difference in pressure or hydraulic head between two points divided by the distance between the points (Figure 5-1a). The flow is retarded, or resisted, by viscous forces due to the fluid flowing through the channels; these retarding forces are called hydraulic conductivity.

5.2.1 Flow Rate

For delivery and recovery, a parameter of particular interest is the flow rate through porous materials. Cross-sectional area, hydraulic conductivity, and hydraulic head gradient are all parts of Darcy's law, which governs flow through porous media. The hydraulic gradient and the cross-sectional area can be affected by field techniques. Hydraulic gradient can be affected by the use of a pump; area can be affected by technique, such as drilling versus use of a trench. Hydraulic conductivity and distribution coefficient (K_d), however, are controlled by conditions at the site.

Figure 5-1 shows the initiation of NAPL recovery, with oil draining from some of the pores, and with water entering them. In Figure 5-1b, the flow of oil has dropped off, shown schematically by the length of the white arrow. Water has replaced the oil in these pores, and oil can no longer use the pores for flow. Accordingly, the hydraulic conductivity relative to the oil phase has decreased. The

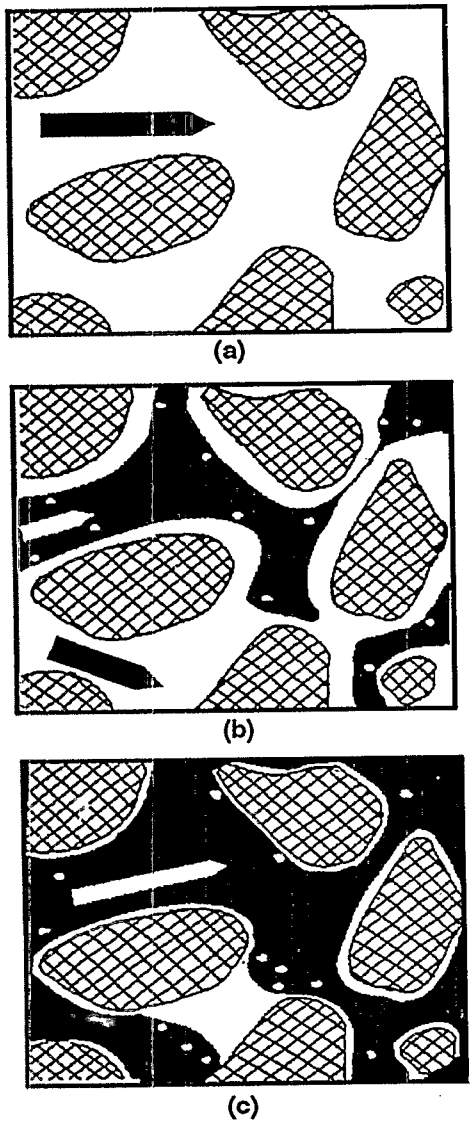

Figure 5-1. Aqueous phase displacing nonaqueous phase (NAPL) in soil.

hydraulic conductivity relative to one phase is thus some function of the degree of saturation of that phase; as the degree of saturation drops from 100 percent, so does the hydraulic conductivity. As the recovery of oil proceeds, the hydraulic conductivity relative to the oil phase will eventually become so low that flow is impossible.

In another important method of transport, components of the oil phase partition into the aqueous phase, and move as dissolved components. While the oil is still flowing, this is of minor importance. When the oil content decreases to a low percentage, it will remain in the porous material only as isolated blobs or ganglion between soil grains, and as adsorbed films on the surfaces of soil grains. There is no continuous oil phase, so the hydraulic conductivity is essentially zero; that is, there is no flow of oil as a liquid. Instead, components of the oil phase will partition into the water phase and will be transported with the water. Thus, the distribution coefficients of the oil phase and the aqueous phase, and the components of the oil phase that are adsorbed onto the soil grains, become essential to transport during the later stages of recovery.

5.2.2 Hydraulic Conductivity

This section discusses how various methods of delivery and recovery relate to their applicability in materials of various hydraulic conductivities (e.g., tight, permeable). Figure 5-2 shows hydraulic conductivity along the bottom

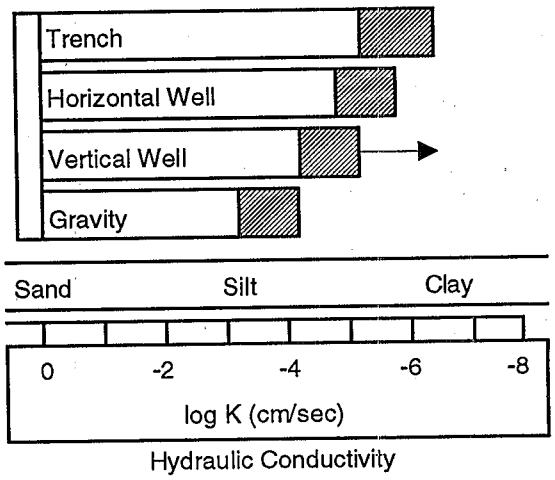

Figure 5-2. Range of hydraulic conductivity where general methods of delivery and recovery are regarded as applicable.

band in terms of log hydraulic conductivity in centimeters per second. The band above it shows some soil materials, ranging from permeable sands to clays, and their conductivities. The top four bands show various methods of delivery and recovery and the types of soil materials and conductivities for which they are generally regarded as applicable. The lower limit of applicability is cross-hatched, because the lower limits of these techniques with respect to hydraulic conductivity involve some uncertainty. The gravity method, for example, which uses infiltration galleries or sprinkler systems for delivering liquids to unsaturated zones, relies on gravity head to produce hydraulic gradient. Gravity delivery methods are limited by the hydraulic gradient achievable by gravity, so it is only applicable in relatively permeable materials.

A pump will increase the hydraulic gradient, and surface area can change depending on the surface exposed with the chosen method. There is more surface area or more screened length available for a horizontal well than a vertical well, and more area exposed in a trench than in a horizontal well. So it is possible to use these methods to a greater degree in areas of lower hydraulic conduc-

tivity. The arrow in Figure 5-2 represents a potential reduction in applicable hydraulic conductivity for vertical wells, using various well stimulation techniques, such as hydraulic fracturing.

5.2.3 Distribution Coefficients

There are a variety of distribution coefficients: the distribution between components adsorbed onto soil grains in the aqueous phase, between components in the nonaqueous phase and aqueous phase, and between the air phase and the water phase.

For a material to be successfully recovered using conventional methods, the distribution coefficient expressed in terms of the concentration in the mobile phase (the phase to be recovered) versus the concentration in the immobile phase should be greater than 10^{-2} to 10^{-3}. Even if the concentration in the mobile phase is 100 to 1,000 times less than the concentration in the immobile phase, some components may still be recoverable. (Distribution coefficients are discussed in more detail in Chapter 2.)

For additional information concerning the movement of liquids, and the distribution coefficient, consult Section 5.4, particularly the works by Bear (1979), Chambers et al. (1991), Repa and Kufs (1985), U.S. EPA (1987), and Willhite (1986).

5.3 FIELD METHODS

The types of field techniques discussed in this section include:

- Vertical wells
- Hydraulic fracturing
- Interceptor trenches
- Horizontal wells
- Soil flushing

The following sections will describe the types of wells, general applications, performance, and advantages and limitations of these five techniques.

5.3.1 Vertical Wells

5.3.1.1 Types

Vertical wells are the most popular method of delivery and recovery. They can be categorized by the type of completion technique and the pump configuration. Completion techniques refer to the way a borehole is modified to make a well. Typically, this involves putting a pipe in the ground to prevent a borehole from collapsing. The pipe is slotted, and, in many cases, some kind of a filter material, such as sand or gravel, is used in the annulus to prevent fine grain sediment from entering the well and damaging the pumps.

The water supply industry provides many pumps used in vertical wells, and there are some specialized pumps for the environmental industry. Turbine pumps and a variety of centrifugal pumps are the most popular methods of recovering water (Driscoll, 1986). In some cases, the pumps are mounted at the ground surface and lift water out of the well with a vacuum, in much the same way that water is sucked out of a glass with a straw. It other cases, pumps are submerged in the well and push the water up to the ground surface.

There are a variety of pumps for environmental applications (Blake and Lewis, 1982; U.S. EPA, 1987). The gas-driven pump, for example, is a popular device, of which a bladder pump is a special variety. With a bladder pump, a chamber, containing check valves and a gas line that goes down to the pump, is lowered below the water table. Water or fluid in the well flows into the chamber, the check valve is closed, and gas is forced into the chamber, pushing the fluid up to the ground surface. One of the reasons for this pump's popularity is its gentleness; if multiple fluids are in the well, it will not mix them up as would a turbine pump. When the fluids are lifted to the ground surface by a gas-driven pump, they are relatively easy to separate.

A skimmer pump is an attachment to the intake of a pump, consisting of a flexible tube and float that ride up and down with the water level. The float is dense enough to sit on the interface between the water and floating product and can skim free product off the water table. Figure 5-3 shows a water-level activated pump with a level control, which consists of a pump and a switch device that turns the pump on and off in response to the level of water in the well, holding the level constant or within a short tolerance. There are two reasons for level

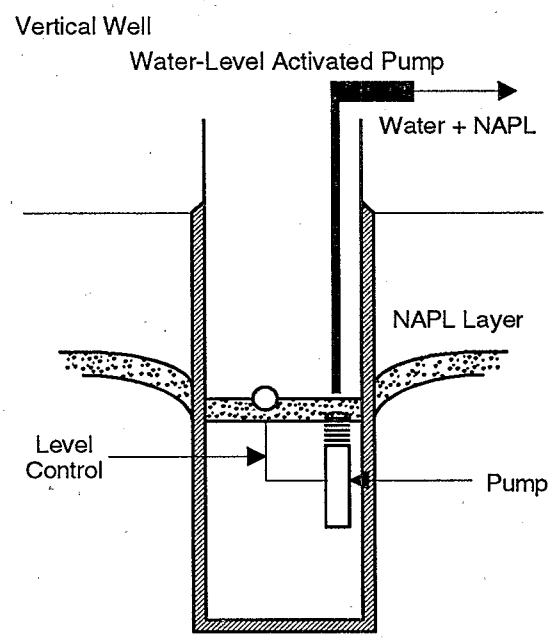

Figure 5-3. Vertical well—water-level activated pump.

control. For some environmental applications, wells are put into formations that are poor aquifers, which are unable to supply water to the well as fast as the pump removes it. Therefore, the pump has to be turned off periodically to prevent the well from being pumped dry and damaging the pump. In addition, a level control device can hold the water level at the intake, allowing the pump to gather floating free product.

A well using water level control is fundamentally different from water supply wells. The pump in a water supply type well supplies a constant flow rate, and the drawdown measurement gives the local performance of the well. If the drawdown is fixed, however, the parameter of interest is the flow rate. The flow rate will vary as a function of time; under ideal cases, it will decrease with time, thus providing fundamentally different performance on a local scale.

A slight variation of the level control pump is the two-pump system shown in Figure 5-4. One pump lifts the water and creates a cone of depression, down which the floating product flows, accumulating in the well. A level

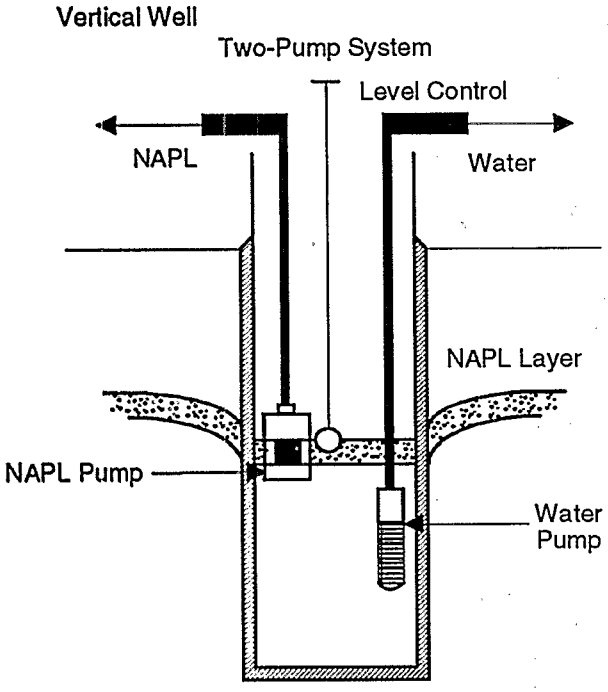

Figure 5-4. Vertical well—two-pump system.

switch holds the water position constant, and the NAPL pump lifts out the floating product. This kind of a system is used to prevent the mixing of free product and water. Figure 5-4 shows a pump used for light nonaqueous phase liquids (LNAPLs); a similar version is used for dense nonaqueous phase liquids (DNAPLs). With DNAPLs, the water pump is still used to create a cone of depression, but, as a result, a zone of relatively low pressure is created in the well, and the DNAPL bulges upward and is more easily recovered.

5.3.1.2 Applications

The remedial manager has several technology options for contaminated ground water at a site. In some cases, a site may be effectively stabilized simply by lowering the ground-water level below the level of the site.

The following are a couple of idealized examples of the use of vertical wells. (For additional case studies, see U.S. EPA, 1989a,b,c.) Figure 5-5 shows regional flow from top to bottom approaching an irregularly shaped contaminated area. One way of addressing this situation is shown in Figure 5-6. The fine lines in the figure are streamlines that go to the three wells. The heavy dotted line defines the capture zone for these three wells; that is, water on the upper side of the capture zone will make it to the wells, while the water on the bottom side of the line will be lost. This approach, using extraction wells, is applied when there is relatively high regional flow and

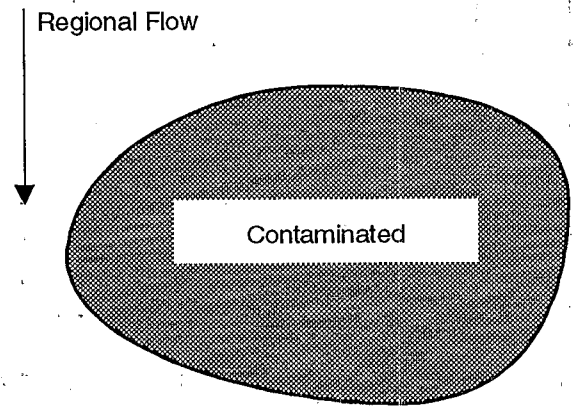

Figure 5-5. Regional flow from top to bottom approaching an irregularly shaped contaminated area.

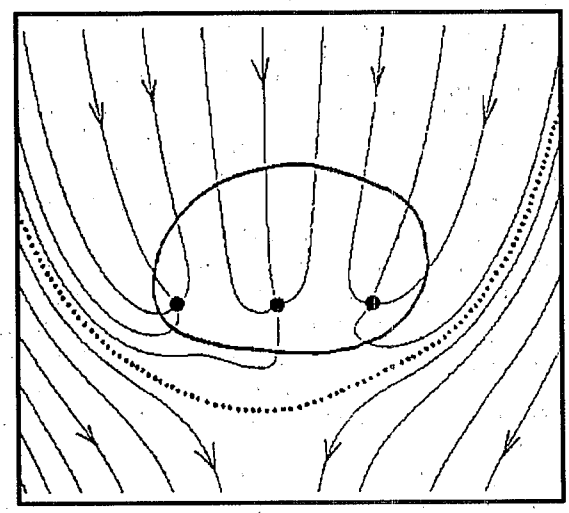

Figure 5-6. Capture of contaminants by a line of extraction wells.

relatively low adsorption of contaminants. The strategy is to place the line of extraction wells on the downgradient side of the contaminants, and use the regional gradient to sweep the contaminants into the wells. The design criteria balance the yield of these wells and the well spacing against the regional flow rate. If the spacing and flow rate of the wells are insufficient to remove the regional flow, then some of the contaminants can escape between the wells.

In cases where the regional flow is low, the line of extraction wells can be supplemented with injection wells to increase hydraulic gradient. Figure 5-7 shows the contaminated area with the same three extraction wells, and

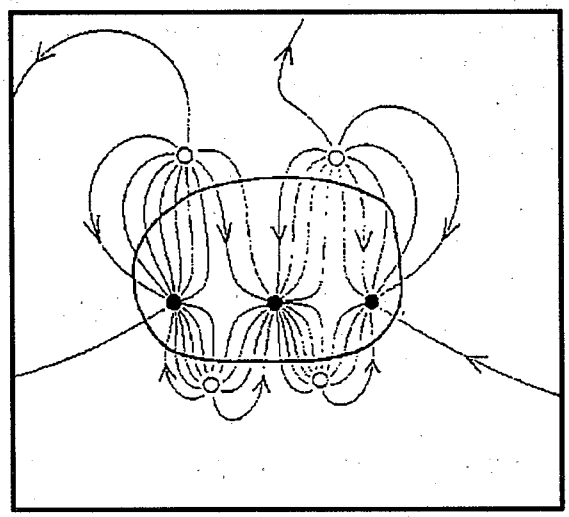

Figure 5-7. Approach to low regional flow using three extraction wells and four injection wells.

an additional four injection wells. For this simulation, the rate of pumping at these wells is balanced with the rate of injection. This results in an efficient sweep into these wells. There are two important points to consider with this kind of an approach. First, the injection wells must be located outside the contaminated area or contaminants can be driven away from extraction wells, potentially spreading contamination. The remedial manager must define the zone of contamination before considering using injection wells. Second, it is important to consider where stagnation zones, areas where the flow rate is negligible, may occur. If there is limited flow in an area, the area will act as a persistent source, allowing contaminants to slowly bleed into the extraction wells over time. Stagnation can occur any time there is more than one well, regardless of the pattern of extraction and injection, so long as the pumping rate remains constant. The key to addressing this problem is to vary the pumping rates so the stagnation point moves around, and the contaminants can be swept out of these areas, without leading to contamination of uncontaminated areas.

For additional reading about the applications of vertical wells, consult references in Section 5.4, particularly U.S. EPA (1989a,b,c), Haley et al. (1991), Keely and Tsang (1983), Keely (1984), and Repa and Kufs (1985).

5.3.1.3 Performance

One measure of performance of an extraction well is the concentration of contaminants from the extraction well over time. The typical performance is a high initial concentration, followed by a rapid dropping off and then a gradual leveling out (see Figure 5-8). Ideally, the concentrations then decrease to negligible values (Figure 5-8a). Often, however, the performance is not so favorable; there is a high concentration, followed by a falling off after the start of pumping. The concentration never really drops to zero, however, and persists above the regulatory limit (Figure 5-8b). This type of performance is the result of a persistent source, either a stagnation point or contaminants that have adsorbed onto soil grains and are slowly desorbing, or some other process. Figure 5-8c shows an even worse situation. The concentration drops off at first, but is followed by a minor increase. Then concentration falls again, until pumping stops, after which the concentration increases markedly. This pattern indicates an obviously persistent source, and is seen often in both pump-and-treat systems and vapor extraction systems.

In the situation of a persistent source, the remedial manager has the option to shut off the wells prematurely or to continue pumping at a very low rate, allowing the concentrations to increase. The pumping rate is then raised to recover water with a relatively high concentration of contaminants. This method is called pulse pumping and has been the focus of recent attention. Pulse pumping decreases the volume of contaminated water to be treated, and so may decrease remediation costs. It can cause problems, however; by turning the pumps down or off, the remedial manager may lose hydrologic control of the site.

5.3.1.4 Advantages and Disadvantages

There are several data issues that must be considered when installing vertical wells, including access, conductivity, adsorption, depth, NAPL, and heterogeneity (Bear, 1979; Driscoll, 1986; Repa and Kufs, 1985). Obviously, the location for the potential well site must be accessible for the drill rig. Hydraulic conductivity at the site must be greater than 10^{-5} cm/s for conventional applications. For adsorption, as mentioned before, the distribution coefficient must be less than 10^{-3}, and the depth must be 8 meters for suction lift, if the pumps are at the ground surface. If downhole pumps or submerged pumps are being used, there is no depth limit. With regard to NAPLs, the important question is whether their density is greater or less than water. Heterogeneities may cause problems for vertical wells or any other method of delivery and recovery, but such problems may be addressed by cycling the flow rates (Keely, 1982 and 1983; U.S. EPA, 1990).

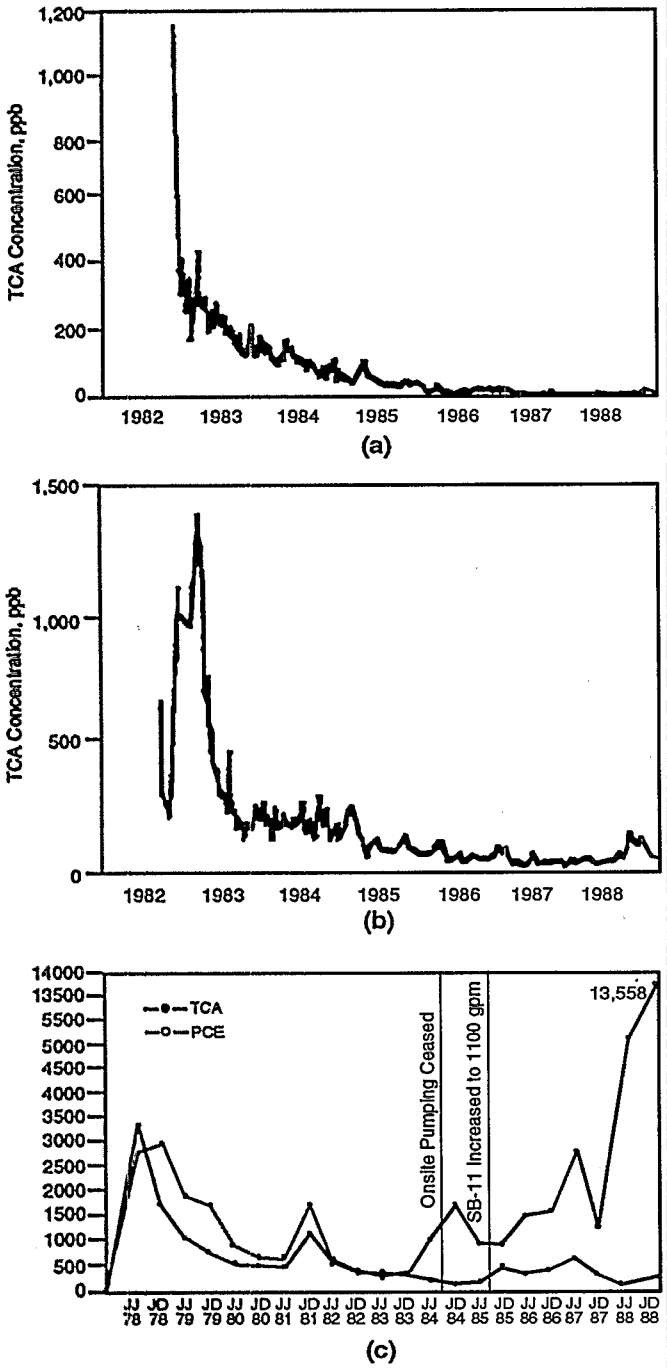

Figure 5-8. Concentration from the extraction well as a function of time. Figure 5-8a represents ideal performance (U.S. EPA, 1989a). Figure 5-8b shows concentrations above the regulatory limit (U.S. EPA, 1989b). Figure 5-8c shows an obviously persistent source (U.S. EPA, 1989c).

Operation and maintenance costs for vertical wells can be fairly high. The radial geometry of flow paths caused by a vertical well also can be a disadvantage. Because of its radial geometry, the flow paths will converge on the well, and energy is required to make flow converge. It is more efficient to move water through porous material if the flow lines remain parallel. This disadvantage can be overcome, however, by changing the geometry of the recovery system by using a trench or a directional well.

5.3.2 Hydraulic Fracturing

Hydraulic fracturing, a technique developed in the oil industry about 50 years ago, has received quite a bit of attention as a method of stimulating well yields. Today, almost every oil well is hydraulically fractured, because this technique consistently increases the yield to the well. Hydraulic fracturing has also been used effectively in water wells, particularly those drilled in hard rock.

One of the potential problems of hydrofracture is introducing uncontrolled fractures (vertical and horizontal) that could contaminate new areas. The technology should work well in highly stratified, over-consolidated deposits (glacial, loess, and lacustrine).

5.3.2.1 Method

Over the past 5 years, University of Cincinnati scientists have shown that hydraulic fractures can be made at shallow depths, such as 5 feet in silty clay. This technique increases the effective permeability, the radius of influence, and the yield of vertical wells in unconsolidated formations. Hydraulic fractures also can be used to deliver solids. The creation of a hydraulic fracture begins with a casing that is sealed in the ground and open at the bottom. A pump injects fluid into the casing, causing the pressure to increase until it exceeds some critical value and the fracture is nucleated. The fracture grows out away from the well, and a granular solid, such as sand or even a slow release nutrient for bioremediation, is pumped in to fill the fracture. When pumping ceases, the fracture closes and the solid remains to prop open the fracture and create a pancake-shaped layer (Figure 5-9).

Equipment for creating fractures at contaminated sites includes a device to store and meter sand, a tank for the fluid, a slurry mixer, a pump, and a special gel used to suspend the sand during pumping. Leveling methods are used to measure the uplift, or doming, which is usually about an inch when the fractures are created.

5.3.2.2 Applications

Hydraulic fracturing has applications for pump and treat, vapor extraction, soil flushing, and bioremediation. It already has been used for some pump-and-treat operations in crystalline rock in New York. It also is used in some cases to increase the area over which a monitoring well can sample, and it can be used to recover leachate. The flat-lying pancake-shaped geometry created by fracturing is ideal for any of these applications.

For bioremediation, this technique can be used to increase the injection of oxygen dissolved in water, or hydrogen peroxide. A recent innovation is the pumping of a solid compound consisting of encapsulated oxygen into

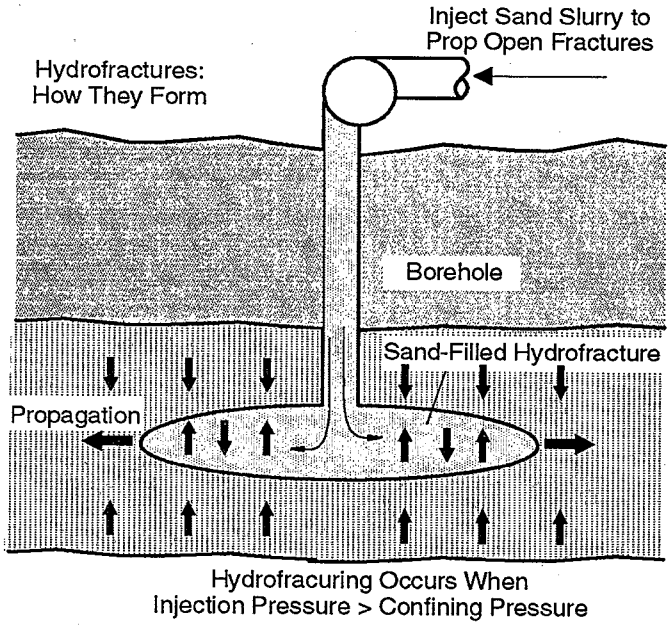

Figure 5-9. Creation of hydraulic fracture.

hydraulic fractures. After being pumped into the fracture, the capsules slowly release oxygen for bioremediation.

One example of an application of hydraulic fracturing is a Chicago industrial facility contaminated with solvent, where remedial engineers wanted to use vapor extraction. The site is underlain by silty clay with low permeability, and hydraulic fractures were used to increase the flow rates. The remedial engineers put in three fractures, one each at 5, 10, and 15 feet. Each fracture was individually screened, so a vacuum or air inlet could be installed and controlled separately.

During one study, fractures were created that resembled those at the Chicago site. Figure 5-10 shows a map of three fractures that were made at one borehole, labeled EL6, in an area that was excavated to reveal the details of the fractures. The figure shows several trenches, indicated by dotted lines, that were used to expose the hydraulic fracture. The heavy lines are the outlines of the fractures. Figures 5-11a and b show the view along the trench, with the lower, middle, and upper fractures. The hydraulic fracture itself looks like a sand bed roughly 1/2 inch thick, filled with coarse-grained, well-sorted sand, that is sandwiched between silty clay glacial material.

At another site where fractures were also created in silty clay, preliminary measurements of flow rate and pressure were taken (Figure 5-12). Over the first week or so, the flow was about 5 cfm from the fractured well. The flow rate fluctuated, decreasing when water infiltrated after rainfall and increasing when the water was removed from the well, but typically ranged between 3 and 4 cfm. At a nearby conventional well, used for control, the yield was a uniform 0.30 cfm. Thus, the yield from the fractured well

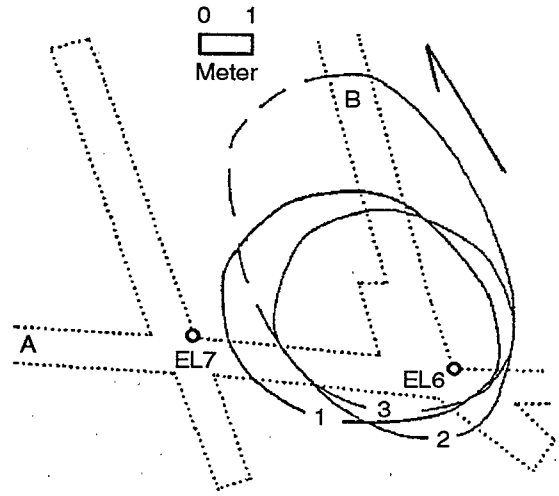

Figure 5-10. Map of three fractures created at borehole EL6.

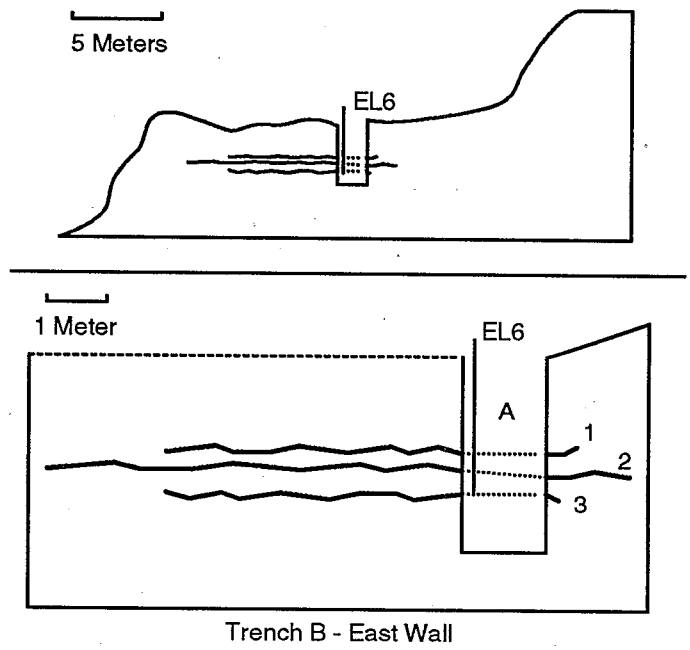

Figure 5-11. Cross-sections of three fractures created at borehole EL6 showing topographic profile (above) and details of fracture traces (below).

was roughly an order of magnitude greater than from a conventional well. Similarly, the radius of influence of the conventional well was found to be between 2 and 3 feet, whereas it was roughly 25 feet from the fractured well.

5.3.2.3 Advantages and Disadvantages

The advantages of hydraulic fracturing include the ability to increase well yield from tight materials, increase the radius of influence, form a flat-lying planar sink thus avoiding some geometry problems, and inject solids. The

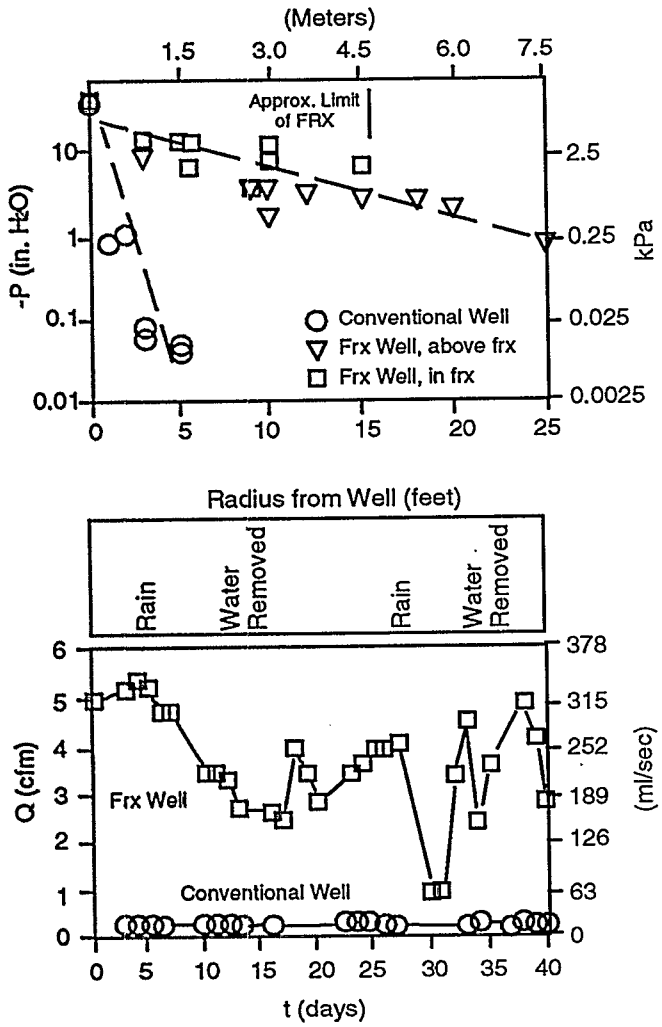

Figure 5-12. Suction head as a function of distance from conventional vapor extraction well and well intersecting two hydraulic fractures (above). Vapor discharge from 1 hp blower as a function of time (below).

technique is easy to perform, and is similar to injection grouting.

The disadvantages are that this technology is currently limited to rock or overconsolidated soil, there are limited performance data on soils, the technology causes surface deformation of about 1 inch, and availability is limited for soil. Some oil field service companies can perform hydraulic fracturing in rock, but so far the University of Cincinnati is the only group doing it in soils. The hydraulic fractures shown in the example discussed were created in overconsolidated soil. In normally consolidated soil, hydraulic fractures will be vertical and may be too small to be useful during remediation.

Getting this technique into general use will require demonstrations at contaminated sites and encouraging field results. Currently, three sites are utilizing hydraulic fracturing; two are using vapor extraction and one bioremediation (Davis-Hoover et al., 1991; Murdoch et al., 1991). The demonstration program aims to get several more sites under way.

For additional reading concerning hydraulic fracturing, consult the references in Section 5.4, particularly Davis-Hoover et al. (1991), Gidley et al. (1989), Howard and Fast (1970), Murdoch et al. (1991), Murdoch (1990), Murdoch et al. (1990), and Smith (1989).

5.3.3 Trenches

Figure 5-13a-c shows an example of the use of a trench to prevent a contaminant from entering a water supply well. Figure 5-13a shows the line of extraction wells. In Figure 5-13b, the contaminant has escaped between the wells either because the spacing is too great or the flow rate is too small. In either case, the system is poorly designed, and the contaminants are escaping to the water supply well. One possibility is to construct a trench instead of a line of wells (Figure 5-13c). Interceptor trenches, by cutting off the contaminants and preventing them from moving downgradient, provide a greater working surface area and a more reliable method than wells.

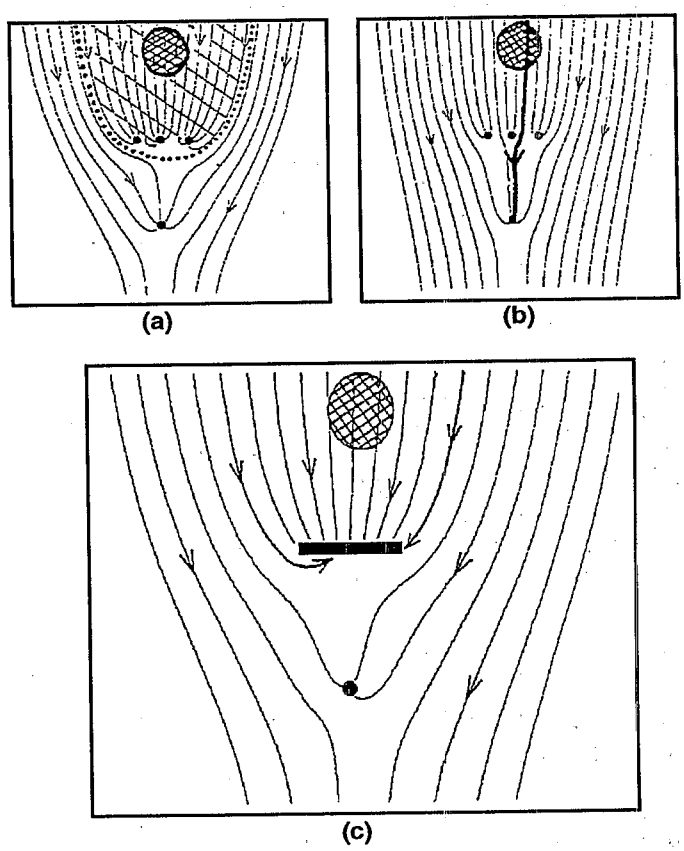

Figure 5-13. Use of trench to prevent a contaminant from entering a water supply.

5.3.3.1 Construction

A large backhoe is typically used to build interceptor trenches. One method of keeping the trench open is to fill it with guar gum, or other gel, in a manner similar to the filling of cutoff trenches with bentonite slurry. Guar gum gel will not penetrate into the trench wall, so it will not plug soil pores as can a bentonite slurry. Guar gum is also used for hydraulic fracturing and can be purchased from a number of vendors. Figure 5-14 shows a side view,

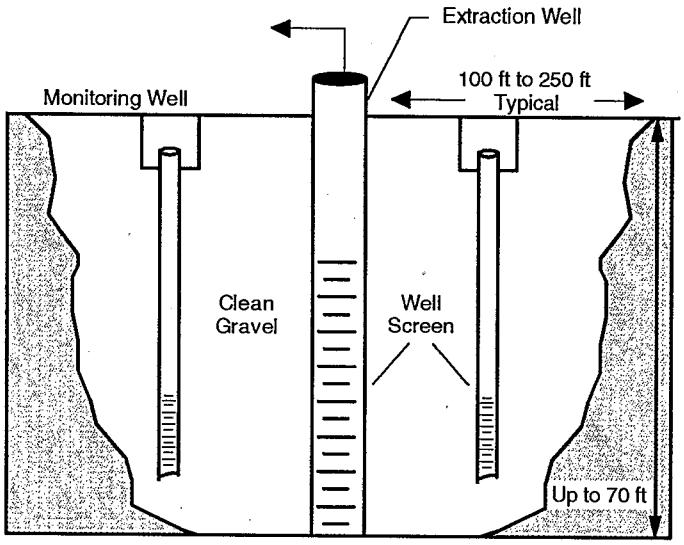

Figure 5-14. Side view of an interceptor trench.

normal to the plane of the trench. The trench has been backfilled with gravel, and a pipe has been inserted to house a pump. The data issues that need to be considered in constructing trenches are access; hydraulic conductivity, which must be greater than 10^{-6} cm/sec; adsorption; and depth, which should not exceed 40 to 65 ft.

5.3.3.2 Applications

The general applications for trenches are 1) to intercept ground water, 2) to lower the water table, 3) to stabilize contaminant migration, and 4) to use with a barrier. An example of the fourth application is using a trench on one side of the contaminants and a barrier on the other to prevent uncontaminated water from entering the trench. Uncontaminated water would dilute the contamination, increasing the volume of contaminant to be treated.

5.3.3.3 Advantages and Disadvantages

Trenches have a better capture effectiveness than vertical wells and are relatively simple to construct, especially the shallow ones. Trenches also have a greater yield in tight soils than wells and, as a result, can have lower operating and maintenance costs. The disadvantages are that excavated contaminated material from trenches could require disposal as hazardous waste, and access can be difficult, especially with a large backhoe. In addition, the depth limit for conventional excavation techniques is about 15 feet, although more specialized trenches can be built to a depth of 40 to 65 feet. Another disadvantage of trenches is the difficulty of abandoning them.

For additional information concerning trenches, consult the references in Section 5.4, particularly Day (1991), Gilbert and Gress (1987), Meini et al. (1990), Repa and Kufs (1985), U.S. EPA (1990), and Zheng et al. (1988).

5.3.4 Directional Drilling

If the remedial manager desires the linear geometry of a trench, but is constrained by some of the disadvantages mentioned above, one option is directional drilling. Directional drilling, which installs horizontal wells, will improve access and will have some geometric advantages such as greater working surface area. It also can address problems related to heterogeneities, such as preferred flow paths induced by vertical fractures. This method of drilling is gaining in popularity.

Directional drilling, as defined here, requires a rig that is surface launched and has a drilling head that can be steered in any direction. It also must include an electronic device to monitor location. Two systems meet these requirements: one from the oil industry and one from the utility industry.

The oil industry directional drilling rigs used in remedial actions are scaled down from oil well drilling applications. They are state-of-the-art, and the major manufacturers are Eastman Christensen (Karlson and Bitto, 1990) and Petrolphysics (Dickinson et al., 1986; 1987; and 1991). Eastman Christensen has already installed several wells, some of them at the Savannah River site. They have conducted demonstrations using vapor extraction with those wells, and have obtained some promising results.

The trajectory of the borehole from an Eastman Christensen rig starts on an incline and then curves to the horizontal after about 60 feet, at which point it can continue horizontally for several hundred feet (Figure 5-15). The Petrolphysics rig also puts in a horizontal well, but the geometry is somewhat different, perhaps significantly depending upon the application. This equipment starts with a vertical hole and turns sharply to a horizontal (Figure 5-16). These horizontals can go out at various depths, even stacked on top of one another or at different angles like the spokes of a wheel. This configuration has obvious advantages in tight locations where there is no room to gradually achieve the horizontal.

The directional drilling rigs from the utility industry (Wemble et al., 1990) are relatively small rigs, about an order of magnitude smaller than the oil drilling rigs. They are used to drill holes to install utilities, electric lines, and gas lines. Manufacturers include Underground Technologies and Ditchwitch. Utility rigs are smaller, more compact,

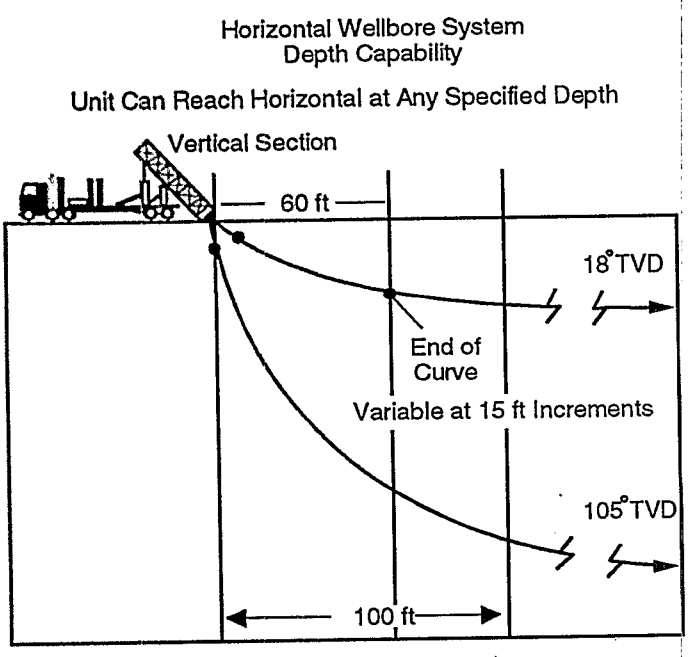

Figure 5-15. The trajectory of the borehole from the Eastman Christensen rig.

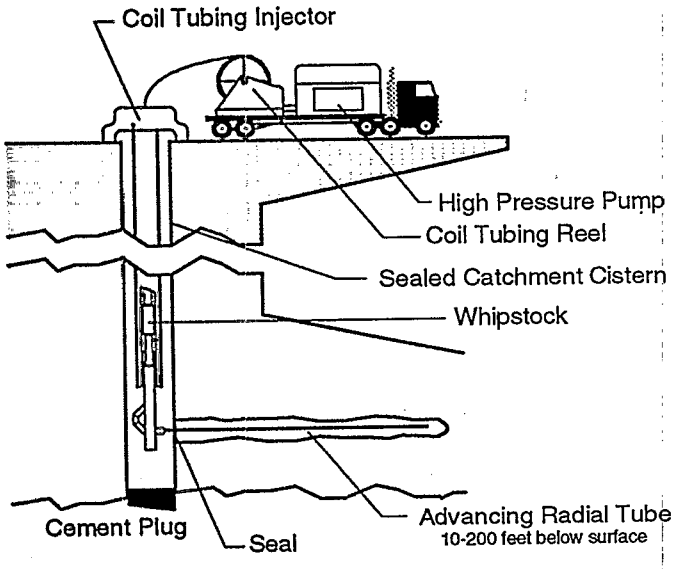

Figure 5-16. Petrolphysics rig with a shallow radial system.

more maneuverable, and more easily mobilized than the oil industry rigs.

Utility industry rigs can have remarkable directional capabilities. It is possible for them to drill borings that go down and level off, then take a right-hand turn and curve around, and keep curving until they essentially drill a bore that looks like a horseshoe, turning 180° and coming up about 100 feet away. Directional drilling allows the remedial manager to tailor the well to the specific situation. This technique currently uses a radio transmitter and receiver that monitors location and depth from the ground surface.

5.3.4.2 Advantages and Disadvantages

Figure 5-17 shows three situations where directional drilling can be applied. Directional drilling increases accessibility, because it can go underneath structures, allowing for stabilization under buildings. This makes it easier to use in retrofitting landfills with leachate collection systems or monitoring and sampling from beneath tanks and other potential sources that cannot be drilled through (Dickinson et al., 1986 and 1987; Wemble et al., 1990). Directional wells also will show improved performance in situations where contaminants occur as layers, either as a floating layer or resting along the interface between bedrock and overburden. There is more screened length with a directional well than with a vertical well. Where vertical fractures provide the majority of permeability, directional wells also are likely to intersect many more of those vertical fractures (Dickinson et al., 1986 and 1987).

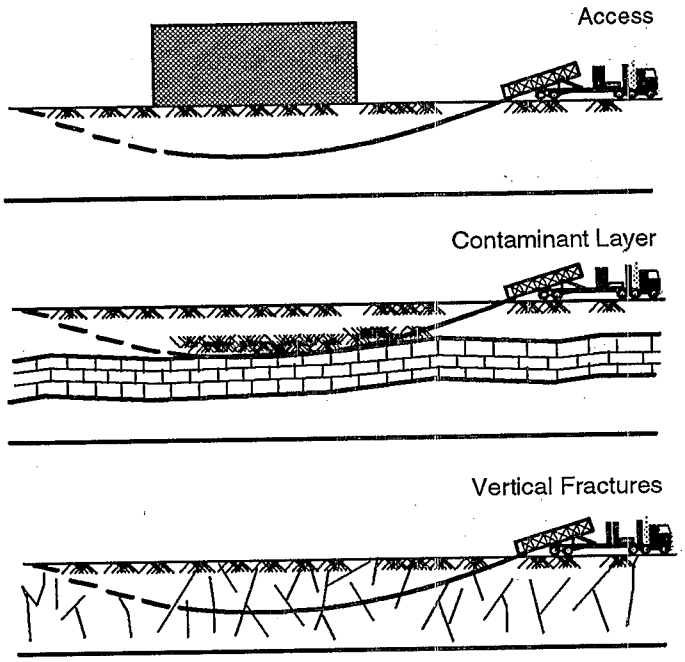

Figure 5-17. Three situations where directional drilling could be beneficial.

One of the disadvantages of this technique is cost, which ranges widely for the two systems. The oil industry rigs generally cost approximately $100 to $300 per foot; the utility rigs cost $20 to $50 a foot. Another potential problem is availability. Eastman Christensen and Petrolphysics are currently available to install wells, but they only have a few rigs and mobilization may be a factor. The utility rigs are widely available, but, so far, they have only been used to create wells in a few locations.

Techniques for sampling with both types of rigs are still under development, although some techniques are currently in the prototype stage.

Hole collapse for bores made with utility rigs can be a problem, depending on the formation. The initial hole that is drilled is relatively small—2¾ to 4¾ inches. After drilling the small hole, however, the engineer can attach a reamer and enlarge the hole to 10 or even 24 inches or more, depending upon the rig. One of the techniques under development is the use of a reamer behind the drill head (about 20 feet back), so that the small 2-inch hole is enlarged as it is created.

Completion techniques are available for holes that stay open, but holes that collapse require different techniques. The most reliable way to accomplish completion in the latter case is to advance the casing as the hole is drilled.

For additional information concerning directional drilling, consult the references in Section 5.4, particularly Dickinson et al. (1986), Dickinson et al. (1987), Dickinson et al. (1991), Kaback et al. (1989), Kaback et al. (1991), Karlsson and Bitto (1990), Langseth (1990), Looney et al. (1991), Wemble et al. (1990).

5.3.5 Soil Flushing

The previous sections in this chapter have reviewed various geometries of physical systems for delivery and recovery. In some situations, the contaminants are tightly bound to soil grains, so no matter what the geometry of the physical system, it is necessary to inject fluids to enhance recovery. Soil flushing is a technique of delivering fluids to enhance recovery.

5.3.5.1 Applications

Soil flushing has a variety of applications, some in initially unsaturated and others in saturated ground. In saturated ground, infiltration techniques that target certain types of contaminants, such as bioreactive, semi-volatile, and inorganics, have been used. With initially saturated ground, soil flushing can be used on water soluble compounds, low solubility compounds, or NAPLs.

5.3.5.2 Methods

When many people refer to soil flushing, they mean chemical flooding. Soil flushing, or chemical flooding, involves mixing a compound with water and injecting it to increase mobility (Amdurer et al., 1986; Begor et al., 1989; Carter and Knox, 1986; Trost et al., 1989) or degradation (Amdurer et al., 1986; Chambers et al., 1991) of contaminants. Mobility is enhanced, for example, by adding a surfactant for oily compounds, or a viscosifier to help push out thick fluids. For some inorganics, mobility can be enhanced by altering pH and redox potential.

5.3.5.3 Data Issues

Some of the issues at a site that must be considered for soil flushing include heterogeneities, ground-water and soil chemistry, adsorption, and biodegradation (Amdurer et al., 1986). Probably the most important consideration is achievement of hydrologic control of the site, so that the effluent can be captured. If not contained and recovered, the flushing agent can mobilize the contaminant to new areas, exacerbating the problem. In some cases, the compounds used for chemical flooding are fairly toxic or hazardous, so they must be recovered. At the Laramie Tie site, for example, an extensive slurry wall and array of wells are used to achieve hydrologic control and ensure recovery of an alkaline surfactant used during chemical flooding.

With respect to contaminants, an important consideration is the octanol-water partitioning coefficient. If the K_o is less than 1, soil flushing can be accomplished with water alone. If K_o is greater than 3, a surfactant increases removal efficiency (U.S. EPA, 1990a). In the "gray area" in between, the necessity for a surfactant depends on site characteristics. Before considering soil flushing at any site, the remedial manager must perform bench-scale studies as well as carefully controlled pilot studies (Sale et al., 1989; Trost et al., 1989).

For additional information concerning soil flushing, consult the references in Section 5.4, particularly Amdurer et al. (1986), Chambers et al. (1991), Repa and Kufs (1985), Sale et al. (1989), U.S. EPA (1990), Trost et al. (1989).

5.3.6 Other Techniques

There are a variety of other techniques for addressing problems with moving liquids, including heating, freezing, and electrical techniques. Heating by steam injection, radio frequency radiation, or electrical resistance can increase mobility of some liquids and increase recovery by driving liquids into the vapor phase. Ground freezing has been used to enhance migration of contaminants, which are excluded from ice crystals and pushed ahead of a freezing front. Electrical osmosis uses electrical gradients to drive fluid flow and is especially effective in fine-grained soils.

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CHAPTER 6
Vapor Extraction, Bioventing

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6.1 INTRODUCTION

This chapter presents the fundamentals of both vacuum extraction and bioventing and some of their potential applications in the realm of stabilization. Vapor extraction, or gas control, has been referred to as soil vapor extraction (SVE), forced air venting, and in situ air stripping. The process involves extraction of air from unsaturated soil, and is applied in the vadose zone. Moving air through the subsurface by vacuum extraction and moving water through the subsurface by pumping and treating are parallel types of processes, applied to different media. Section 6.2 describes the process of vacuum extraction, and Section 6.3 describes some of the applications of this technology. In many situations, SVE systems can be modified to introduce oxygen to the subsurface to enhance degradation. Section 6.4 discusses the use of bioventing to enhance the biodegradation of soil chemicals by microorganisms. Section 6.5 is a list of references for further information.

Vapor extraction technology offers several remedial benefits and can be used to stabilize sites by controlling the migration of subsurface vapors, preventing vapors from affecting people or the environment, removing explosive vapors or harmful gases, removing sources of light and dense nonaqueous phase liquids in the vadose zone, and enhancing bioremediation. The following is a simplified discussion of vapor extraction system principles.

6.2 PROCESS DESCRIPTION

6.2.1 System Components

The principle of vapor extraction is based on the Henry's Law constant, or air/water partition coefficient (K_h); the concentration of a chemical in air compared to the concentration of the chemical in water (C_a/C_w). The higher the K_h, the greater the tendency for the chemical to partition into the air phase of the subsurface.

Figure 6-1 is a schematic of ventilated soil. The arrows represent advection, or air that is being pushed or pulled through the zone under pressure or suction. In the figure, the air is going through a subsurface system, where the irregularly shaped material represents soil particles, such as sand, silt, or clay. Surrounding those particles under most field conditions, except in arid areas, is a layer of water. Chemicals in the water around the soil will partition

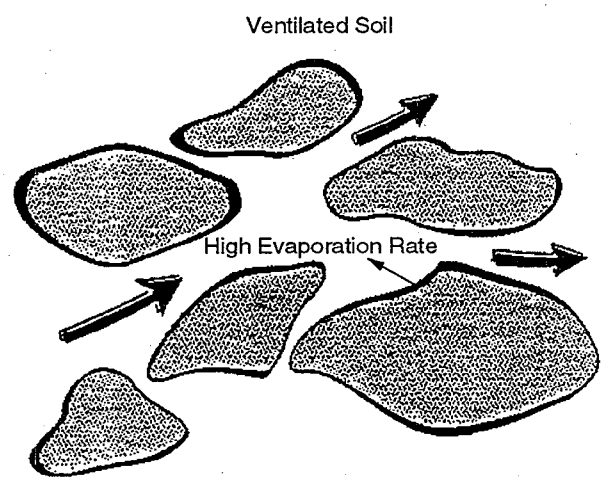

Figure 6-1. Schematic of ventilated soil (Valsaraj and Thibodeaux, 1988).

between the water and the air phases based on Henry's Law constant (K_h).

If the K_h is high, the chemical has a greater affinity to partition into the air phase. The driving force, when constantly depleting vapor concentration established through advection, is similar to hydraulic head or electrical potential, a flow of mass or charge from an area of high to low potential energy. The process motivates the chemical to move into the gas phase from a high concentration zone (aqueous phase) into a low concentration zone (air phase).

Vacuum extraction works because the system is deliberately kept out of equilibrium. If there was no advection of air, the chemical would partition from the water phase to the air phase until it reached the K_h value, and then stop. The air compartment would be filled, the water compartment would still contain chemicals, and the system would achieve equilibrium. By advecting air through the system, however, and keeping one phase relatively clean, the chemical is continuously drawn from the water to the air and stripped away in the air phase. Vacuum extraction actually frustrates an equilibrium system by not letting the system ever attain a Henry's Law constant value.

A simple approach to performing a chemical mass balance in the laboratory is to put the contaminant from the soil in a flask and collect the vapors in a sorbent tube (see Figure 6-2). The tube will contain resin, generally an

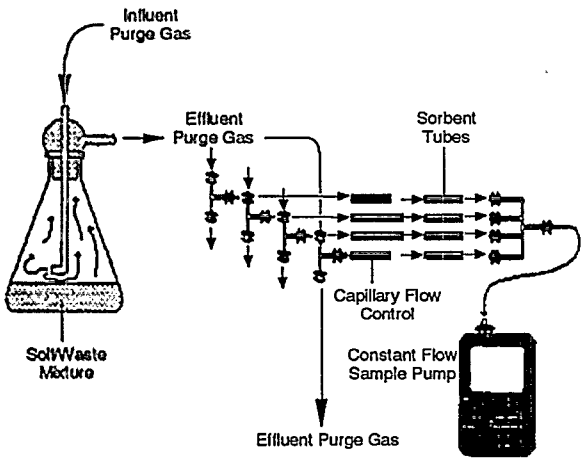

Figure 6-2. Laboratory flask apparatus used for mass balance measurements (Sims et al., 1989).

organic polymer with high surface area and functional site density, for the sorption of the chemical. By eluting the chemical off the sorbent tube, the mass of material that has moved into the air phase can be calculated. This procedure is often useful with mixtures of chemicals, such as oil and grease, in the subsurface. Measuring the tendency of the chemical in the mixture to be in the air phase can indicate the potential usefulness of applying vacuum extraction under experimental conditions that may or may not reflect site conditions. This technique is a first step in remedy selection.

The following is an example of the misinterpretation of soil vacuum extraction operational data. Figure 6-3 shows

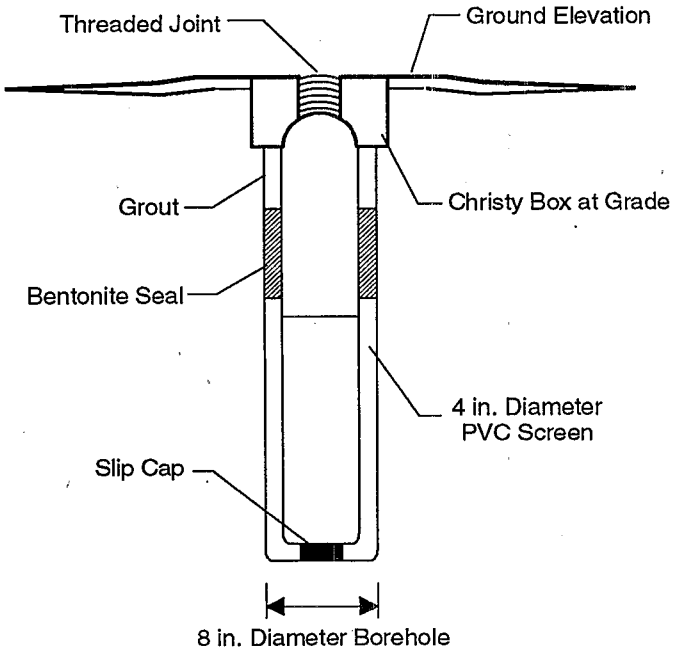

Figure 6-3. Schematic of a gas extraction well (U.S. EPA, 1991a).

a gas extraction well, which is designed to remove air from the subsurface by suction or to measure the extent and rate of cleanup at a site. If a remedial engineer were to measure the concentration of the chemicals in the gas phase coming out of the well, he or she might suppose that the site was clean because the chemical concentration in the gas had decreased. Actually, however, the air advecting through the high permeability sand and gravel in the subsurface may have been cleaned by the air relatively quickly. Because sand and gravel have larger particles than clay or silt, their surface area to volume ratio is much less; thus, they hold fewer contaminants. The clay still might be highly contaminated, but because little air goes through clay-textured materials, these contaminants do not show up in the air phase at the gas extraction well. High volumes of clean air from the sand and gravel mix with low volumes of very contaminated air from the clay, resulting in a total volume of air that is relatively clean. If the remedial manager were to shut off the well, later the air would be contaminated again. In the interim, the chemical would have desorbed from the clay into the air phase, and become available. The heteroge-

neity in the subsurface and diffusion and desorption cause chemicals to move from the more highly contaminated material back into the less contaminated sand and gravel.

Two different kinds of wells are needed for vacuum extraction: some for monitoring and some for extraction of the gas phase. The extraction wells should be used to extract the contaminated gas. Monitoring wells placed around areas that are less permeable to air, such as silts and clays, can be used to monitor the rate and extent of cleanup. The position of the monitoring wells will depend on whether the chemicals are associated with the nonaqueous phase or are in the clays. When the monitoring wells indicate that cleanup has been achieved, the remedial manager may still wish to take soil core samples to ensure that the clay also has been cleaned up. For the application of vacuum extraction of mixtures of nonaqueous chemicals, for example, in gasoline or petroleum (NAPL) phases, Raoult's Law rather than Henry's Law is applicable. For a discussion of Raoult's Law refer to Nonaqueous Fluids in Section 6.2.2.2.

6.2.2 System Variables

To explore system variables, this section will examine the chemical and site characteristics that make vacuum extraction more or less applicable.

6.2.2.1 Chemical Characteristics

To measure the tendency of a chemical to be in the air phase, vapor pressure is used for the pure-phase chemical and the Henry's Law constant is used for compounds dissolved in the water phase. The vapor pressure of a pure chemical, as a rule of thumb, should be greater than 14 mm of mercury at 20° C, although lower values have been suggested (U.S. EPA, 1991b). The Henry's Law constant, as a rule of thumb, should be greater than 0.01 mg/L in air per mg/L in water for vacuum extraction to be appropriate. In a spill of a pure chemical, such as acetone, the chemical will move down through the unsaturated zone. When acetone traveling through the soil becomes dissolved in water, the Henry's Law constant is used, because there is both a water phase and an air phase.

Acetone, which is used in chemistry laboratories to dry glassware, has a very high vapor pressure. It is, however, completely miscible (will completely dissolve) in water. If a lot of water is present in the soil, the acetone will dissolve and the Henry's Law constant will be extremely low, so vacuum extraction will not work.

Table 6-1 presents the vapor pressures of some commonly occurring compounds. The vapor pressure of perchloroethlyene (PCE) is 14.3 mm Hg. PCE, with its 4 chlorine atoms, is appropriate for vacuum extraction based on its chemical characteristics. When PCE loses a chlorine, it may be transformed from 4 to 3 chlorine atoms and become trichloroethylene (TCE). The vapor pressure for TCE is almost 60 mm Hg. If the chemical transforms to two chlorines and becomes dichloroethylene, the vapor pressure goes to 591 mm Hg. If another chlorine atom is removed, the vapor pressure is 2,660 mm Hg. As this chemical is transformed in the subsurface, biotically or abiotically, especially under anaerobic conditions, each transformed product has a greater vapor pressure.

Table 6-1. Vapor Pressures of Some Commonly Detected Compounds

Compound	Vapor Pressure (mm Hg) at 20°C
Vinyl Chloride*	2,660
1,1-Dichlorethylene (1,1-DEC)*	591
Methyl Ethyl Ketone	100
Benzene*	95.2
Trichloroethylene (TCE)*	57.9
Bis(chloromethyl) ether	30
Toluene	28.4
Perchloroethylene (PCE)*	14.3

*Known or suspected carcinogen.
Source: U.S. EPA (1991a).

Vertical as well as horizontal movement of chemicals with high vapor pressures may result in the spreading of contamination within the unsaturated zone. Also, runoff or precipitation events may result in leaching of compounds that are also soluble in water.

Table 6-2 shows the Henry's Law constants for selected compounds. The table presents some of the same chemicals as in Table 6-1. In the table, the Henry's Law constant for naphthalene is five times higher than the cutoff value of 0.01 mg/L in air per mg/L in water. Vacuum extraction is appropriate for all of the chemicals in this table, based upon the criterion of 0.01 dimensionless Henry's Law constant. Again, perchloroethylene has a dimensionless Henry's Law constant of 0.34, but with one less chlorine atom (TCE), it goes up to 0.42. Vinyl chloride with one chlorine atom is 99 mg/L in air per mg/L in water; it is basically a gas. Dechlorination of these chemicals results in an increased tendency for a chemical to be in the air phase.

6.2.2.2 Site Characteristics

The important site characteristics that affect the remediation process are soil moisture content; soil texture; distribution of contaminants, or heterogeneity; and immiscible fluids.

Table 6-2. Henry's Law Constants for Selected Compounds

Compound	Henry's Law Constant (mg/L / mg/L)
Vinyl Chloride*	99.0
Mercury (Hg°)	0.48
Trichloroethylene (TCE)*	0.42
Perchloroethylene (PCE)*	0.34
PCB-1260	0.30
Benzene	0.24
Methylene Chloride	0.13
Naphthalene	0.05

Source: U.S. EPA (1991a).

Soil Moisture Content

Figure 6-4 shows the effect of moisture on VOC adsorption and desorption in soil at two moisture contents. In the figure, the two bars represent a dry soil and a wet soil. The benzene rings represent the organic compound that is being removed with vacuum extraction; the dots represent water. In the dry soil, the benzene ring, or the organic chemical, becomes adsorbed to the soil, and the surface area is occupied by benzene. Under precipitation or irrigation, the water competes for the surface area and forces the benzene or the organic compound into the water phase. The chemical will then behave based on the principle of the Henry's Law constant (i.e., a water phase and an air phase).

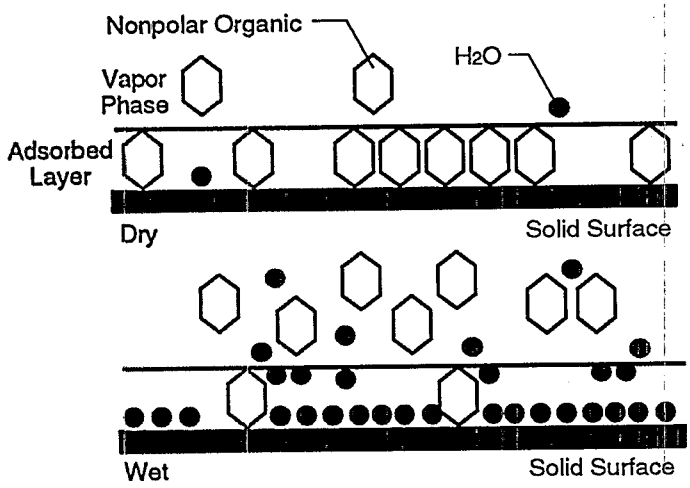

Figure 6-4. Effect of moisture on VOC adsorption and desorption in soil—VOC adsorption with two moisture regimes (Reible, 1989).

Water also will vaporize from the subsurface because it has a vapor pressure of 17 mm Hg at 20°. As water is removed, the chemical becomes more adsorbed to the soil surface. A monitoring well may show that the air has become clean, but the chemical may be even more tightly adsorbed to the soil. If water is then added to the soil, the chemical may partition from the soil into the gas phase and contaminate the gas again. This competition between water and the organic chemical indicates that water content of the soil is very important.

Benzene has a very high K_h, but when it is removed from the soil and the soil becomes dry, K_h is no longer appropriate because there is no water phase. When water is added, the Henry's Law constant is relevant again and the chemical goes back into the air phase. By simply adding water to the soil, the remedial engineer can control the efficiency of vacuum extraction. In using vacuum extraction systems in arid regions, it is important not to dry the soil out, as the efficiency of vacuum extraction will actually decrease due to water removal.

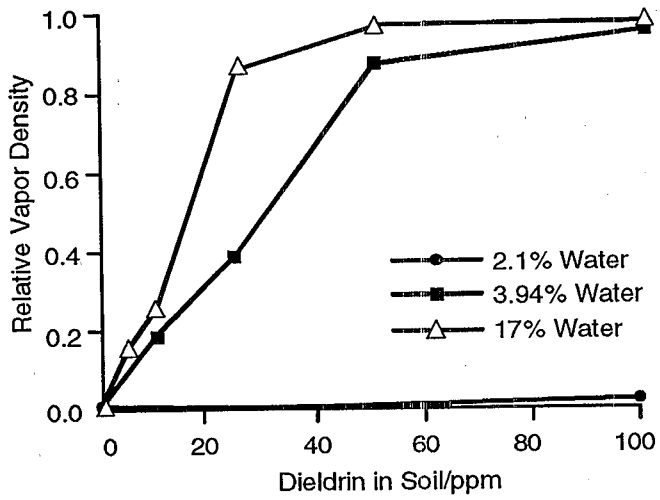

Figure 6-5. Effect of soil water content on dieldrin vapor pressure (modified from Spenser and Cliath, 1969).

Figure 6-5 shows the relative vapor density of dieldrin in soils with three different water contents. At a vapor density of 1, dieldrin vaporizes into the air. As shown in the figure, when the soil has 2 percent water by weight (2 grams of water per 100 grams soil dry weight), the dieldrin is adsorbed to the soil. If water is added to 4 percent, or 4 grams of water per 100 grams of soil dry weight, the dieldrin changes from the soil phase to the air phase. This 4 percent point is known as the Critical Soil Moisture Content for Vacuum Extraction. The change from 2 to 4 percent provides just enough water to push the dieldrin

off the surface of the soil into the water, where it can operate by the Henry's Law constant. Increasing the water content to 17 percent, however, does not effect the same dramatic increase in the dieldrin in the gas phase. The range of 2 to 5 percent water content may be a good low optimum for use with vacuum extraction.

Texture

Clay-textured soil areas, because they are less permeable to any fluid—NAPL, water, or air—represent more of a challenge to the use of vacuum extraction. Chemical characteristics may indicate that vacuum extraction would be viable, but if there is appreciable clay at the site it may be necessary to first increase the permeability by fracturing. If the chemical permeates the soil in fractures, it is possible to remove it from those fractures, but if the chemical has permeated by diffusion, it will be more difficult to remove. Because of the low permeability of clay, vacuum extraction will be much more successful at a site with a sandy loam texture than at a site with clay and clay loam textures.

In the soil texture triangle in Figure 6-6, vacuum extraction is more applicable for the soils near the bottom left of the triangle and less applicable for those such as clays at the top.

Heterogeneity

At a site with different soil textures, heterogeneity can be used to assess how much of the chemical is in the clay and how much is in the sand. This information can help

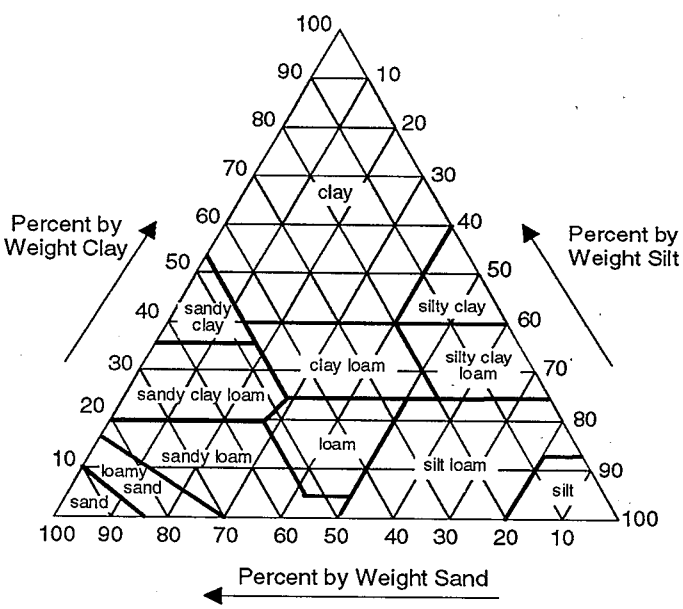

Figure 6-6. Soil texture trilinear diagram (Soil Conservation Service, 1971).

determine where to install monitoring wells to evaluate the rate and extent of cleanup, and how relatively fast or slow to expect the rate of cleanup.

In Figure 6-7, the area labeled molecular diffusion is the low permeability strata, where diffusion dominates the

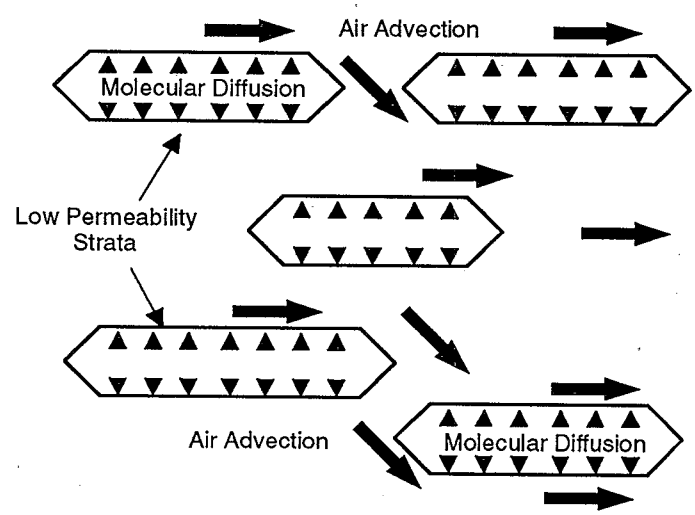

Figure 6-7. Diffusive release of contaminants from the soil phase into the gas phase (U.S. EPA, 1989).

movement of chemicals within clay. The arrows show air advection through a more permeable area consisting primarily of silts and sands. Advection will proceed easily through the silts and sands, cleaning that area very quickly. The chemical that is in the clay, however, can take 50 years or more to come out by diffusion, unless fracturing is used. The chemical diffuses very slowly back into the area where the sand and silt are being cleaned up. A gradient for molecular diffusion shows the chemical starting at a very high concentration, then steadily declining. But if treatment ceases, after several weeks the concentration rises again because of the slow diffusion or desorption in tighter materials, primarily clays and silts.

Monitoring for Heterogeneity. It is important to place monitoring wells so as to obtain an accurate assessment of the cleanup. If the well is placed through the whole system, the clean air will dilute the contaminated air, allowing potential misinterpretation of monitoring results. Instead site personnel should locate the clay stringers and install monitoring wells in those areas, sampling the air right around the clay and not diluting the air around the silts and sands. This is called monitoring a rate-limiting flow path.

Figure 6-8 shows the vapor concentration of a chemical, such as benzene, decreasing as the pump begins to advect air through the subsurface. The site manager turns off the pump when a level is obtained that is acceptable,

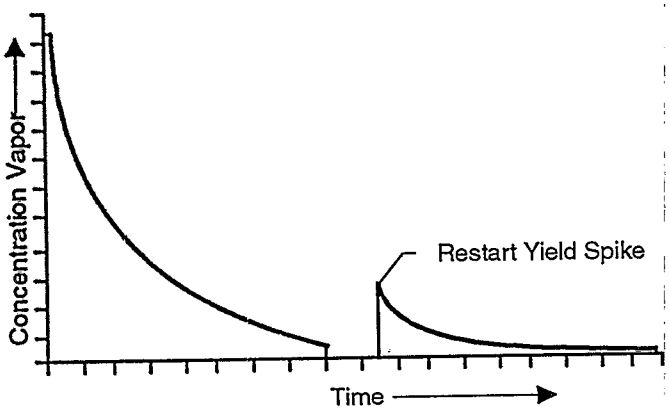

Figure 6-8. Concentration vs. time profile showing restart spike (DiGiulio et al., 1990).

then waits for several weeks before turning the pump back on. The initial sample shows a higher concentration of benzene in the advected air than the concentration when the pump was stopped. This observation is called a restart spike or yield spike, and is due to the sources in the subsurface that continue to sponsor chemicals in the air phase due to diffusion. This phenomenon is common in pump-and-treat systems and can be observed in vacuum extraction systems as well. If the pump is turned on again, the concentration will decrease further, because there is only a finite mass of material to remove, assuming all the drums, rock piles, etc. have been removed. The slope of the curve in Figure 6-8 presents a rough estimate of the rate of cleanup.

Nonaqueous Fluids

The following is a simplified discussion of the application of Raoult's Law to nonaqueous fluids remediation.

When a site has a combination of liquids such as gasoline or petroleum in the subsurface, then Henry's Law is no longer applicable because there is no water phase. The chemical, however, will tend to volatilize out of the pure liquid in proportion to its concentration in that liquid.

Raoult's Law is expressed as the following: a chemical will volatilize in proportion to its concentration and its vapor pressure. Therefore, vacuum extraction can never remove 100 percent of the hydrocarbons present. It will only remove the percent that can be volatilized, maybe 40 percent. Fifty or 60 percent of the hydrocarbons remain in the subsurface, because they are not volatile.

Figure 6-9 shows the volatilization of a combination of liquids. The fewer the number of carbons, the lighter the molecule and the higher the vapor pressure, and the more of the chemical that will be removed with vacuum extraction. In the figure, the lighter components of the mixture are labeled C4 and C5. When the mass of this material is removed via vapor extraction, the residual mass left over will contain the heavier constituents, C6, C7, and

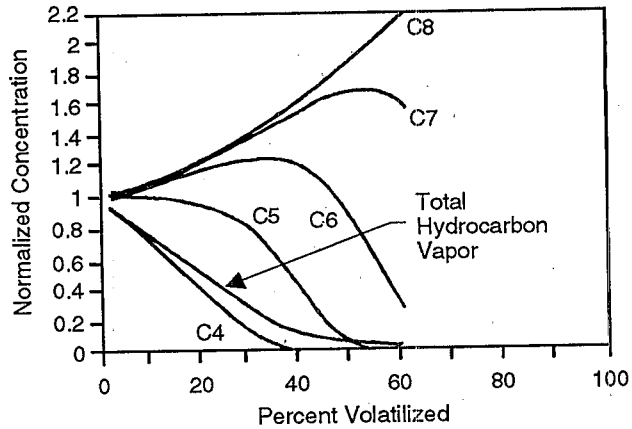

Figure 6-9. Volatilization of a combination of liquids (Johnson, 1989).

C8, that do not volatilize as readily. The result is an increase in the concentration of the high molecular weight compounds.

6.3 APPLICATIONS OF VAPOR EXTRACTION TO REMOVE LIGHT NAPLS

Vacuum extraction will remove the lighter components of a contaminant in water systems based upon Henry's Law, and will remove the lighter components of a contaminant in nonwater systems based upon Raoult's Law.

The design of extraction wells in the field needs to address spacing as well as depth. The wells should be placed apart according to media properties, and should be as deep as the contaminant. Where contamination is deep and permeability is high throughout the profile, the slotted (screened) interval should be extended to the maximum depth possible.

Figure 6-10 shows the effect of well spacing on total solute mass removal from the subsurface over a period of about 12 days. Wells should be placed more closely to achieve overlapping cones of influence, as in pump-

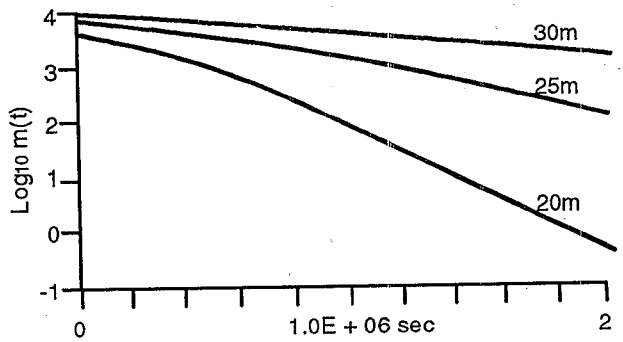

Figure 6-10. Total solute mass in the subsurface vs. time showing the effects of well spacing on vacuum extraction effectiveness (modified from Wilson et al., 1989).

and-treat systems. If the wells are spaced 20 meters apart, the site is stabilized more rapidly than if the wells are spaced 30 meters apart. Then more of the vapor phase is able to be moved more quickly to clean up the site. The spacing is also a function of soil texture. In clay environments, the wells need to be closer together; for gravel, they can be farther apart.

The remedial manager must be concerned with the possibility of explosion of collected vapors, which is normally alleviated with an open air valve on the collection line.

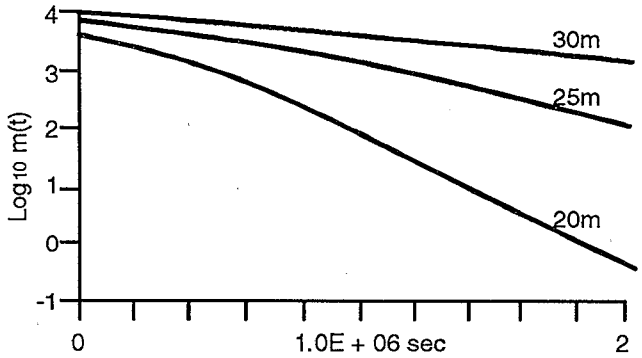

Figure 6-11. Total solute mass in the subsurface vs. time showing the effects of well depth on vacuum extraction effectiveness (Wilson et al., 1989).

Figure 6-11 shows the effects of well depth on the total solute mass with the same axes as in Figure 6-10. The well depth can be considered the distance between the ground water and the end of the well in the vadose zone. In these three examples, the vacuum extraction well was screened 3, 6, and 9 meters above the ground water. The closer the well screening is to the ground water, the more rapid the cleanup of the site. This is because it is easier to pull air downward through the vadose zone to a well screened near the ground water than to pull air upward from a location near the ground water to a well screened near the ground surface. Therefore, when the vadose zone is contaminated from the ground surface to ground water, it is more effective to screen the vacuum extraction system close to the ground water.

6.4 BIOVENTING

Vacuum extraction can enhance biodegradation of volatile and semi-volatile chemicals in the soil by providing oxygen to the soil for use by microorganisms. Larger amounts of oxygen can be supplied per volume of air than per volume of water. This use of vacuum extraction to enhance biodegration is also known as bioventing.

Hill Air Force Base in Ogden, Utah, had a gasoline spill that penetrated the soil to a depth of more than 100 feet. The remedial team decided to apply vacuum extraction, or bioventing, to remove the gasoline, and then incinerate the gasoline once at the surface. At this site, 50 to 60 percent of the cost of vacuum extraction is attributed to aboveground treatment of the vapors. The bioventing system lowered the concentration of jet-fuel in the subsurface, but the remedial team had to add fuel from an outside source to burn the residual fuel they were extracting from the subsurface. The remedial team then began to look at the possibility of degrading the residual vapor phase in the subsurface with microorganisms that would biodegrade fuel constituents including benzene, xylene, and toluene. In this case, they decided to use bioventing to control the residence time of the gas phase in the subsurface. Using bioventing to enhance biological processes significantly reduced the costs of site remediation using aboveground treatment.

When trying to accomplish subsurface in situ remediation of the gas phase, the remedial team found that adding water to the subsurface stimulated CO_2 production and mineralization of the gasoline components. Moisture is important for vacuum extraction, whether it is used as a physical-chemical process or a biological process. Figure 6-12 shows the enhancement of bioremediation of gasoline components using bioventing of soil amended with

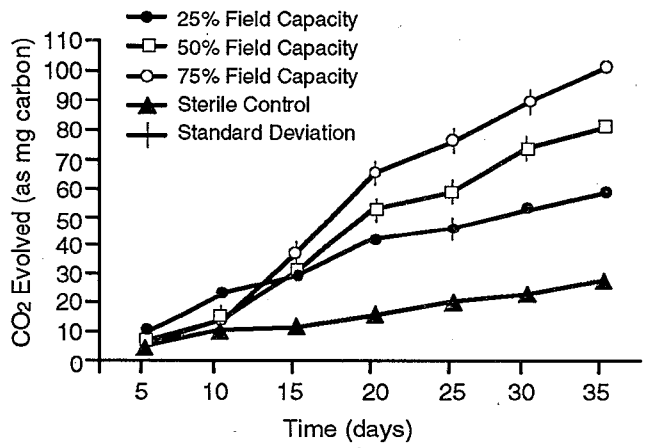

Figure 6-12. Enhancement of bioremediation of gasoline components using vacuum extraction of soil amended with nutrients and moisture (Hinchee, 1989).

nutrients and soil moisture at 25, 50, and 75 percent field capacity. Field capacity is the ability of the field to hold water against the force of gravity. One hundred percent field capacity is the moisture content of a soil 2 to 3 days after a rainfall, when gravity has drained away the water.

Bioventing, using vacuum extraction systems, also can be a very good way to supply oxygen to the subsurface. Vacuum extraction systems not only remove chemicals in the gas phase, but they drag a fluid phase (air) through the subsurface, which is 20 percent oxygen by volume. Figure 6-13 shows the effect of bioventing combined with bioremediation. Because there is a lot of oxygen demand

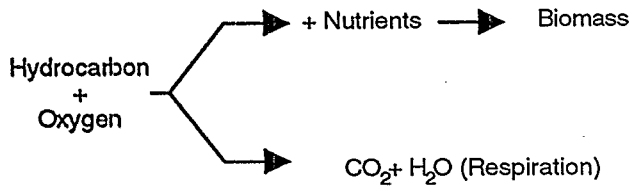

Figure 6-13. Aerobic biodegradation (Hinchee, 1989).

in a contaminated subsurface, the subsurface is often anaerobic. The addition of oxygen and nutrients can stimulate indigenous biomass to degrade hydrocarbons to CO_2 and water.

Table 6-3. Oxygen Supply

	lb carrier/lb O_2
Water	
Air Saturated	100,000
Pure O_2 Saturated	25,000
500 mg/L H_2O_2	10,000
Air	4

Table 6-3 illustrates the amount of water or air required to supply the oxygen necessary to biodegrade hydrocarbons. About 100,000 lb of water, saturated with air, are required to supply 1 lb of oxygen. Also about 4 lb of air are required to biodegrade 1 lb of benzene. Therefore, to degrade 1 lb of benzene, 400,000 lb of water are required to supply the needed oxygen. Since it requires only 4 lb of air to degrade 1 lb of benzene in the subsurface, air is a more efficient way to supply the terminal electron acceptor (oxygen molecule) without increasing leaching potential.

Bioventing systems are composed of hardware identical to that of conventional soil vacuum extraction (SVE) systems, with vertical wells and/or lateral trenches, piping networks, and a blower or vacuum pump for gas extraction. They differ significantly from conventional systems, however, in their configuration and philosophy of design and operation. As indicated above, the primary purpose of a bioventing system is to employ moving air to transfer oxygen to the subsurface where indigenous organisms can utilize it as an electron acceptor to carry out aerobic metabolism of soil contaminants. As such, bioventing system extraction wells are not placed in the center of the contamination as in conventional SVE systems, but on the periphery of the site (Figure 6-14), where low flow rates maximize the residence time of vent gas in the soil to enhance in situ biodegradation and minimize contaminant volatilization.

Because it is a biological treatment approach, however, bioventing does require the management of environmental conditions to ensure maintenance of bioactivity at the site. Management of soil moisture and soil nutrient levels to avoid inhibition of microbial respiration within the vadose zone can be accomplished fairly easily, and have been used to optimize contaminant biodegradation at field sites when other variables, i.e., toxicity, do not limit microbial activity.

Cyclic or "surge" pumping of vent systems may minimize system operating costs. Surge pumping in a bioventing

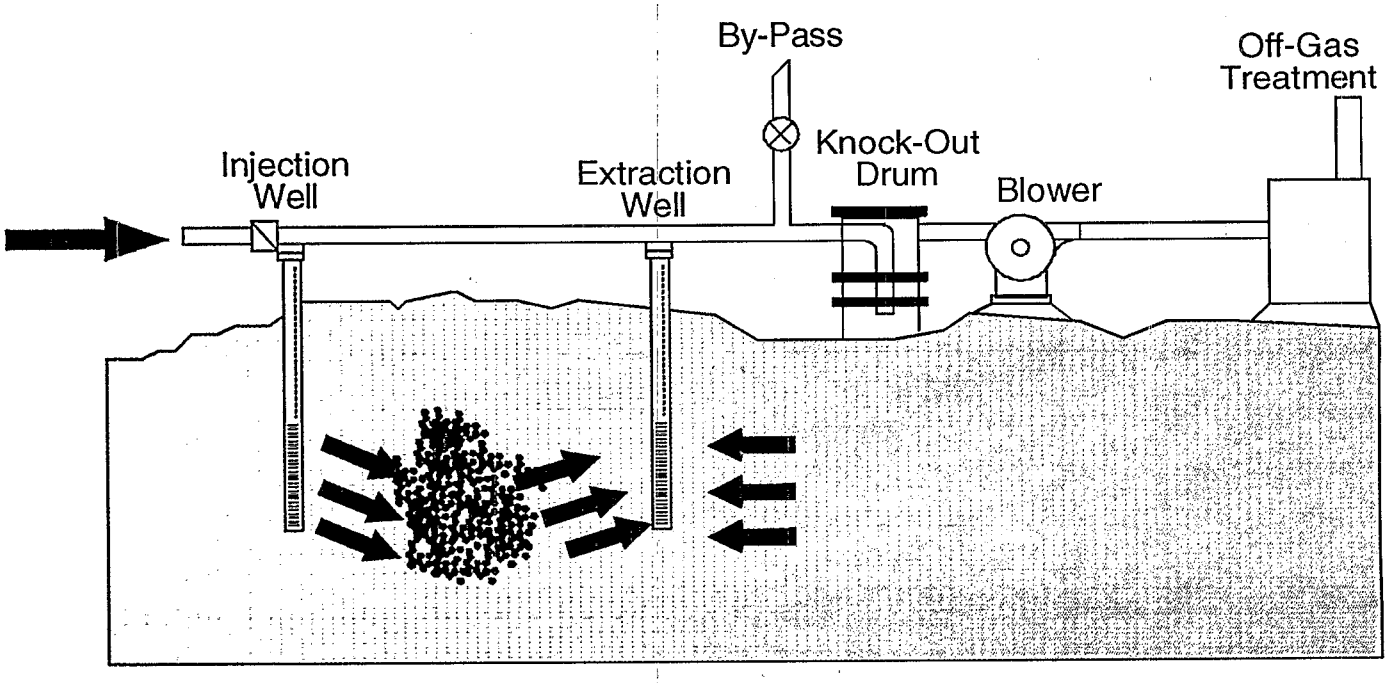

Figure 6-14. Schematic of recommended bioventing system layout.

mode entails operating the blower system until soil gas oxygen levels reach near ambient conditions throughout the site being remediated. The system then would be shut off for some period of time during which soil-gas oxygen concentrations would be routinely monitored until they reach a level that inhibits aerobic microbial activity. Once this limiting soil-gas concentration is reached, the vent system would be restarted, and the on-off cycle would continue once again. Based on a Henry's Law constant for oxygen, this oxygen limitation would be expected to occur at a soil-gas concentration of approximately 2.0 volume percentage, corresponding to soil water oxygen concentrations of approximately 1 mg/L. An inhibition of soil respiration has been reported at the 2.0 volume percentage soil oxygen level in venting systems treating jet fuel contaminated soils and in vented soil piles contaminated with PCP waste (McGinnis, 1992), suggesting that this value represents a good operating number for field-scale applications.

The two major design considerations for bioventing systems are 1) whether the contaminants of concern are biodegradable under prevailing site conditions, i.e., whether inhibition or toxicity is evident at the site, and 2) whether the required terminal electron acceptor, i.e., oxygen, can be effectively transported within the soil to encourage aerobic contaminant biodegradation. The first question can be answered using soil-gas composition and in situ respiration measurements, while the second question is answered from in situ air permeability measurements.

Bioventing system design today can be carried out by estimating the equivalent daily oxygen demand and vent airflow rate as determined from in situ respiration measurements, and by estimating pump operating conditions at these required air flow rates based on field-determined in situ air permeability measurements. The feasibility of surge pumping and vacuum pump/blower scheduling can be assessed based on required versus maximum oxygen transfer rates possible under a given set of field and pump/blower operational constraints.

6.4.1 Application of Bioventing

Figure 6-15 is a diagram of the Hill Air Force Base site showing the O_2 concentration in the air phase with depth near a vacuum extraction well. Wells were installed to depths of 50 to 70 feet. The chemicals at Hill Air Force Base, a jet fuel spill, have a high vapor pressure, and thus tend toward being in the air phase. Site characteristics show that the soil texture is a sandy material. As discussed previously, vacuum extraction was used as a method of remediation. Vacuum extraction pulled out 80 percent of the benzene, xylene, and toluene. When the chemicals reached such low concentrations that the incinerator had to be supplemented with an external supply of fuel, the remedial team shut off the system and began

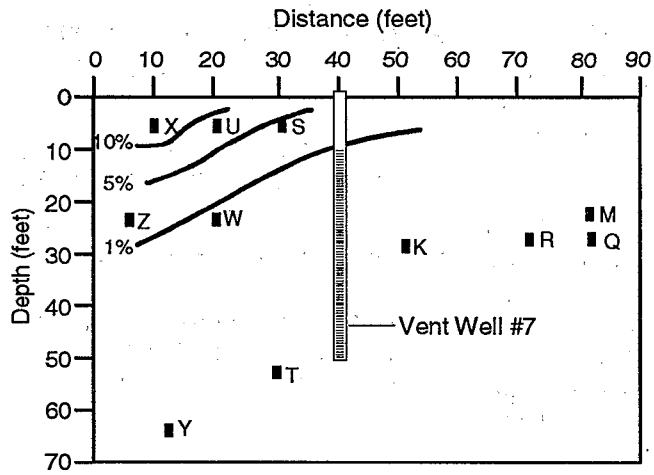

Figure 6-15. Oxygen concentration in vadose zone before venting (U.S. EPA, 1989).

considering the use of vacuum extraction to supply oxygen to the subsurface.

Before venting was initiated, the oxygen concentration was 10 percent at 10 feet below the surface, 5 percent at 20 feet below the surface, and 1 percent at 30 feet (Figure 6-15). After initiating bioventing, the oxygen went up to 15 percent at 10 feet and 10 percent at 20 feet (Figure 6-16). Even at depths of 60 and 70 feet there was

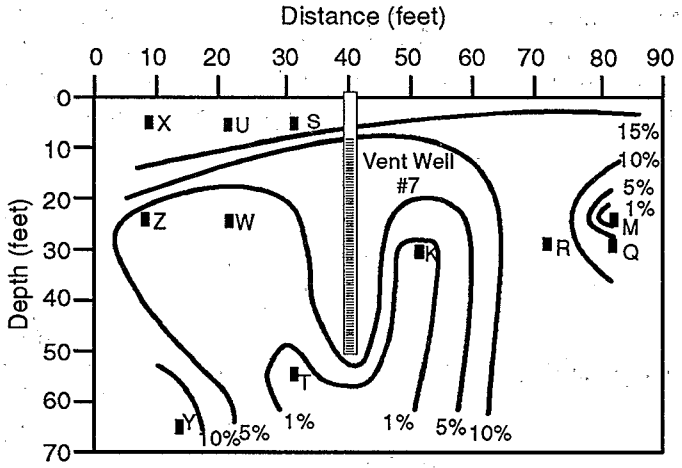

Figure 6-16. Oxygen concentration in vadose zone after venting (U.S. EPA, 1989).

10 percent oxygen in the soil. This process of adding oxygen using vacuum extraction combined with increasing the soil moisture content to 75 percent field capacity enhanced biological remediation. Bioventing was observed to reduce the volatile organic contaminants in the vapors off the surface to less than 20 ppm. (The State of Utah cleanup level was 50 ppm.) So, in this example, vacuum extraction was part of a treatment train, where it

was used first as a physical-chemical process and then to augment biological processes. In the first case, the process extracted the chemical and destroyed it above ground, and in the second case the chemical was destroyed in situ through biodegradation.

There is very little temperature change below 20 or 30 feet because the soil acts as a temperature buffer. In hot climates, however, there may be changes in the temperature in the subsurface at 6 or 8 feet, which will augment volatilization. Sometimes injecting steam will increase the temperature for several feet, but, because of the buffering capacity of the soil, significant and continuous energy input to the subsurface is required to sustain this effect.

6.4.2 Monitoring

Hill and Tyndall Air Force Bases were monitored by measuring oxygen concentration with an oxygen probe and carbon dioxide using a CO_2 probe. Figure 6-17

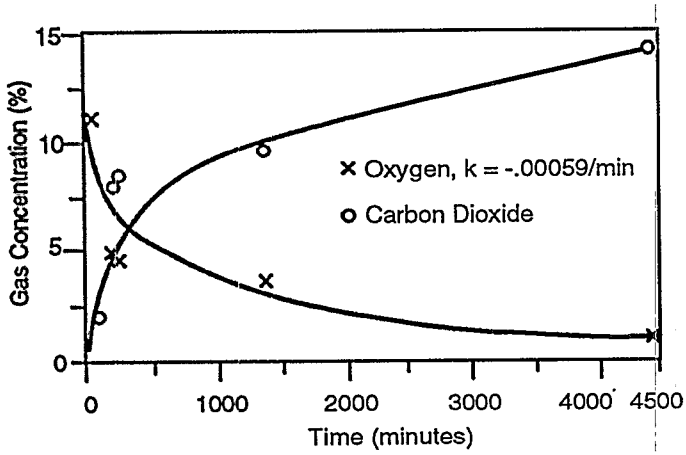

Figure 6-17. The increase in CO_2 and decrease in oxygen as a result of degradation of the jet fuel components (U.S. EPA, 1989).

shows the increase in CO_2 and decrease in oxygen as a result of degradation of the jet fuel components. The vacuum extraction well was shut off, and the parameters were measured. Oxygen depletion indicates biodegradation, and an increase in CO_2 production indicates mineralization. Ultimately, when the hydrocarbon is removed by biodegradation, these lines (Figure 6-17) will flatten out because oxygen is no longer being produced. When this flattening occurs (meaning that biological activity has slowed down), it is an appropriate time to sample a soil core and determine if the hydrocarbons in the core have been removed. If hydrocarbons are still present, even after biological activity has slowed or ceased, the process probably needs more oxygen, moisture, and nutrients.

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APPENDIX A
Case Studies

This appendix contains brief summaries of selected case studies presented at the U.S. EPA's RCRA Corrective Action Conference, held February 25-27, 1992. The case studies were presented by EPA staff, consulting engineers, and private industrial representatives. They examined RCRA stabilization efforts that illustrate experience with key stabilization techniques, technologies, and concepts. Three of the case studies represented were selected for inclusion in this document to elaborate on the application of stabilization strategies at RCRA Corrective Action facilities. Unfortunately, it was not possible to include all of the presentations in this document.

Each case study in Appendix A contains three parts:

- **Introduction.** The statement of problems; descriptions of waste management units requiring stabilization; site descriptions including history, topography, geology, and hydrology; pre-RCRA activities; and/or contaminant releases including those across media and site boundaries.
- **Stabilization Strategies.** The stabilization action rationale, the spectrum of strategies considered, and/or the selected strategies with their constraints.
- **Implementation and Future Actions.** Stabilization action design criteria, construction, timing, and/or system operations.

A.1 GROUND-WATER CONTAMINATION STABILIZATION WITH LNAPL COLLECTION SYSTEM: JAMESTOWN, NY, by Frank Gardner, U.S. EPA, Region IX, San Francisco, CA

A.1.1 Introduction

This case study covers the selection, design, construction, and operation of a light non-aqueous phase liquid (LNAPL) collection system for the stabilization of contaminated ground water at a former industrial site in Jamestown, New York. This project was conducted from July 1989 to August 1990. The LNAPL collection system consists of a subsurface trench with a network of perforated and corrugated metal pipes installed at the oil-water interface. LNAPL is periodically or continuously vacuumed, pumped, or skimmed from system manholes.

The case study illustrates the use of an interim measure to stabilize subsurface contamination by removing LNAPL (the contamination source) from the ground-water contamination plume. The system selected was designed for integration into the final ground-water contamination remedy.

The formerly industrial site of this case study is presently municipally owned. The city discovered subsurface contamination during the initial stages of constructing a parking lot. Upon discovery of the contamination, the city stopped construction, contacted regulatory agencies, and conducted a preliminary hydrogeologic investigation. The investigation confirmed contaminated soils and ground water, and #6 fuel oil (the LNAPL) floating on the water table. The #6 fuel oil was thought to be spilled product, as opposed to spilled waste, due to the lack of heavy metals or other contaminants.

The LNAPL is contained by a remnant building foundation. While LNAPL migration has stopped, it continues to contaminate ground water below, which flows under the foundation. The several remedies considered include extraction wells with submersible or dual phase pumps, open trenches, and subsurface trenches. Subsurface trenches were selected based on:

- Site hydrology
- Nature of the contamination
- Limited financial resources
- Compatibility with a long-term remedy
- Compatibility with the planned use of the site

A.1.1.1 Site Background

The case study site is in Jamestown, New York, about 80 miles southwest of Buffalo. The site is located in an industrial/commercial sector of the city about 250 feet from the north bank of the Chadakoin River, which flows from Chautauqua Lake. The site is located at the base of a hill from which the land slopes down towards the eastwardly flowing river. The Chadakoin River is used only for recreation, not for drinking water. Ground water on the site flows towards the river, and, while not presently used, is protected as a potential drinking water source.

The history of the 1.9-acre site includes the following major elements:

- Prior to 1902, the site was probably undeveloped or agricultural.
- From 1902 to 1984, the site contained a tool factory that manufactured adjustable wrenches.
- After 1984, the site was used for a metal fabricating operation and then donated to the city. The city proposed to construct a municipal parking lot after demolishing the buildings.
- In 1989, during the construction of a storm sewer for the proposed parking lot, the city found subsurface petroleum contamination.

Upon discovery of contamination, appropriate regulatory agencies, including the New York Department of Environmental Conservation (NYDEC), were contacted and an investigation was initiated.

A.1.1.2 Site Hydrology

During the hydrogeologic investigation, five soil boring/ground-water monitoring wells (MW-1 through MW-5) were installed to characterize site hydrology and assess the extent and nature of the subsurface contamination. The depth of the borings ranged from 14 to 16 feet, and ground water was encountered 3 to 10 feet below the soil surface. The shallow soils beneath the site consisted of surficial silt and sand fill overlaying a native gray medium clay formation with traces of silt and sand. In two of the borings, peat was found between undisturbed clay and fill materials. Since peat commonly occurs in the region, it may be found throughout the site.

Ground water flows primarily to the south toward the Chadakoin River; however, this overall flow pattern is affected by remnant foundations from the tool plant in the site's subsurface. The ground water flows under the foundations. The overall difference in ground-water elevation across the site is about 9.4 feet, which corresponds to a gradient of 0.031 ft/ft. Due to the site's proximity to the river, however, it is possible that the direction of ground-water flow is reversed during flood periods. This phenomenon has been observed in similar sites nearby, but has not been confirmed at this site.

A.1.1.3 Nature and Extent of Contamination

During the installation of the soil borings, soils heavily contaminated with total petroleum hydrocarbons (TPH) identified as #6 fuel oil were found the entire depth of MW-2. MW-2 was located within the former tool plant foundation and near the location where contamination was first discovered. The other four borings, all outside the underground foundation, did not detect contaminated soils.

The borings were developed into monitoring wells, after which ground-water samples were taken to determine the extent of contamination. TPH ranging from 190 to 920 micrograms per liter (ppb) was detected in all five wells and was identified as #6 fuel oil. In addition, LNAPL consisting of #6 fuel oil was discovered in MW-2. The quantity of LNAPL is estimated at 5,000 to 10,000 gallons. The source of the LNAPL is believed to have been underground fuel oil storage tanks or floor drains at the former tool plant.

Prior to December 1989, volatile organic analysis of MW-2 detected ethylbenzene and xylenes in the ground water. In December 1989, five additional monitoring wells (MW-6 through MW-10) were installed to better define the lateral extent of the ground-water contamination within the foundation area. In January 1990, all 10 wells were sampled for VOCs, confirming the presence of ethylbenzene and xylenes in MW-2, MW-7, and MW-8, all within the foundation area. None of the other well samples contained VOCs. The concentrations detected are listed in Table A-1.

Table A-1. VOC Concentrations in the Foundation Area

VOC	Concentration	MCL*	SMCL**
Ethylbenzene	300 µg/L	700 µg/L	30 µg/L
Xylenes	170 µg/L	10,000 µg/L	20 µg/L

* EPA Maximum Contaminant Level
** EPA Secondary Maximum Contaminant Level

As the table indicates, site concentrations of ethylbenzene and xylenes were below the Maximum Contaminant Levels (MCLs) but above the Secondary Maximum Contaminant Levels (SMCLs). Other analyses, such as the EP Toxicity test for metals and PCBs, did not reveal any additional contaminants in the soil or ground-water samples.

A.1.2 Stabilization Strategies

A.1.2.1 Remedial Options

While no operational drinking water supplies are near the site, the NYDEC requires protection of potential ground-water uses. The NYDEC required the city to install an interim remedial system to remove the LNAPL from the water table, predicated on the city's willingness to implement more complete ground-water remediation if required in the future. The corrective action was required to contain and remove the LNAPL. The four interim remedial options included:

- Extraction wells with submersible pumps
- Extraction wells with dual phase pumps
- Open trenches
- Subsurface trench systems

Extraction wells with submersible pumps remove the LNAPL and the ground water together by creating a gradient towards the well for both liquids. An oil/water separator separates the two before disposal. Extraction wells with dual phase pumps are able to pump LNAPL and ground water separately and simultaneously. Dual phase pumps eliminate the need for oil/water separators and the risk of emulsifying oil in water, but they are more expensive to buy and maintain than are submersible pumps.

Open and subsurface trenches recover oil by providing a conduit of negligible hydraulic conductivity enabling vacuuming, skimming, or pumping of the oil. Both types of trenches use similar excavations. Subsurface trenches, however, are backfilled with high permeability materials, such as gravel or perforated drainage pipes, so they can be covered with soil. Trenches are technologically simpler, less costly to operate and maintain, and more effective on soils with low hydraulic conductivity than are extraction wells. Disposal costs for contaminated excavated soils, however, can dramatically increase total costs for both options.

A.1.2.2 Interim Measure Selection

A number of physical, financial, and logistical constraints were considered in selecting the appropriate remedial option for stabilizing this site, including:

- Site hydrogeology
- Nature of the contamination
- Available financial resources
- Compatibility with a long-term remedy
- Compatibility with the site's long-term use

Based on an analysis of these factors, the subsurface trench was selected because it was the only option to satisfy all five constraint categories. These factors are summarized in Table A-2 and the paragraphs below.

Table A-2. Impact of Constraints on Remedial Alternatives

	REMEDIAL ALTERNATIVE			
Constraint	Extraction Well/Submersible Pump	Extraction Well/Dual Phase Pump	Open Trench	Subsurface Trench
Hydrogeology	✗	✗	✗	✗
Contamination			✗	✗
Cost			✗	✗
Long-Term Compatibility	✗	✗	✗	✗
Planned Site Use Compatibility	✗	✗		✗

Site Hydrogeology

All four options are compatible with the site hydrology. The native geology of the site consists primarily of a low-permeability clay formation. The clay overlays fill in some areas of the site which were probably former building sites. Trench systems, with larger wetted perimeters, are more effective than extraction well systems for low-permeability soils. Properly designed extraction wells, however, also can be effective for these soils.

Nature of the Contamination

The recovery target LNAPL is #6 fuel oil, which is fairly viscous and much less mobile than water in the soil media. The best suited remedy would address a large horizontal collection area to compensate for the relatively immobile LNAPL. This factor favored the trench options because trench systems are inherently suited to cover a large horizontal area. Extraction wells, in contrast, rely on drawing contaminants toward the well and would not be as effective for this LNAPL.

Available Financial Resources

The city is relatively small with limited financial resources. Clearly, the trench system is less expensive. Estimated costs for the trench system are from $45,000 to $60,000. The trench options also allowed for removal of the LNAPL without the water, which reduced waste volume and associated disposal costs. These low estimates are partially due to the presence of tight clay soils, which make sheeting and shoring (a significant component of trench system costs) largely unnecessary. Also, the soil turned out to be nonhazardous. If it had been hazardous, the trenches, which require more voluminous excavations than do wells, would have incurred much higher costs.

Estimated costs for the extraction well system are from $98,000 to $160,000. These estimates are based on using the local publicly owned treatment works (POTW) for ground-water disposal. If the POTW were not available, then costs would be much higher.

Compatibility with a Long-Term Remedy

The state indicated that the final corrective action remedy will include some comprehensive ground-water treatment. Both extraction wells and trench options are compatible with long-term remedies, since both are able to accommodate pumping large volumes of ground water. Extraction wells are easily upgraded into long-term remedies with the addition of more extraction wells. Similarly, well-constructed and -located trenches of sufficient depth are well suited for extracting large quantities of ground water.

Compatibility with the Site's Long-Term Use

A parking lot is the planned use for the site. The extraction well and closed trench options are both compatible with this use, while an open trench cannot coexist with a parking lot.

A.1.3 Implementation and Future Actions

A.1.3.1 Design and Construction

The trench system consists of a network of perforated and corrugated pipe (CMP), underlain and backfilled with crushed stone, with two access manholes. The most important design parameter to effectively remove LNAPL from ground water is the burial depth of the CMP. If the centerline for the CMP is not at the oil/water interface, then the trench system could be ineffectual. Other important design parameters include pipe layout pattern, pipe diameter, perforation size, and backfill type.

The elevation of the oil/water interface at three monitoring wells varied temporally and spatially between 1,289 and 1,295 feet above sea level. It was assumed that the water table would equilibrate to a single elevation within the pipe. Therefore an intermediate elevation of 1,291.5 feet above sea level was selected.

The main trunk of the CMP network was configured to intercept the LNAPL plume along the entire downgradient (southern) edge. The remnant foundation was left to serve as a downgradient barrier. Two lengths of CMP were also installed as branches, perpendicular to the trunk, to facilitate LNAPL collection from the central area of the plume. Manholes, consisting of vertically placed sections of 6-foot diameter CMP, were installed at the two intersections for access and LNAPL removal. The manhole inverts were set 2.5 feet lower than the CMP invert to accommodate water table drawdown from possible future remediation involving ground-water extraction. In addition, the manholes have locking covers and concrete aprons at ground level to accommodate parking lot vehicular traffic loads.

The selected CMP diameter of 3 feet provides a large surface area and encompasses the range of temporal water table variation while keeping the size of the excavation within reasonable width. The chosen perforation size of 0.25 inches, coupled with crushed stone backfill between 0.5 and 1.0 inches, prevents the backfill from entering the CMP network. The CMP is underlain with 1 foot of crushed stone and backfilled with 6 feet of the material.

The high hydraulic conductivity of the crushed stone provides a margin of safety for the system. That is, if the oil/water interface rises or falls below the CMP due to natural changes or ground-water extraction, then the system will still function.

The LNAPL collection system was constructed quickly during a 3-week period in August 1990. The project was uneventful except for field modifications in system layout due to the unexpected discovery of additional subsurface concrete structures. The additional subsurface structures, which included an interior wall foundation and a very large machine pedestal, caused the pipe layout to contain more zigzags than planned. The interior foundation was breached to allow the CMP network to pass through and collect the LNAPL in that area, and the layout was modified to go around the machine pedestal. Construction costs, including the field modifications, totaled about $50,000.

A large quantity of contaminated soil was excavated during construction. Based on the TCLP analysis, the soil was not hazardous waste and was disposed of in a local solid waste landfill for $27,000. If the soil had been classified as RCRA-hazardous waste, then the project would have incurred an additional $50,000 in disposal costs.

Construction costs totaled $77,000. The city constructed a parking lot immediately after completion of the LNAPL collection system. Parking lot paving ensured access to the two manholes and monitoring wells.

A.1.3.2 System Operation

The system is designed to recover LNAPL either on an occasional basis by a vacuum truck or on a continuous basis using skimming technology. The city chose the vacuum truck based on the negligible startup costs. The truck vacuums up a significant amount of water (50 to 75 percent water) along with the oil, however, unnecessarily increasing the volume of waste requiring disposal and the associated costs. Last year the truck collected 500 gallons of oil and water, which cost $250 (or $0.50 per gallon) to dispose of. Consequently, the city is pursuing installation of a skimming system.

The city is likely to choose an oleotrophic rope skimmer to remove the LNAPL from the water surface without removing any water. Collecting dramatically decreases both the volume and consequently the disposal costs. This type of skimmer has been used successfully at similar sites, and the skimmer manufacturer guarantees its performance.

Ground-water remediation will probably be required as a long-term solution.

A.1.4 Conclusions and Discussion

Although this facility is not a RCRA or CERCLA site, the interim measure selection and implementation were consistent with the goals of the RCRA Stabilization Initiative. Once the contamination was identified, interim measures were applied to stabilize the subsurface contamination by removing the LNAPL. This provided time to more completely characterize the site and to determine the necessity of long-term ground-water remediation. Several interim measures were analyzed based on technical, lo-

gistical, and cost criteria. The subsurface trench system was selected due to the clay geology, the LNAPL's relatively immobile nature, the low estimated cost, and compatibility with potential long-term remedies and planned use for the site. The system has operated since September 1990 and was constructed for about $77,000.

A.2 LANDFILL STABILIZATION: BFI SOLLEY ROAD FACILITY, GLEN BURNIE, MD, by Dennis Zielinski, U.S. EPA, Region III, Philadelphia, PA

A.2.1 Introduction

Browning-Ferris Industries (BFI) owns and maintains a 65-acre closed landfill on Solley Road in Anne Arundel County in Glen Burnie, Maryland (see Figure A-1). The site is located approximately 3 miles south of Baltimore and approximately 2 miles east of Glen Burnie, in the south-central portion of Marley Neck peninsula (see Figure A-2). The peninsula is bounded on the west by Marley Creek, on the east by Stony Creek, and on the north by Curtis Bay. The areas north and west of the site are generally considered wetlands. The site was used for the disposal of both hazardous and nonhazardous municipal and industrial waste from 1963 until 1982.

The area surrounding the site is sparsely populated and zoned for light industry. It is estimated that approximately 750 people live within 1 mile of the site. Only 20 of these people live northwest of the site. This is fortunate because the contamination plume is moving in that direction. Residential development within the area has remained scattered, with very few residences found north

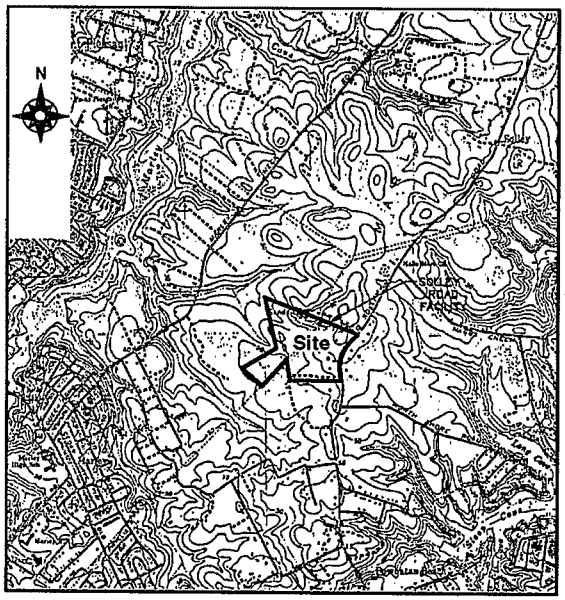

Figure A-1. Location of case study site, Browning-Ferris Industries (BFI) landfill.

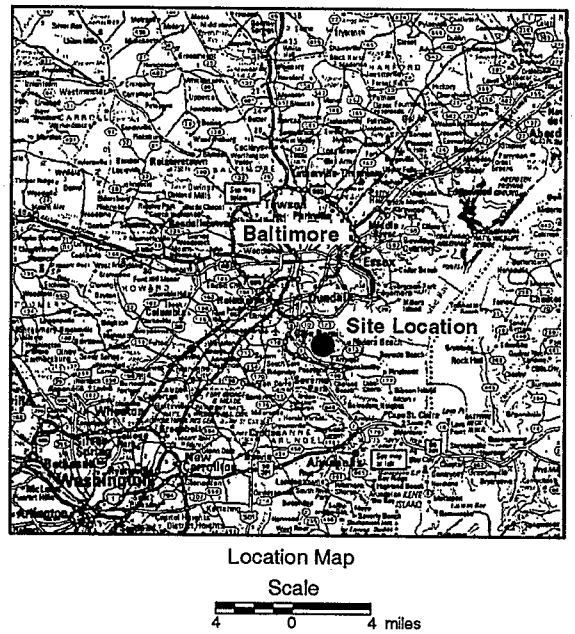

Figure A-2. BFI landfill site in relation to Baltimore and Glen Burnie, Maryland.

and west of the site. Private drinking water wells are not located in close proximity to or downgradient of the site.

Stabilization is being performed in lieu of waiting 2 to 3 years for a full-scale corrective action. The stabilization action, which is a cooperative effort among EPA, the State of Maryland, and BFI, is still in the preliminary stages of review for BFI's proposed plans.

The following subsections discuss the site's solid waste units, geology and topography, ground-water contamination, regulatory chronology, and risk.

A.2.1.1 Solid Waste Management Units

The Solley Road site was developed as a sanitary landfill in the early 1960s by the former owner of the site. BFI purchased the site in 1973.

The site consists of four SWMUs: two closed landfills with leachate collection systems and two sedimentation ponds. The landfills are divided by overhead electrical transmission lines, with a 120-foot wide right-of-way running in a north-south direction.

The site received mostly municipal refuse, and had an East Fill and a West Fill. The East Fill, the area first developed as a landfill, lies in the northern portion of the area east of the right-of-way. The West Fill, a triangular shaped fill located west of the right-of-way, was the second area to receive waste at the site, and accumulated the majority of the volume. This case study focuses on the West Fill, which was closed in late 1977.

A permitted "Active Cell" within the East Fill started operating in July 1980 as a secure hazardous waste dis-

posal site. This cell occupies 8 acres in the southern portion of the East Fill. The rest of the East Fill was closed in 1980 and did not receive municipal wastes after the "Active Cell" was opened. The entire site was closed on December 31, 1982.

In 1990, BFI installed a leachate collection system in the southernmost section of the East Fill. The leachate is carried by double-lined pipes on the ground to an underground double-lined tank, which stores the leachate for less than 90 days. Monitoring systems in the outside piping and tank walls will detect a release. The material in the tank is pumped weekly to a tank truck and transported by a licensed hazardous waste transporter to an approved hazardous waste facility.

The West Fill was not designed or constructed with a leachate collection system, since operations at the West Fill predated regulations requiring these systems. The West Fill, however, does have a well system that collects leachate. Leachate is pumped directly from the wells to a tank truck, which takes the leachate to an approved facility.

Rain water runoff from the site is collected in a sedimentation pond located south of the West Fill. The rainwater runoff may contain contaminants from the landfills as a result of erosion of the landfill covers. There is no evidence that hazardous wastes, or hazardous waste constituents, have been released from the permitted hazardous waste cell to the ground water, surface water, or the land surface.

A.2.1.2 Geology and Topography

BFI's Solley Road site is situated on an outcrop of the Patapsco Formation, which is a multilevel aquifer system consisting of water-bearing sands alternating with confining beds of clay or interbedded clays, silts, and sands. The surficial soil is a red clay, silt and interbedded clay, and silt and sand (see Figure A-3). It is approximately 80

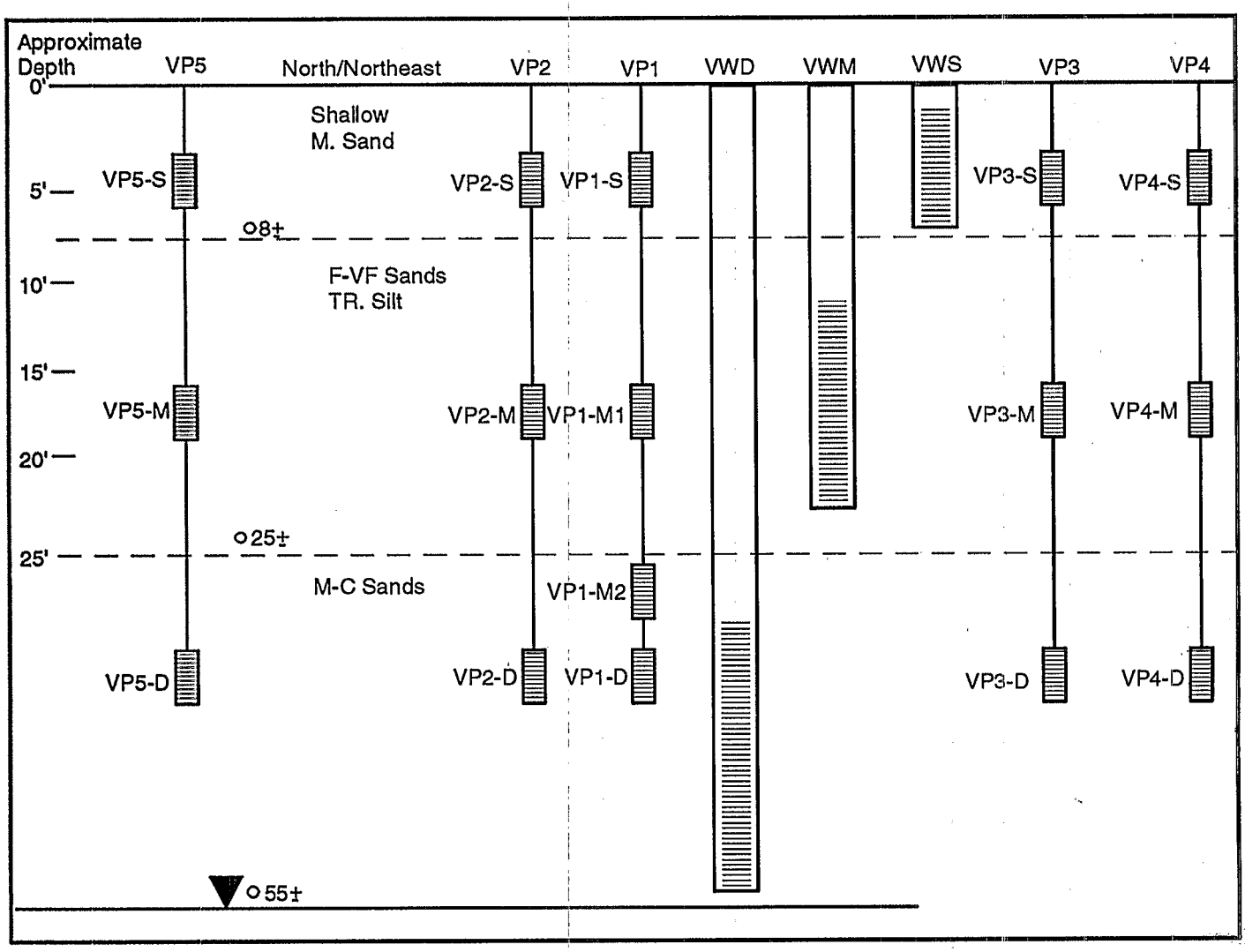

Figure A-3. Soil geology of the site showing clay, silt and interbedded clay, and silt and sand.

to 100 feet thick along the eastern boundary of the site, and thins to less than 20 feet in the western portion of the site. Contact between the overlying clay and underlying sands of the upper portion of the Patapsco Aquifer is well defined at the eastern portion of the site, but becomes transitional towards the west. A second semi-continuous zone of clay or interbedded clay, silt, and sand separates the upper portion of the aquifer from the middle. A similar sequence of clay or interbedded clay, silt, and sand separates the middle and lower portions of the Patapsco Aquifer.

In general, ground water flows to the north and west at approximately 8 to 10 feet per year. The Patapsco Aquifer is the first continuous water-bearing zone underlying the site. The top of the Patapsco Aquifer beneath the site varies from 10 feet above mean sea level to 30 feet below mean sea level.

A.2.1.3 Ground-Water Contamination

The site has two contamination plumes, both located near the West Fill, one in the upper Patapsco Aquifer and the other in the middle Patapsco Aquifer. The contaminated plume in the upper Patapsco Aquifer begins on the west side of the West Fill and is approximately 1,000 feet along the fill and 700 feet to the west of the fill. The total VOCs isoconcentration contours range from 5 to 1,000 ppb. The plume in the middle Patapsco Aquifer is approximately 1,200 feet along the west side of the West Fill and 200 feet west of the fill. The total VOCs isoconcentration contours range from 5 to 500 ppb. The plumes have not changed significantly since 1985, but they have migrated.

The water quality analyses of samples taken in June and December 1989 indicated that the contaminants in the plume consisted of VOCs, including aromatics and chlorinated aliphatics. Of the 15 chemicals of concern, 5 had concentrations greater than the MCL (see Table A-3).

One important difference between the June and December samplings was that in December the farthest well in the northwest location showed VOCs for the first time.

Table A-3. Contaminants with Concentrations Greater Than the MCL

Contaminant	Number of Multiples of the MCL Measured by the Highest Sample on 6/89	Number of Multiples of the MCL Measured by the Highest Sample on 12/89
1,1-DCE	5	NA
Trans-1,2-DCE	8	10
Vinyl Chloride	20	50
Benzene	100	65
TCE	1,300	80

This might be due to continued slow migration of contaminants from the site. Table A-4 summarizes the results of water quality analyses of samples taken in June and December 1989.

A.2.1.4 Risk — Current/Potential

There is no immediate human health threat at this site. The contamination plume is moving towards the Marley Neck Creek, which feeds into the Patapsco Aquifer and then into the Chesapeake Bay. BFI has performed a public health assessment of the Solley Road site and assessed the "potential" risk posed by possible future exposure to the chemicals of concern in ground water, surface water, and/or sediments. They assessed "potential" exposure because none of the chemicals of concern have been detected in any residential well. Human exposure to surface water and sediment is not known to have occurred.

From past sampling, the 15 chemicals listed in Table A-4 were identified as the chemicals of concern. In addition, chromium also was considered a chemical of concern in sediments and surface water. Fifteen downgradient wells were used to determined the average concentrations of the chemicals. Then the wells were grouped into three zones based on their distance from the northern and western boundaries of the landfill. Zone 1 wells are less than 100 feet from the landfill; zone 2 wells are 100 to 600 feet from the landfill; and zone 3 wells are greater than 600 feet from the West Fill.

Of the 15 organic chemicals of concern, only benzene, chloroform, trichloroethene (TCE), and vinyl chloride are potential carcinogens. Table A-5 lists lifetime carcinogenic risks, using conservative concentrations posed by average intake from all routes of exposure, of these chemicals in the ground water.

Acceptable Intakes for Chronic Exposure (AICEs) were used to assess the noncarcinogenic risks posed by hypothetical intake of the chemicals of concern. The total intake/AICE value for a particular chemical was used to assess the potential for toxic effects. Total intake/AICE values less than 1 indicate that the level of intake would not adversely affect human health. Table A-6 summarizes total intake/AICE values for an adult, using conservative concentrations.

The noncarcinogenic risks due to intake of chromium from wading and ingestion were very low. Values for total chromium intake/hexavalent chromium reference dose (RfD) and total chromium intake/trivalent chromium RfD are 3.48×10^{-3} and 1.74×10^{-5}, respectively, indicating that adverse health effects should not result from the chromium intake level calculated for the average 10-year-old child for either species of chromium.

In summary, the conservative analysis of the carcinogenic and noncarcinogenic risks posed by hypothetical expo-

Table A-4. Summary of Sampling Data on VOC Concentrations (ppb)

Compound	Number of Wells w/VOCs*	Range	MCL
June 1989			
Acetone	1	56	3,500[1]
4-Methyl-2-pentanone (MIBK)	2	35-83	1,800[1,2]
Benzene	8	4-470	5
Toluene	8	4-33	1,000
Ethyl Benzene	2	10-12	700
Xylenes	13	8-37	10,000
Chloroform	1	5	100
Trichlorofluoromethane	0	N/A	1,800[1]
1,1-Dichloroethane (1,1-DCA)	1	6	580[1]
Vinyl Chloride	3	24-37	2
1,1-Dichloroethene (1,1-DCE)	2	38-40	7
Trans-1,2-DCE	6	3-830	100
Trichloroethene (TCE)	13	4-640	5
Chlorobenzene	0	N/A	100
1,1,1-TCA	0	N/A	200
December 1989			
Acetone	0	N/A	3,500[1]
MIBK	0	N/A	1,800[1,2]
Benzene	3	15-340	5
Toluene	4	5-23	1,000
Ethylbenzene	1	2	700
Xylenes	2	9	10,000
Chloroform	0	N/A	100
Trichlorofluoromethane	0	N/A	1,800[1]
1,1-DCA	3	6-11	580[1]
Vinyl Chloride	1	96	2
1,1-DCE	1	2	7
Trans-1,2-DCE	10	2-970	100
TCE	17	3-380	5
Chlorobenzene	0	N/A	100
1,1,1-TCA	3	2-6	200

[1] No MCL, the health-based concentration in drinking water exists. Using the health-based concentrations, no adverse health effect would be expected if individuals were to drink 2 liters per day of water containing any single one of the VOCs shown at levels indicated.
[2] Health-based limit for methyl ethyl ketone, not 4-methyl-2-pentanone.
* 37 total wells

sure to the chemicals of concern indicates low lifetime risk for receptors using ground water in zones 2 and 3. Lifetime cancer risks posed by hypothetical lifetime exposures to benzene, chloroform, TCE, and vinyl chloride in zone 1 exceeded the upper bound of the EPA acceptable risk range.

Table A-5. Summary of Carcinogenic Risks

Chemical	Zone	Risk
Benzene	1	1×10^{-4}
Benzene	2	6×10^{-8}
Chloroform	1	1×10^{-7}
TCE	1	7×10^{-5}
TCE	2	3×10^{-5}
TCE	3	1×10^{-5}
VC	1	2×10^{-3}
Total Risk	1	2×10^{-3}
Total Risk	2	3×10^{-5}
Total Risk	3	1×10^{-5}

Table A-6. Summary of Noncarcinogenic Risks

Chemical	Zone	Total Intake/AICE
Acetone	1	3.44×10^{-4}
Chloroform	1	5.86×10^{-4}
1,1-DCA	1	6.44×10^{-4}
1,2-DCE	1	1.48×10^{-1}
1,2-DCE	2	2.07×10^{-2}
1,2-DCE	3	1.17×10^{-2}
Ethylbenzene	1	1.35×10^{-3}
Isophorone	1	5.44×10^{-3}
MEK	1	2.24×10^{-3}
MIBK	1	9.08×10^{-3}
Naphthalene	1	2.70×10^{-5}
Toluene	1	1.39×10^{-3}
Toluene	2	1.24×10^{-5}
1,1,1-TCA	1	1.76×10^{-4}
1,1,1-TCA	2	1.61×10^{-4}
Xylene	1	7.00×10^{-5}
Sum of intake/AICE	1	1.69×10^{-1}
Sum of intake/AICE	2	2.08×10^{-2}
Sum of intake/AICE	3	1.17×10^{-2}

A.2.2 Stabilization Strategies

Due to the many studies performed over the years, BFI felt confident that it accurately characterized the ground-water contamination. BFI wanted to limit or delay further study and proceed with a pump-and-treat measure. They requested a permit modification under 40 CFR Section 270.42 to incorporate the stabilization measure into their permit. The permit requires posting of signs, regular inspections of fences, maintenance of covers, verification investigation, a RCRA Facility Investigation (RFI), a Corrective Measures Study (CMS), and initiation of corrective measures. If the stabilization effort is effective in reducing ground-water contamination, then BFI wants it to become the final corrective measure.

The following subsections discuss various aspects of the pump-and-treat strategy, including an overview, extraction

well data, air stripper description, reinjection well location, leachate collection system design, and monitoring system setup and operation.

A.2.2.1 Pump-and-Treat Stabilization Measure — Overview

BFI has submitted a Remedial Engineering Plan to the State of Maryland and EPA for approval. This plan is currently under review by both regulatory agencies. This plan is designed to stabilize the ground-water contamination associated with the Solley Road site using pump-and-treat technology with a leachate collection system. BFI will pump contaminated ground water from the Patapsco Aquifer to an air stripper (see Figure A-4). The contaminants of concern will be removed and the water will be reinjected, through three reinjection wells, back into the Patapsco Aquifer downgradient of the plume, thereby reversing the flow of contaminants in the Patapsco Aquifer in that area. Secondary impacts to other ground-water users in the area are expected to be negligible. The extraction wells will draw about 120 gallons per minute out of the middle and upper aquifers. The site will be capped with a vegetative cover and have a leachate collection system.

A.2.2.2 Data and Flow of Wells

BFI will install four extraction wells designated as X-1, X-2, X-3, and X-4. Well X-1 will be located 500 feet south of the northwest corner of the West Fill. The well will be screened over the length of the upper Patapsco Aquifer with a solid section across the clay layer, and pumped at a rate of 20 gallons per minute (gpm). Well X-2 will be located 450 feet north of X-1. It will be screened over the lower portion of the upper Patapsco Aquifer and be pumped at 35 gpm. Well X-3 will be located 40 feet north of X-2, screened over the middle Patapsco Aquifer, and pumped at 30 gpm. Well X-4 will be installed 80 feet east of X-3, screened over the middle Patapsco Aquifer, and pumped at 35 gpm.

A.2.2.3 Air Stripper

The air stripper system will be designed to reduce TCE concentrations in contaminated ground water from 212 ppb to an effluent concentration of less than 5 ppb. The system will be designed to operate at flow rates between 80 and 160 gpm, with a normal flow rate of 120 gpm (see Figure A-5).

Extracted water will be treated in a 34-ft tall 2.5-ft diameter packed tower. The tower will contain 24 feet of 2-inch polypropylene packing and will be equipped with a 1.5 horsepower blower, and will provide air-to-water ratios ranging from 40:1 to 85:1. The process will effectively remove 98 percent of the influent VOCs, and the treated ground water will be reinjected into the aquifer.

To determine influent design concentrations, the concentrations of VOCs detected for all sampling events were averaged for each well. Based on the location of these wells and the recovery wells, and the design flow rates of the recovery wells, a weighted average concentration

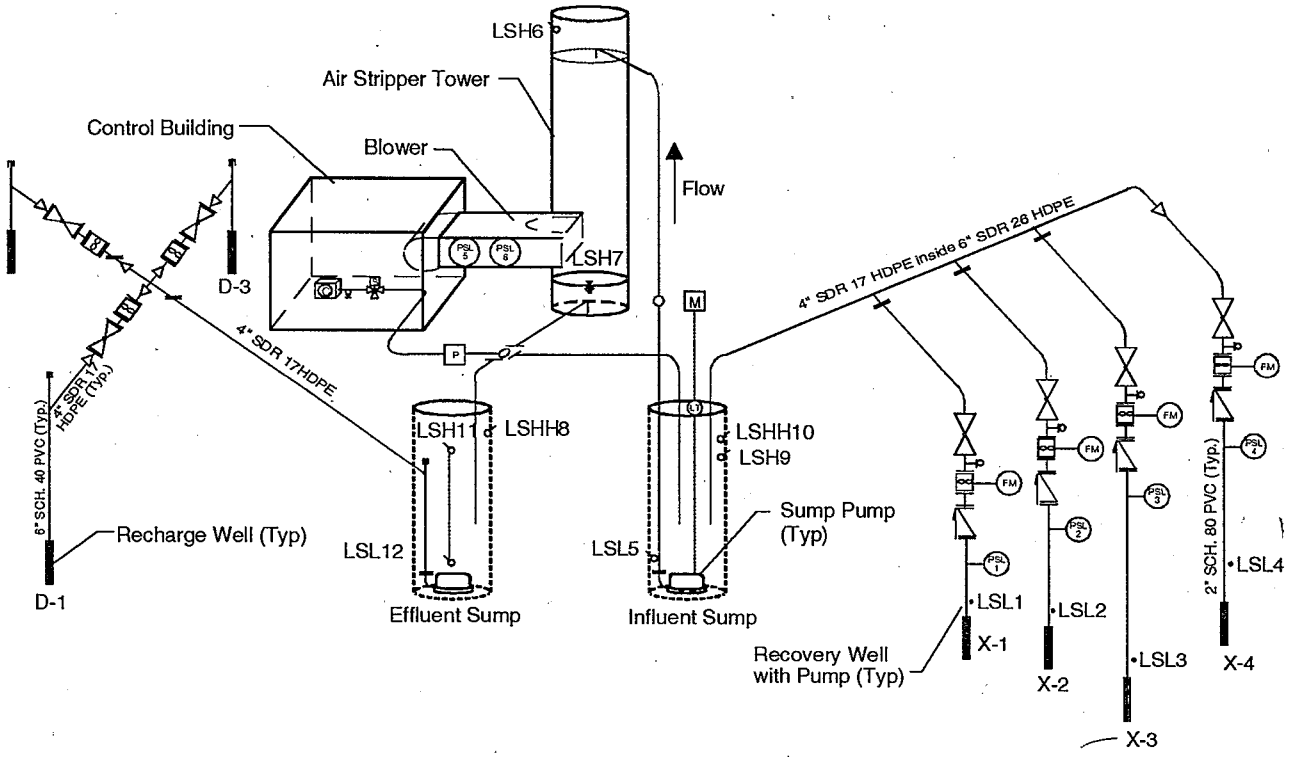

Figure A-4. Pump and treat with air stripper at Solley Road site.

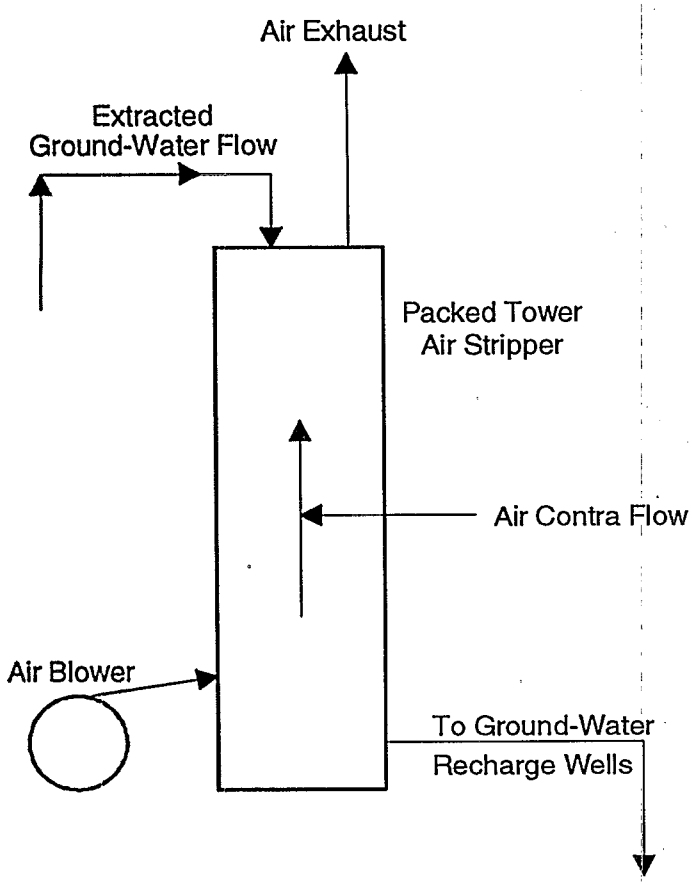

Figure A-5. Air stripper system at Solley Road site.

was calculated. For additional safety, the design concentrations were set at double the weighted average concentrations. The design effluent concentration was based on the Safe Drinking Water Act primary MCLs for VOCs.

A.2.2.4 Reinjection Wells

BFI will install three reinjection wells designated as D-1, D-2, and D-3, which will be located in a line approximately 100 feet east of Marley Neck Road. These reinjection wells will be screened in all three layers of the Patapsco Aquifer and will receive a total of 120 gpm: well D-1 will receive 55 gpm; well D-2, 40 gpm; and well D-3, 25 gpm. The flow rates to wells D-1 and D-2 are greater than those to D-3 because some mounding potential exists near D-3, due to the enhanced recharge from the stream.

A.2.2.5 Leachate Collection System

The leachate collection system consists of excavated trenches in which filter geotextile, aggregate, and perforated pipes are placed along the perimeter of the East and West Fills. These trenches and pipes gravity drain to four reinforced concrete standpipe risers, which provide access for leachate removal via pumps or vacuum trucks. A clay cap, topsoil, and vegetative layer will be placed over the trenches.

A.2.2.6 Monitoring Systems

A monitoring system will verify the performance of the pump-and-treat system's removal efficiency, the hydraulic response of the aquifers, and changes in ground-water quality.

The removal efficiency of the air stripper will be measured to verify that the effluent discharge limits are being met. A portable gas chromatograph (GC) will be used at the site to monitor contaminant concentrations in the stripper influent and effluent. Laboratory analysis also will be performed to verify system performance. The sampling frequency will be as follows: first week — daily; next 6 months — weekly; next 6 months — monthly; next year — every other month; and the remainder of the project — quarterly.

BFI will monitor the hydraulic response of the aquifer to pumping to verify that the capture zone of the system is sufficient to recover the majority of the ground-water contamination plume. This monitoring will use the same sampling frequency as above.

Ground-water quality monitoring will consist of baseline monitoring 4 weeks prior to startup to provide a "snapshot" of existing conditions, and routine monitoring at regular intervals. Routine sampling on 19 wells will be performed quarterly for the first year after startup and semi-annually thereafter. Routine sampling will verify the systems' performance relative to the baseline.

A.2.3 Implementation and Future Actions

BFI believes that, having studied the site for years, they have characterized the ground-water contamination. They would prefer to limit or delay further investigative stages for ground water, and start implementing a pump-and-treat measure to stabilize the ground-water contamination. The site may request a modification to their corrective action permit under 40 CFR Section 270.42 to incorporate the stabilization effort.

The modification of EPA's corrective action permit should take place in March or April 1992. Installation of the pump-and-treat system should begin in April and the system should be operational by August 1992.[1]

A.2.4 Conclusions and Discussion

In summary, there is no indication that contamination from the landfills presents an immediate threat to human health

1 Due to EPA and Maryland's concern with media transfer of contaminants, BFI also will be installing a carbon adsorption unit to treat the effluent from the air stripper. EPA now plans to modify BFI's permit by November 1992. This modification will require BFI to install the new system in March or April 1993, and begin pumping and treating in September 1993 (Zielinski, 1992).

and the environment in the site vicinity. BFI has identified a localized plume consisting of VOCs in concentrations as much as 100 times the MCL, migrating in the upper portions of the Patapsco Aquifer. Therefore, instead of performing additional studies required in EPA's corrective action permit, BFI would like to stabilize the site by installing a pump-and-treat system. BFI also would install a leachate collection system to eliminate significant releases to the environment. They would continue to study the impact to the other media (e.g., air and soils), as well as the ground water, while pursuing the cleanup of ground-water contamination. Modeling and pilot studies performed by BFI indicate that VOCs in the ground water can be successfully treated using air stripping.

Table A-7. Regulatory Chronology

Date	Event
10/72	MDHMH* issues Refuse Disposal Permit for East and West Fills
1973	BFI buys the site
8/78	MDHMH amends Refuse Disposal Permit to allow hazardous waste disposal into "Active Cell" in the East Fill
1979	MDHMH requires installation of monitoring system with 6 wells
7/82	MDEP** issues BFI a Treatment, Storage, and Disposal Facility (TSDF) Permit
1982	MDHMH determines that the monitoring system is damaged and requires installation of 10 more wells
12/82	Entire facility was closed; state permit was amended with an approved post-closure plan with comprehensive monitoring
1984	Ground-water quality data collected indicate contamination extends north and west of the site
4/85	Remedial Investigation starts
8/88	Remedial Investigation agreement is amended to include studies to prevent further migration of contamination
10/86 and 3/89	BFI submits Evaluation Reports that indicate that ground-water contamination is *not* emanating from the East Fill
10/89	BFI submits a Remedial Engineering Plan, which includes construction on adjacent sites; BFI had difficulties accessing the adjacent land
10/90	MDEP issues Post-Closure Permit
8/91	EPA Region III issues a Corrective Action Permit consistent with the MDEP Post-Closure Permit
9/91	BFI acquires parcels of land adjacent to the site to implement remediation plan
11/91	EPA Region III suggests that BFI consider the state's ground-water remediation plan as a "stabilization" activity under the EPA permit to avoid the delay involved by waiting for the full corrective action permit start date of 1994

*MDHMH = Maryland Department of Health and Mental Hygiene
**MDEP = Maryland Department of Environmental Protection

Table A-7 presents a summarized chronology of regulatory action.

If this interim measure effectively cleans up the ground-water contamination, it will become the final corrective measure.

A.2.5 References

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A.3 GROUND-WATER CONTAMINATION STABILIZATION: ROMIC CHEMICAL CORPORATION FACILITY, EAST PALO ALTO, CA, by Glenn Heyman, U.S. EPA, Region IX, San Francisco, CA

A.3.1 Introduction

The Romic Chemical Corporation owns and operates a solvent recycling and wastewater treatment facility in East Palo Alto, California. Romic has owned the site since 1979 and has operated the facility since 1963. Solvent recycling operations began on this site in the late 1940s. The facility currently recycles about 7 million gallons of halogenated and nonhalogenated solvents annually.

The 10-acre site is slightly less than ½ mile west of the southern end of San Francisco Bay. It is bordered by industrial sites and auto dismantling shops on the south and west, a former salt evaporation pond to the east-

northeast, and salt marsh and tidal sloughs on the north and east. A nearby industrial site to the south is on the National Priority List of Superfund sites.

The following subsections discuss the site's hydrogeology, contamination, environmental concerns, and regulatory activities.

A.3.1.1 Hydrogeology

The Romic site is underlain by recent alluvium composed of approximately 70 feet of interbedded sand and clay. Three shallow interconnected aquifers occur at depths from near surface to 15 feet, 30 to 40 feet, and 60 to 70 feet and are informally referred to as the A, B, and C zones, respectively. Their flow directions are variable and are connected to the surface water system in the tidal slough. A deep underlying aquifer at approximately 150 to 170 feet below surface is utilized as a drinking water supply. The nearest extraction wells for the drinking water are about 1 mile west-southwest of the site. While water in zone A is affected by tides, ground-water flow in all zones is generally eastward toward the bay.

A.3.1.2 Contamination

VOCs have been detected above regulatory levels in the ground water and slough sediments. Ground-water contamination extends horizontally beyond site boundaries and vertically to the aquitard. Romic has conducted a RFI pursuant to its permit and Section 3008(h) Consent Order. This investigation has shown that releases from the site have contaminated surface water, soils, subsurface gas, and shallow ground water down to at least the base of zone C. VOC contaminants also have been detected in the shallow ground water and subsurface gas horizontally beyond the site boundaries. Analysis of soil and ground-water samples have detected about 27 organic compounds along with lesser inorganic contamination. Tables A-8 through A-10 contain contaminant profiles for site ground water, adjacent surface water, and slough sediments, respectively.

Table A-8. Major Ground-Water Contaminants

Contaminant	Concentration on 8/91 in ppm	Subpart S Action Levels in ppm	MCLs in ppm
Vinyl Chloride	16.0	—	0.002
cis-1,2-Dichloroethylene	34.0	—	0.007
1,2-Dichloroethane	3.4	—	0.005
Trichloroethene	1.9	—	0.005
Freon 113	0.4	—	—
Methylene Chloride	64.0	0.005	—
Acetone	120.0	4	—
Methyl Ethyl Ketone	840.0	2	—
Tetrahydrofuran	94.0	—	—

Table A-9. Major Surface Water Contaminants

Contaminant	Concentration on 8/91 in ppm	Marine Chronic Criteria in ppm
Organic Contaminants		
cis-1,2-Dichloroethylene	0.150	224
1,2-Dichloroethane	0.044	113
Vinyl Chloride	0.104	—
Tetrahydrofuran	2.300	—
Inorganic Contaminants		
Copper	0.270	0.0029
Lead	0.399	0.0056
Mercury	0.005	0.00025
Nickel	0.039	0.0083

Table A-10. Major Slough Sediment Contaminants

Contaminant	Concentration on 11/91 in ppm	PSDDA SL in ppm*	PSDDA ML in ppm**
Vinyl Chloride	7.200	—	—
1,1-Dichloroethylene	0.240	—	—
cis-1,2-Dichloroethylene	3.500	—	—
Trichloroethene	0.130	0.160	1.600
Toluene	1.000	—	—
Tetrachloroethane	0.029	0.014	0.210
1,4-Dichlorobenzene	0.031	0.026	0.260
Ethylbenzene	0.260	0.010	0.050
Total Xylene	0.780	0.012	0.160
Tetrahydrofuran	0.130	—	—

*PSDDA SL stands for Puget Sound Disposal Data Analysis Safe Level, which indicates no observed effect.
**PSDDA ML stands for Puget Sound Disposal Data Analysis Minimum Level, which indicates an observed adverse effect.

The primary contamination sources appear to be unpaved drum storage areas and two former surface ponds in the northern part of the site. These ponds had received surface runoff, process wastewater, dimethyl sulfoxide salts, and miscellaneous waste materials between the 1950s and the late 1970s. Beginning in the late 1970s, the ponds were filled and drum storage buildings built over them. These buildings were constructed over concrete slabs poured over a synthetic liner that covered the filled ponds. An additional contamination source consists of a trough that carried wastewater from the process area to

the ponds. The contamination covers all three zones A, B, and C. Because of a high background level of inorganic contamination in surface water from the proximity of other industries, assessing Romic's contribution of metals to surface water is difficult.

A.3.1.3 Environmental Concerns

Ground-water contamination migrating off site presents potential hazards to nearby water supplies and surface waters. The closest drinking water supplies are municipal water wells located about 1 mile southwest of the site. These drinking water wells, however, are isolated from the shallow aquifer by a confining clay layer. The wells draw on an aquifer about 170 feet under the surface, and the protective clay layer over the aquifer is about 100 feet thick. Shallow ground water from this site discharges directly to an adjacent salt marsh, abandoned salt evaporator, and surface water body. In addition, two species listed on state and federal endangered species lists, the California clapper rail and the saltmarsh harvest mouse, inhabit the adjacent wetlands.

A.3.1.4 Regulatory Activities

The State of California and EPA have been involved with this site since the 1980s. California issued an operating permit in 1985, and in December 1988 EPA and Romic signed a RCRA Section 3008 (h) Consent Order to initiate a RFI, CMS, and a CMI Plan. The RFI is now almost complete. Sampling conducted as part of the RFI includes:

- Installation of 34 monitoring wells
- Drilling and sampling of 32 soil borings
- Sampling of slough sediment at 8 locations
- Establishment of 8 surface water sampling locations
- Completion of a soil-gas survey

The permit-required sampling originally discovered the VOC contamination in the soils and the ground water.

A.3.2 Stabilization Strategies

Romic began stabilizing this site in the 1970s by filling the settling ponds, covering them with a synthetic liner, and paving the site. In April 1991, the final Interim Corrective Measures Evaluation and Feasibility study was completed. Its guiding philosophy is to stop offsite migration of contaminated ground water and soil gas and to begin long-term remediation of the ground water beneath the site. Interim corrective measures will be in place as a conditional remedy until the facility closes, at which time a determination of final remediation will be made.

The preliminary stabilization plan is a pump-and-treat option involving extraction wells and granular activated carbon adsorption treatment. Once the preliminary system is installed and evaluated, additional source controls (such as slurry cutoff walls) and treatment technologies will be evaluated. Treatment technologies initially under consideration included ultraviolet oxidation using peroxide, a biological reactor for ketones, and air stripping for volatile chlorinated solvents. Ultraviolet oxidation using peroxide was rejected, however, after a pilot-scale treatability test.

Testing of the preliminary system cannot begin until the wastewater discharge issue is resolved. The local POTW has denied Romic a discharge permit. Romic has submitted a National Pollutant Discharge Elimination System (NPDES) permit application in the event that the local POTW denies Romic's permit denial appeal.

A.3.3 Implementation and Future Actions

One of the impediments to stabilizing this site is the need for gaining access to adjacent parcels of land to complete evaluation studies. Romic has not been able to gain access to an adjacent hiking and biking trail to complete determination of the eastward extent of contamination.

Another impediment is obtaining the requisite permits to discharge effluent to the sanitary sewer. Discussions with the local sanitary district began in June 1991. The discharge permit application was denied in September 1991, and has been subsequently resubmitted.

Current activities at the site include a RCRA Facility Investigation and stabilization activities. The RFI activities include:

- Borings and well installations to delineate the horizontal and vertical extent of the VOC contamination
- Preparation to conduct an air pathway monitoring program using surface flux chambers
- Detailed ecological assessment preparation

Stabilization activities include NPDES permit application revisions requested by the Regional Water Quality Control Board (RWQCB), additional pump tests, and groundwater modeling to determine recovery well spacing.

A.3.4 Conclusions and Discussion

The overarching lesson from this case study is the need for thorough and clear communication. It is important to first realistically evaluate local politics to assess the most expeditious investigation, treatment, and disposal options. In addition, all local agencies must be educated about their roles in the process, since, as in this case, the peripheral agencies may present the largest obstacles to proceeding with stabilization efforts. Another lesson is the importance of thoroughly exploring reuse options for treated ground water.

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