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Assessing UST Corrective Action Technologies: *In Situ* SVE-Based Systems for Free Product Recovery and Residual Hydrocarbon Removal

Edited by

Milovan Beljin,
Roy Chaudet, Duane Graves,
Jeff Schubert, and Joe Tyburski
IT Corporation
Cincinnati, Ohio 45246

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Project Officer

Chi-Yuan Fan
Water Supply and Water Resources Division
National Risk Management Research Laboratory
Edison, New Jersey 08837

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

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

The number of confirmed releases of petroleum products from underground storage tank (UST) systems has increased significantly since promulgation of the final UST regulations by the U.S. Environmental Protection Agency in December 1988. This increase has outpaced the resources of both industry and government to clean up and close these sites. At sites where cleanups have begun, the selection of inappropriate corrective action technologies has often contributed to the increased cleanup times and costs.

A common approach to corrective action may involve the use of a favored technology, which alone does not fully achieve the remedial goals. When corrective action options are evaluated, the different contaminants present in different matrices and in different physical states must be considered along with their location, amount, and mobility. Therefore, the use of multiple corrective action technologies in an integrated system may be needed to effectively remove these contaminants from locations of concern.

This manual presents the data, methods, and tools required for evaluating free product or nonaqueous phase liquid (NAPL) recovery and soil-vapor-extraction (SVE)-based systems. The SVE-based systems examined include soil vapor extraction, bioventing, and air sparging. In addition, an overview of natural attenuation/biodegradation is also provided. The manual is intended to provide assistance in developing a conceptual understanding of the factors influencing hydrocarbon migration and retention in the subsurface and to identify key process parameters that are used to select, design, and monitor corrective action systems.

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Chapter 1
Introduction

1.1 Background

Over the past five years, since promulgation of the final underground storage tank (UST) regulations by the U.S. Environmental Protection Agency (40 CFR Part 280), the number of sites with confirmed releases from USTs has far exceeded the resources of both industry and regulatory agencies to clean up and close out these sites. As of March 1994, approximately 254,250 sites had confirmed releases, 194,860 of these sites had initiated corrective action, and only 96,840 sites had completed cleanups. Delays in initiating corrective action allow mobile contaminants to migrate further from the source, thereby increasing the likelihood of more severe environmental impacts and ultimately higher cleanup costs.

A variety of conventional and emerging technologies are being proposed to address the increasing number of sites with confirmed releases. These technologies are sometimes selected and designed without an adequate understanding of site and contaminant information that is needed to evaluate and determine appropriate application or to design a remedial system that will effectively meet the remedial objectives for the site. Consequently, if inappropriate or ineffective technologies were chosen, designed, and operated on a "trial-and-error" basis, the result is increased cleanup time and costs. Therefore, an understanding of the site and contaminant information is essential for evaluating proposed corrective action technologies.

A common approach to corrective action typically involves implementing one or two technologies during a particular stage of the cleanup. For example, the use of free product "pump-and-treat" systems has traditionally been a favored conventional corrective action technology. At many sites, a properly designed pump-and-treat system may in fact be the most effective technology.

After the recovery of free product is completed, soil vapor extraction (SVE) is sometimes installed as a supplementary technology. Biodegradation occurs as part of the SVE process as an added benefit, but is often not considered in the overall design and operation of SVE systems. The SVE process could be optimized as an integral part of an augmented SVE approach that includes bioventing.

More recently, SVE has been used in combination with in situ air sparging. Claims have been made that this technique can be used to successfully remediate contamination in the saturated zone. This system is proposed to State UST regulatory agencies for cleanup of both the saturated and unsaturated zones. Many of these practitioners favor air sparging simply because it is a "new technology" even though they do not understand the applicability and performance limitation of the technology at a given site. Unfortunately, there is a lack of substantive performance data to support the claims of practitioners who propose using these coupled technologies. Consequently, there is a need to examine in detail the fundamental processes of these technologies, and to develop an approach that utilizes the more effective technologies.

As part of an effort to provide a better understanding for the use of multiple corrective action technologies, the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) National Risk Management Research Laboratory in conjunction with the Office of Underground Storage Tanks in EPA Regions 5 and 7 developed several workshops on corrective action technologies (EPA, 1993). In these workshops, several leading experts discussed their current approach for evaluating and using free product recovery and SVE-based systems. The information compiled from these presentations has been used to develop sections of this manual.

1.2 Purpose

The purpose of this manual is to provide information for evaluating several corrective action technologies that can be used either individually or in combination. This manual is unique in that it provides an overview of selected corrective action technologies (e.g., free product recovery, SVE-based removal of residuals, and biological degradation) not commonly contained in a single document. It provides the following:

- A conceptual presentation of the factors influencing hydrocarbon migration and retention in the subsurface.
- Identification of process parameters that are used in the selection and design of nonaqueous phase liquid (NAPL) and SVE-based corrective action systems.
- An overview of approaches and tools used in system design for these technologies.
- An example of the types of monitoring requirements that may be needed to determine system effectiveness.
- An example of cost estimates for selected corrective action technologies.

The scope of the information presented in this manual represents the author's current understanding of the design criteria and performance of these technologies.

Performance characteristics and monitoring methods are still being determined for certain emerging technologies (e.g., in situ air sparging). Preliminary results from laboratory and field studies using these technologies have been included in this manual.

The information provided in this manual is directed toward a broad audience with a science background. It is intended as a resource document that can serve as a starting point in understanding the appropriate selection and use of the technologies discussed.

1.3 Approach and Organization

The approach for examining the technologies in this manual is based on an understanding of the characteristics of the porous media and the contaminants, and the distribution of the contaminant phases at various locations in the subsurface. Hydrocarbon contaminant releases from leaking USTs into a porous media will be distributed among four phases: (1) nonaqueous phase liquids (NAPL) or the "immiscible phase," (2) the soil moisture or "dissolved phase" in interstitial water, (3) the "adsorbed phase," and (4) the "vapor phase." The distribution of contaminants into the different phases is dependent on the chemical and physical characteristics of the hydrocarbon, the degree of weathering that has occurred, and the characteristics of the porous media. These phases are present and transient between one or more of 13 locations, referred to as physico-chemical-phase locations or loci (EPA, 1990a).

Figure 1-1 illustrates the distribution of the contaminant phases in the subsurface where the total mass of the contaminant is distributed by the movement of vapors or liquids and diffusion of contaminants. The contaminant distribution will change as the contaminant moves from the unsaturated zone to the saturated porous and fractured media. The mass of contaminant in a given volume of NAPL may be orders of magnitude greater than the mass present if the same volume of soil were contaminated with vapor, dissolved, or sorbed (Mackay and Cherry, 1989). Therefore for many sites where NAPL is present, the initial cleanup efforts should focus on first removing the NAPL sources if possible. For NAPLs that cannot be removed directly or that remain as residuals, the contaminant mass may be partly removed by volatilization and dissolution into groundwater. These removal methods require considerable volumes of gas or liquid, and the cleanup process for contaminants can be lengthy and expensive. Biodegradation processes may be a cost-effective option for attenuation of groundwater plumes, or for decreasing contaminant concentrations to acceptable levels in both the saturated and unsaturated zones. This approach to corrective action is based on an evaluation of the contaminant mass in each phase and mobility of the contaminants.

A generalized site characterization and corrective action process is presented in Figure 1-2. The site characterization should provide sufficient information to evaluate potential risk to human health and the environment for evaluating and making decisions regarding remedial action that may or may not be needed. This information is obtained during

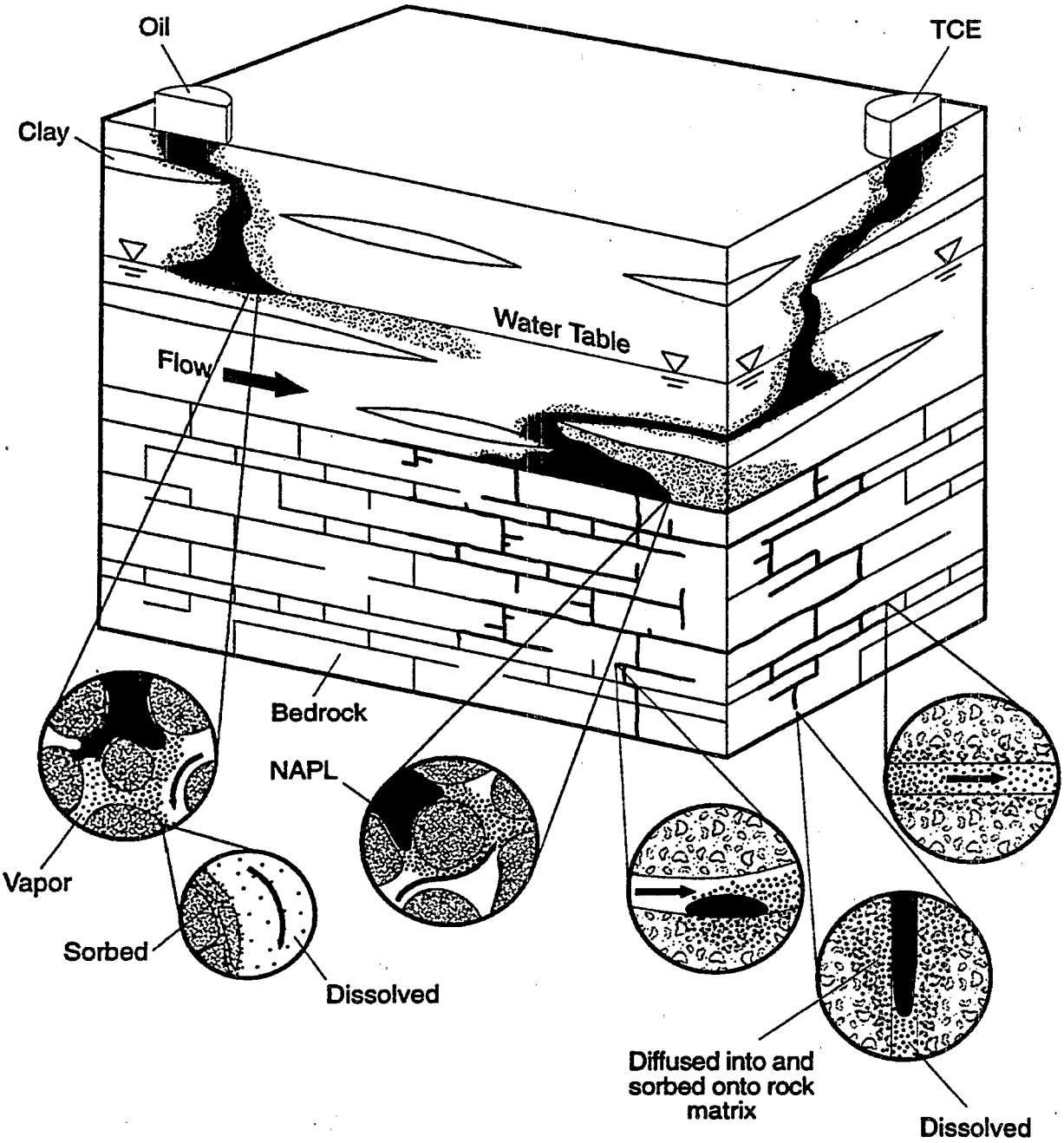

Figure 1-1. Distribution of phases in the subsurface.

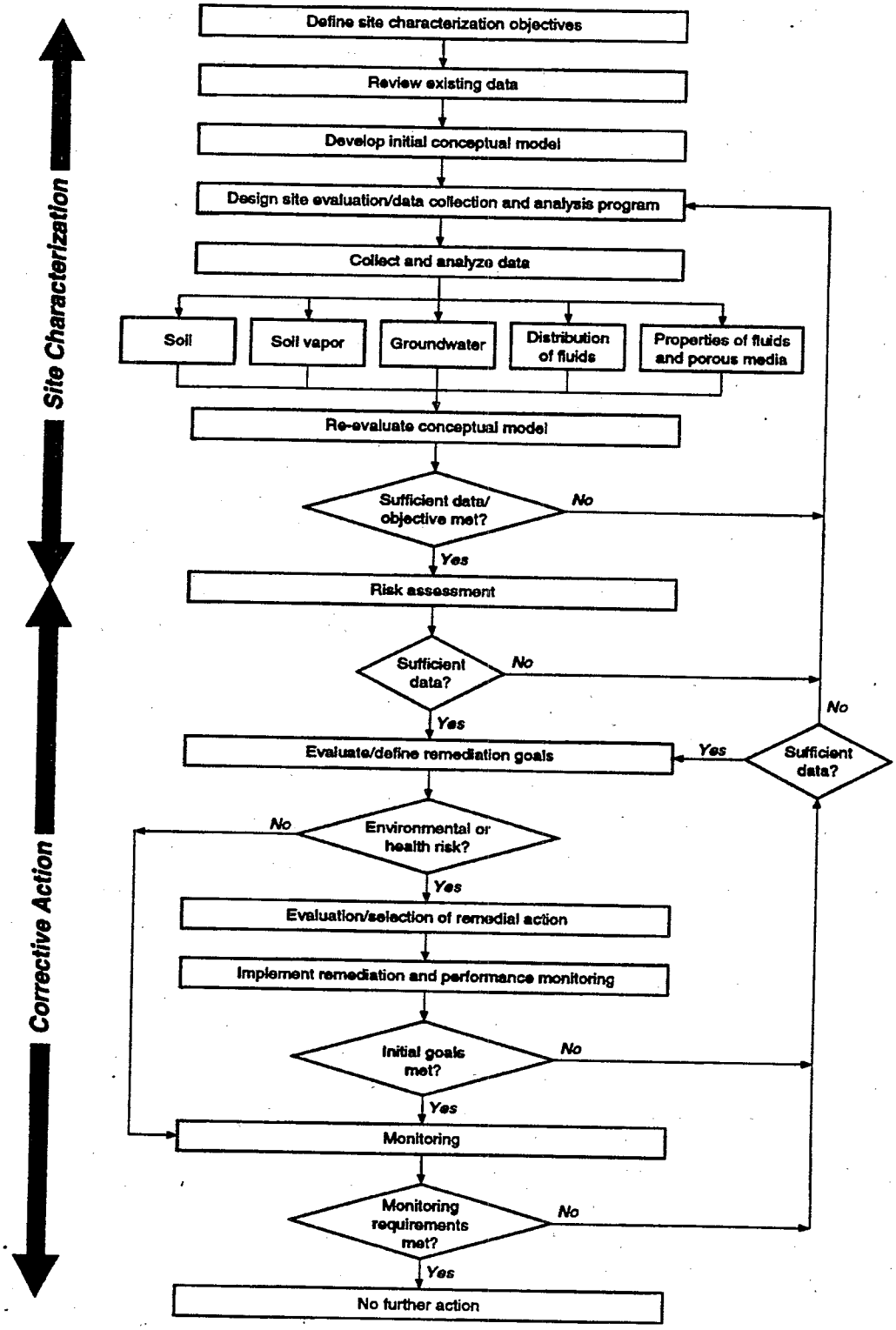

Figure 1-2. Overview of corrective action process.

the site characterization by an iterative process that involves developing an initial conceptual understanding based on available data of the type and locations of contaminant phases, an evaluation of the relative mass, composition, and mobility of each phase, and the properties of the contaminated media (EPA, 1990a).

As site and contaminant information is obtained, the conceptual model for the site is also reevaluated. For example, background information may initially indicate that the majority of contaminant mass is located in shallow soils in the vadose zone. Further investigation may reveal that at certain locations the contaminant may have migrated to the capillary fringe, and what was initially thought to be a problem limited to the vadose zone has actually impacted the groundwater. Chapter 2 presents a discussion of the site characterization process and methods for collecting and analyzing samples.

Sites with subsurface contamination vary greatly in terms of complexity, physical and chemical characteristics, and in the risk that they may pose to human health and environmental resources. The risk-based corrective action process presented in the emergency standard guide for petroleum release sites (ASTM Designation: ES 38 - 94, July 1994) recognizes this diversity, and utilizes a tiered approach where assessment and remediation activities are appropriately tailored to site-specific conditions and risks. This flexibility allows risk-based corrective action to be more cost-effective than traditional approaches under which all sites conform to uniform standards and procedures.

Depending on the level of risk evaluation, different types of data and analyses may be required. This information would either be estimated based on the information already collected or on information collected as another iteration of the site characterization process. The risk evaluation can be used to evaluate and define remediation goals. If a diagnostic evaluation shows no significant environmental or health risks, the site may simply require either confirmatory sampling or short- or long-term monitoring. If risks do exist, then the site characterization information will be used to evaluate and select a remedial action.

The remedial action will utilize a corrective action technology whose feasibility is evaluated at this point in the process based on the subsurface properties and contaminant mass, phases, locations, and mobility. Once a technology is selected, designed, and implemented, the performance of the system is monitored to determine if remediation goals can be met by using the selected technology. If the goals are not met, then a reassessment of the remedial system, site condition, and remedial goals (if necessary) may be needed. If the goals are met, then the site can proceed with monitoring only. When the monitoring requirements have been met, then it is appropriate to recommend closing the site. If concentrations rebound and exceed the monitoring requirements over a specified time frame, the remediation goals and action may have to be reevaluated.

The majority of this manual focuses on the data needed and methods and tools used for evaluating selected corrective action technologies, including useful information on free-product recovery and SVE-based systems. Chapter 2 focuses on site characterization, approaches, and techniques for obtaining the data needed for making corrective action decisions. Chapter 3 presents the fundamental considerations for free product migration and recovery. Chapter 4 discusses the remediation of residual organics using soil vapor extraction. Chapters 5 and 6 expand on Chapter 4 by discussing bioventing and intrinsic bioremediation and in situ air sparging, respectively. Cost estimates are provided for relative cost comparison between product recovery, SVE, and air sparging-SVE systems. Chemical properties of organic contaminants typically encountered are provided in Appendix A.

Chapter 2
Site Characterization

In determining appropriate action for addressing petroleum releases, three-dimensional site characterization is required to provide a sufficient contaminant definition of behavior and to support corrective action decisions. Because released contaminants are present and transient in the subsurface (EPA, 1990a), a site characterization should be conducted to define the relative amount and composition of each phase present, the location of most mobile or major phases, and the properties of the porous media in the subsurface. Based on an understanding of these phase locations and the mechanisms affecting the movement and disposition of the contaminants in and out of these locations, appropriate technologies can be identified and selected as part of a corrective action strategy. A detailed discussion of the technology identification and selection process is based on the use of worksheets for evaluating potential technologies (EPA, 1990b,c).

In this section, the site characterization process will first be presented to provide an overall context for discussion of site characterization activities. As part of this process, the data needed to make a decision will be identified and described. This step will be followed by a review of sampling and analysis techniques that are currently available for generating this data.

2.1 Site Characterization Strategy

A comprehensive site investigation strategy should be designed to collect appropriate and sufficient data to assist in the selection, design, and implementation of an effective corrective action. An overview of the site characterization process is shown in Figure 2-1. The first and the most important step in site characterization is to clearly define the objectives. The specific objectives vary depending on the site chosen and the reasons for the site characterization such as release confirmation, risk determination, and corrective action evaluation. The second step is the review of existing data to develop an initial conceptual model. For example, the amount of released light nonaqueous phase liquid (LNAPL) and the depth-to-groundwater table can indicate whether a free product is potentially present at the site. Once the overall objectives are defined and a working conceptual model is being developed, the collection program and the level of effort in gathering field data should be adjusted accordingly. The type of information that is often collected at sites is shown in Figure 2-2 and includes the following:

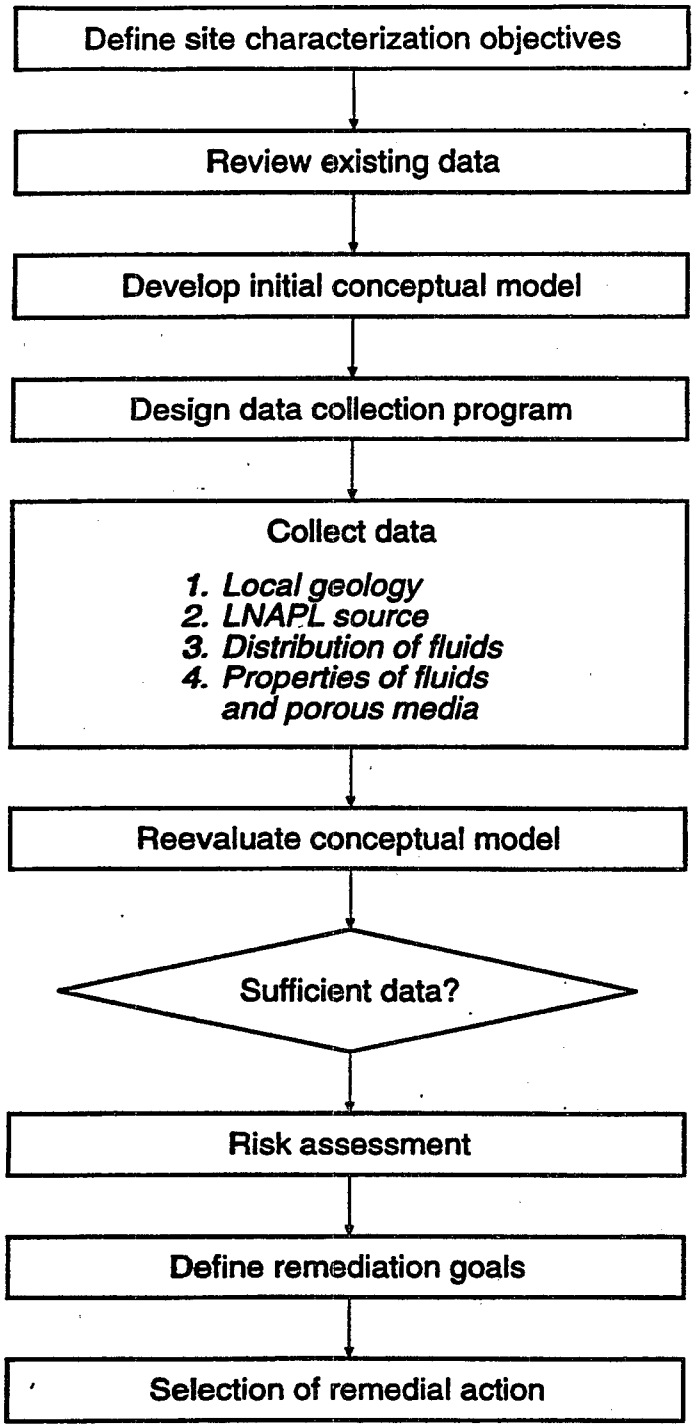

Figure 2-1. Flowchart for site characterization.

LOCAL GEOLOGY AND HYDRO-GEOLOGY

- Stratigraphy/Lithology
- Depth-to-Water Table
- Potentiometric Surface Map
- Capillary Zones
- Heterogeneity/Anisotropy
- Aquifer Thickness
- Hydraulic Gradient
- Groundwater Flow Direction
- Production Wells

LNAPL SOURCES

- Released Quantity
- Time of Release
- Chemical Composition
- Area Infiltrated
- Man-made Hydraulic Structures

DISTRIBUTION OF FLUIDS

- Free Product
- Dissolved LNAPL
- Moisture Content
- LNAPL in Vadose Zone
- Vapors
- Residual Saturation

PROPERTIES OF FLUIDS

- Density
- Viscosity
- Capillary Pressure
- Solubility
- Volatilization
- Sorption
- Wettability

PROPERTIES OF POROUS MEDIA

- Porosity (Total and Effective)
- Permeability
- Hydraulic Conductivity
- Storativity
- Surface Area
- Sorption Capacity
- Soil pH
- Grain Size Distribution
- Soil Organic Content
- Clay Content

Figure 2-2. Data needs for site characterization.

- Local geologic and hydrogeologic conditions
- Source(s) of contamination
- Distribution of fluids in porous media
- Physical and chemical properties of fluids
- Properties of porous media.

The initial conceptual model will be modified or even rejected as the data are being collected. This should be considered as an iterative process. When the amount of data is considered sufficient, risk assessment, definition of remediation goals, and the selection of remedial action would follow.

Site investigations traditionally involve the installation of soil borings and groundwater monitoring wells. The investigations may proceed in more than one phase to define the extent and degree of contamination in the subsurface; additional sampling and well installations are completed as results of previous sampling events become available. This approach may extend over several months or more. A new and developing array of sampling technologies is becoming available that will improve the site assessment procedures and create the opportunity for an accelerated site closure.

Conventional site characterization practices commonly focus on the "edge" of the contaminant plume, rather than on the contaminant source, and ignore the three-dimensional nature of the contaminant source and plumes. Monitoring wells, for example, provide averaged data over the screened interval from which the groundwater sample was extracted. Discrete sampling techniques are available to sample both the groundwater and soils at specific horizons, to develop an accurate comprehensive assessment of the subsurface conditions, and to support the remediation strategy and decisions.

The sampling strategy to determine the vertical and horizontal extent of contamination will depend on the site and specific release factors. Where the contaminant source is known or suspected, sampling may be selective and concentrated at the suspected source area. Selective samples are biased samples collected near the source area. If contaminants are identified, additional lateral samples are collected at progressively more distant locations until the extent of the affected area is delimited. Vertical extent is determined by collecting and analyzing samples at incremental depths.

When the source area is unknown, a sampling grid may be employed for collecting samples at predetermined sample intervals. The chosen intervals will depend on the site, proximity to a potential source, hydrogeology of the site, and the nature of the site geologic materials (API, 1993). Depth profiling will also be employed to determine the vertical extent of contamination.

The following sections present regulatory considerations and discuss the source characterization approaches, contaminant characterization, and unsaturated and saturated zone characteristics in the site characterization strategy.

2.1.1 Local Geology and Hydrogeology

It is important to estimate the hydrogeologic characteristics that influence the contaminant distribution. These characteristics include: (1) stratigraphy, (2) hydraulic properties of aquifers and confining beds, (3) hydraulic gradients, (4) recharge/ discharge rates, and (5) sorption potential. If fractures are present, an evaluation should be made of their orientation, spacing, and vertical and lateral extent. The spatial distribution of hydraulic properties, gradients, and contaminants can be very complex and requires vertical and horizontal assessment. Groundwater contamination is often conceptualized as forming plumes. At some sites, however, heterogeneities in hydraulic properties (especially in fractured media) and a complex distribution of contaminant sources may result in very erratic contaminant distributions that must be assessed (Cohen and Mercer, 1993).

2.1.1.1 Depth-to-Groundwater Table

Depth-to-groundwater is a measure of the elevation to which water rises in a well that is open to the atmosphere. Depth to water is measured from a reference point that has been surveyed, usually the top of the well casing. This information is expressed in terms of a relative datum that represents the groundwater table elevation. Water levels are presented in a two-dimensional contour map representing water surface elevation.

Shallow aquifers are important sources of groundwater and they are also the most vulnerable to contamination. Contaminants infiltrate through the vadose zone above the water table. This zone plays an important role in distribution and the fate of the contaminants in the subsurface.

2.1.1.2 Fluctuation of Water Table

Temporal groundwater fluctuations may occur because of seasonal variations or meteorological events. The fluctuations may influence groundwater flow patterns or rates of movement. These effects are quantified by determining seasonal groundwater elevations and plotting the potentiometric maps for comparison. Fluctuations in the water table can lead to the spread of contaminants and an increase in the potential for residual oil to occur in the vadose zone. If the water table rises faster than the oil table can rise, pockets of free oil may be left below the water table. In addition, residual oil can cause difficulties in remediation selection. Although volatile constituents may be removed via soil vapor extraction, the nonvolatile compounds may remain in the soil and require treatment through other techniques such as bioremediation (Fetter, 1993).

Because of seasonal changes in groundwater elevations, a minimum of one year is needed to observe the changes. The site complexity and the results of the first-year monitoring might require a longer period of monitoring.

2.1.1.3 Hydraulic Gradient

The hydraulic gradient in an aquifer represents the change in the hydraulic head along the flow line. This gradient is an indication of the potential for flow in the system.

Under natural conditions, groundwater moves relatively slowly, from inches per day to several feet per day. Groundwater velocity is proportional to the hydraulic gradient, and inversely proportional to the porosity.

2.1.1.4 Groundwater Flow Direction

Groundwater is in constant motion from areas of recharge (precipitation, surface water bodies, and artificial recharge) to areas of discharge (springs, rivers, and well fields).

Hydraulic head measurements are used to determine groundwater flow directions and rates of groundwater movement (EPA, 1991a). Groundwater flows from higher to lower hydraulic heads and is generally perpendicular to potentiometric contours.

2.1.1.5 Saturated Thickness

The saturated thickness of an aquifer is the thickness of the saturated zone that occurs below the water table, where pore space is filled with water at a pressure greater than atmospheric. The hydraulic head in this interval is measured with a piezometer. The upper boundary is defined by the water table or a confining layer and the lower boundary by an impermeable layer.

2.1.2 Source Characterization

Source characterization includes a determination of the mobile and residual contaminants; amount of free product; estimates of the quantity of the release; contaminant composition, properties, and extent; and the geologic conditions that control contaminants movement. Noninvasive and invasive techniques are used to investigate the source areas. Depending on the nature of the suspected problem, these techniques can be applied in steps as needed.

Noninvasive methods may be employed in the characterization depending on site conditions. Noninvasive methods are primarily surface geophysical surveys, soil gas analyses, and photogrammetry techniques. These methods can be used to identify the contaminant source areas, geologic controls, and contaminant movement. Surface geophysics include ground-penetrating radar, electromagnetic methods, electrical methods, seismic and acoustical surveys, magnetometer surveys, and metal detector surveys.

Soil vapor surveys are used to screen wide areas of a suspected affected site for volatile organic compounds in the vadose zone. They provide chemical distribution data quickly and at a fraction of the cost of conventional detailed investigations. The information generated is used to target subsequent more detailed investigative efforts.

Aerial photographs are employed to determine historical disposal practices, geologic conditions, site development, and other factors relating to potential chemical migration. Photographs are available from a variety of sources and are used to define historical changes over time. These changes suggest specific areas to be investigated or they

suggest the nature of the disposal that has occurred. This information can better focus the characterization activities.

Invasive methods include traditional subsurface exploration techniques such as soil drilling and well installation and test pit excavation. These techniques will allow more definitive information in the following areas (Cohen and Mercer, 1993):

- Contaminant source area
- Stratigraphy, lithology, structure, and hydraulic controls on the movement of groundwater
- Fluid properties
- Nature and extent of contamination
- Monitoring and remedial systems.

Specific innovative methods will be discussed later in this chapter.

2.1.2.1 Release Information
Release information initially comes from the development of historical release information found in available records, reports, previous investigations, and interviews. The site characterization strategy is based on a review of facility design drawings, transfer and production procedures, surrounding land-use practices, underground utilities, and potentially affected areas.

2.1.2.2 Chemical Composition
The chemical make-up of the constituent of concern is identified through appropriate methods for analyzing samples of soil and groundwater. Hydrocarbons contain the elements hydrogen and carbon, with minor amounts of nitrogen, oxygen, and sulfur. The migration potential of each phase is dependent on the physical and chemical properties of the specific hydrocarbon compounds (API, 1989).

2.1.3 Distribution of Fluids

2.1.3.1 Extent of Contamination
The ultimate objective of site characterization is to determine the nature and extent of contamination so that informed decisions can be made regarding remediation that is based on the determined level of risk. Chemicals may contaminate soil, bedrock, groundwater, surface water, surface water sediments, and air; and the extent to which this occurs must be determined.

This assessment includes the extent of contamination in soil and an analysis of groundwater flow and chemical transport. Emphasis is often placed on the latter component through intensive groundwater quality monitoring. This information is used to help: (1) identify contaminants, (2) determine the distribution and concentration of contaminants, (3) determine sources of contaminants, and (4) determine the contaminant phase--dissolved, sorbed, or nonaqueous.

2.1.4 Properties of Fluids

Chemical and physical properties are determined for contaminants of interest to evaluate chemical migration and remediation alternatives. The specific parameters for characterization are discussed in the following sections.

2.1.4.1 Viscosity

The fluid viscosity (μ) is a measure of fluid resistance to relative motion and shear deformation during flow. The more viscous the fluid, the greater the shear stress τ at any given velocity gradient dv/dy

$$T = \mu \frac{dv}{dy} \tag{2-1}$$

where the constant of proportionality μ is the dynamic viscosity. This equation is known as Newton's law of viscosity. The kinematic viscosity (ν) is defined as

$$\nu = \frac{\mu}{\rho} \tag{2-2}$$

where ρ is the fluid density.

2.1.4.2 Fluid Density

The fluid density (ρ) is defined as the mass of the fluid per unit volume of the fluid

$$\rho = \frac{mass\ of\ the\ fluid}{volume\ of\ the\ fluid} \tag{2-3}$$

The fluid density is a function of pressure (ρ) and temperature (T)

$$\rho = \rho(p,T) \tag{2-4}$$

Groundwater density is often assumed to be constant.

2.1.4.3 Specific Gravity

The specific gravity or relative density (G) of a fluid is defined as the ratio of the density of the fluid to that of pure water at 4°C (60°F) as a standard temperature. The specific gravity for a gas is given as a ratio of its density to the density of hydrogen or air at a specified temperature. Where the specific gravity is less than 1.0, the substance is lighter than water, and is referred to as a light nonaqueous phase liquid (LNAPL). Where the specific gravity is greater than 1.0, the substance is heavier than water and is referred to as a dense nonaqueous phase liquid (DNAPL).

2.1.4.4 Specific Weight

The specific weight or weight density (γ) is defined as the weight of the fluid per unit volume of fluid. This weight is related to the fluid density ρ by the following relationship

$$\gamma = \rho g \tag{2-5}$$

where g is the gravitational acceleration.

2.1.4.5 Solubility

Water solubility is an important property of organic compounds and refers to the maximum concentration of a chemical that will dissolve in pure water at a particular temperature. For a gas, solubility is measured at a given vapor pressure. For a liquid, it is a function of the temperature of the water and the nature of the substance. Factors affecting solubility include temperature, co-solvents, salinity, and dissolved organic matter. Solubilities may range from compounds that are completely miscible with water to those that are nearly insoluble. The more soluble a compound, the more mobile it may be in the environment. Solubility is an important factor in choosing the appropriate removal process.

2.1.4.6 Capillary Pressure

Capillary pressure causes porous media to draw in the wetting fluid and repel the non-wetting fluid. This characteristic is the result of the dominant adhesive force between the wetting fluid and the media solid surfaces. Capillary pressure is the difference in pore pressure between two liquids in contact. In the vadose zone, these liquids are the air and water interface, and capillary pressure is a negative value. Capillary pressure is a function of interfacial tension, contact angle, and pore size (Cohen and Mercer, 1993).

2.1.4.7 Vapor Pressure

Vapor pressure is a measure of the tendency of a substance to pass from a solid or a liquid to a vapor state. It is the pressure of the gas in equilibrium with the liquid or solid at a given temperature (Fetter, 1993). Vapor pressure is a measure of a chemical's ability to volatilize; the more volatile a compound, the more readily it can be remediated through vapor phase recovery techniques or stripped from the subsurface.

2.1.4.8 Sorption

Sorption processes include adsorption, absorption, and ion exchange. Adsorption is a process by which a solute clings to a solid surface. Cations may be attracted to the region close to a negatively charged clay mineral surface and held by electrostatic forces

(cation exchange). In the adsorption process, the solute is diffused into the porous aquifer particles and sorbed onto interior surfaces (Fetter, 1993).

2.1.5 Properties of Porous Media

The unsaturated (vadose) zone extends from the ground surface to the water table. Chemical releases generally travel through the vadose zone to the water table. The unsaturated zone has more complex flow patterns than the saturated interval and will require characterization to allow evaluation of remediation alternatives. The following sections will discuss the more significant properties of the vadose zone.

2.1.5.1 Porosity

Porosity or volumetric porosity (ϕ) is defined as the ratio of the volume of voids to the bulk volume of a porous medium:

$$\phi = \frac{volume\ of\ voids}{bulk\ volume\ of\ porous\ medium} \tag{2-6}$$

If the void space includes all pores, the porosity is also called the total porosity. Interconnected pores are significant to groundwater flow, and are defined as the effective porosity. The effective porosity, ϕ_e, is the ratio of the interconnected void space and the bulk volume of the porous medium. The specific yield is defined as the drainable porosity or the storativity for unconfined aquifers. Primary porosity is affected by the soil or rock matrix, and secondary porosity is a result of secondary solution or fracturing. Porosity also may affect hydraulic conductivity. In coarse-grained soils, higher porosities may have higher hydraulic conductivities; in fine-grained soils (i.e., silts and clays) that have higher porosities than sands, however, hydraulic conductivities are generally lower.

The porosity of unconsolidated sediments depends on grain packing, particle, shape, and size distribution (Table 2-1).

Table 2-1. Total Porosity of Well-Sorted Soil

Material Type	Diameter (mm)	Total Porosity	Specific Yield (%)
Gravel			
coarse	64.0 - 16.0	28	23
medium	16.0 - 8.0	32	24
fine	8.0 - 2.0	34	25
Sand			
coarse	2.0 - 0.5	39	27
medium	0.5 - 0.25	39	28
fine	0.25 - 0.162	43	23
Silt	0.062 - 0.004	46	8
Clay	<0.004	42	3

Source: Morris and Johnson, 1967.

2.1.5.2 Fluid Content and Saturation

The volumetric fluid content (θ_α) is defined as

$$\theta_\alpha = \frac{volume\ of\ fluid}{bulk\ volume\ of\ porous\ medium} \tag{2-7}$$

The saturation (S_α) is defined as

$$S_\alpha = \frac{volume\ of\ fluid}{volume\ of\ voids} \tag{2-8}$$

The two variables are related to each other by

$$\theta_\alpha = \phi S_\alpha \tag{2-9}$$

where ϕ is the porosity.

In unsaturated flow, the voids are partly filled by air and partly by water; thus, $\theta_w < \phi$ and $S_w < 1$.

2.1.5.3 Bulk Density

The bulk density (ρ_b) is defined as the mass of dry soil (a soil sample after 24 hours of drying in an oven at 105°C) per bulk volume of soil.

$$\rho_b = \frac{mass\ of\ dry\ soil}{bulk\ volume\ of\ porous\ medium} \tag{2-10}$$

The density of solids or the mineral density (ρ_s) is the density of the solid material comprising the soil matrix, and it is defined as the mass of dry soil per volume of solids:

$$\rho_s = \frac{mass\ of\ dry\ soil}{volume\ of\ solids} \tag{2-11}$$

The relationship between ρ_b and ρ_s can be derived by using the above definitions.

$$\rho_b = \rho_s(1 - \phi) \tag{2-12}$$

where ϕ is the porosity.

2.1.5.4 Wettability

Whenever two or more fluid phases occupy pore space, one of the fluids will be adsorbed on the solid surfaces more strongly than the other fluid. The fluid that is most strongly adsorbed is called the wetting fluid or wetting phase. The displaced fluid is the nonwetting fluid. In most cases, liquids are adsorbed more strongly than gases (an exception is a mercury-gas system).

The angle θ between the interface and the solid surface (measured through the denser fluid) is called the contact angle. The contact angle of a wetting fluid is $\theta \leq 90°$ (Bear, 1972).

Wettability represents the preferential spreading of one fluid over the solid surfaces in a two-fluid system and is a function of the interfacial tension. A wetting fluid will tend to coat solid surfaces and occupy smaller openings in porous media, and the nonwetting fluid will tend to be constricted to the larger openings (Cohen and Mercer, 1993).

2.1.5.5 Relative Permeability

Relative permeability is the ratio of the intrinsic permeability for the fluid at a given saturation ratio to the total intrinsic permeability of the soil. The two or three fluids (air, water, and NAPL) in the unsaturated zone will compete for space in which to flow, thereby reducing the total pore space available to either fluid.

Relative permeability curves can be used to describe different types of multiphase flow regimes.

2.1.5.6 Hydraulic Conductivity

Hydraulic conductivity (K) is the rate of flow of water through a unit cross section under a unit hydraulic gradient. This conductivity is a function of the porous medium and the fluid properties. Hydraulic conductivity is an indication of the ease in which fluid will flow through a porous medium.

Hydraulic conductivity is defined as:

$$K = \frac{\kappa \rho g}{\mu} \qquad (2\text{-}13)$$

where:

κ = intrinsic permeability
ρ = fluid density
g = gravitational acceleration
μ = dynamic viscosity of the fluid.

2.1.5.7 Specific Surface

The specific surface (M) is defined as the total surface area of the pores per unit bulk volume of the porous medium.

$$M = \frac{surface\ area\ of\ pores}{bulk\ volume\ of\ porous\ medium} \tag{2-14}$$

The specific surface is also defined with respect to the "unit volume of solid material" or "unit mass of porous medium."

2.1.5.8 Sorption Capacity

Sorption capacity is a function of the cation exchange capacity and specific surface of a soil. Clays possess an overall net negative charge of their particles. Positive ions in the soil fluids become associated with the negative charged soil particles in order to maintain a chemical balance. This process, which is called the cation exchange, in conjunction with the surface area in the soils (very high for clays) available for contact with the solution will determine the sorption capacity of a soil.

2.2 Sampling Technologies

Once a conceptual model of the chemical presence, transport, and fate is formulated from the existing or preliminary site information (Figure 2-1), the site characterization process is applied (Figure 2-2). Site characterization methods include field point measurements and sampling of physical and chemical properties to improve the conceptual model and facilitate the risk and remedy assessment. Soil, soil vapor, pore water, and groundwater sampling and analyses are the principal components of the site characterization process. The objectives of the media sampling are to define:

- Local geology and hydrogeology (i.e., stratigraphy, capillary barriers, and traps)
- Estimated quantities of hydrocarbons released, the source areas, and affected zones
- Nature, extent, migration rate, and fate of contaminants
- Fluid properties (i.e., density, viscosity, solubility, sorptive properties, etc.)
- Media properties (i.e., permeabilities, porosities, organic content).

The remainder of this section presents various soil and groundwater sampling techniques and methods for conducting both on-site field analyses and laboratory analyses to support the objectives.

2.2.1 Soil Sampling Techniques

A wide range of techniques is available for soil sampling. The sampling techniques used to collect samples for measuring hydrocarbon releases in soil differ substantially depending on the following:

- Type of soil being sampled
- Anticipated sampling depths
- Soil sampling capabilities
- Equipment availability
- Cost.

For a more detailed discussion of the sampling techniques, the reader is referred to Driscoll (1986) or EPA (1993b) for a more thorough treatise on the subject.

Table 2-2 presents typical soil sample collection methods and techniques. Generally, samples taken from excavated soil or from the upper 3 feet of soil can be collected with simple hand tools such as trowels, shovels, spatulas, or manual soil boring methods. These samples are suitable for most analytical parameters and physical parameters not requiring undisturbed samples (i.e., bulk density, permeability). Samples are readily attainable, and minimal setup and preparation are required between sample locations.

Hydrocarbons that have migrated vertically from the source to depths greater than 3 feet often require techniques such as tube samplers and augers to collect representative soil samples. Augers consist of a center shaft and a spiral cutting blade that transports soil cuttings upward. Hand augers are generally used to depths not exceeding approximately 5 feet. Below 5 feet, hydraulically or mechanically driven equipment is generally employed. Machine-operated augers are driven by a motor (sometimes hand-held, but usually rig-mounted). The auger is rotated with downward pressure to penetrate the soil. Depths of 100 plus feet are possible, with depths being limited by the drilling rig torque capacity. Two common types of machine-operated augers are hollow-stem augers and solid-stem augers. The hollow-stem auger allows access of a sampling tool through its open annulus, whereas the solid-stem augers require temporary removal of the auger flight for access of the sampling tools (EPA, 1993b). The depth of auger investigations is usually limited by groundwater depth, soil characteristics, and the equipment used. Augers can be used to provide disturbed soil samples or for advancing boreholes so that other types of sampling devices can be used.

Two common sampling devices used in connection with auger drilling are the split-spoon and the conventional thin-walled tube samplers. These sampling devices work well in soils that contain sufficient clay or are cohesive enough for the material to remain stable during sample collection and retrieval. The split-spoon sampler (Figure 2-3) is a thick-walled tube that is split in half longitudinally and can be separated to expose and remove the soil sample. The Modified California Sampler is a split-spoon that

Table 2-2. Summary of Common Techniques for Investigating and Sampling Hydrocarbon Contamination (From U.S. Air Force, 1993)

			Applicable Subsurface Conditions for Approach				
			Unconsolidated Media			Consolidated Media	
Subsurface Media	Hydrocarbon Phase	Sampling Approach	Shallow	Intermediate	Deep	(Any Depth)	Comments on Sampling and Analytical Methods
Unsaturated Soil	Vapor	Excavations	X	X			Direct-reading field instruments could apply to all sampling approaches. Buried accumulators would apply mainly to excavations and shallow borings. Some field and laboratory analytical methods are applicable to vapor samples.
		Subsurface borings using:					
		Ground-penetrating probes[a] (direct push)	X				
		Hand auger[a]	X				
		-Piston sampler	X	X			
		-Drive or core barrel sampler	X	X	X		
		-Coring	X	X	X	X	
		Vapor-well installation using:					
		Hand auger[a]	X				
		-*In situ* sampling (direct push) technology	X	X			
		-Drilling technology	X	X	X	X	
	Liquid, Adsorbed	Excavations	X	X			Some field screening methods (e.g., TPH analyses and mobile-laboratory analyses) are available for assessing hydrocarbon contamination of soil. Laboratory analytical methods also are typically used to confirm contaminant levels.
		Subsurface boring using:					
		Hand auger[a]	X				
		-Piston sampler	X	X			
		-Drive or core barrel sampler	X	X	X		
		-Coring	X	X	X	X	
		Tensiometer and lysimeter probes	X				

Table 2-2. (continued)

			Applicable Subsurface Conditions for Approach				
			Unconsolidated Media			Consolidated Media	
Subsurface Media	Hydrocarbon Phase	Sampling Approach	Shallow	Intermediate	Deep	(Any Depth)	Comments on Sampling and Analytical Methods
Saturated Soil	Liquid Adsorbed	Subsurface boring using: Hand auger[a] -Piston sampler -Drive or core barrel sampler -Coring	 X X X X	 X X X	 X X	 X	Some field screening methods (e.g., TPH analyses and mobile laboratory analyses) are available for assessing hydrocarbon contamination of soil. Laboratory analytical methods also are typically used to confirm contaminant levels.
Groundwater	LNAPL	Excavations and existing subsurface facilities	X				Samples typically are collected using bailers or pumps.
		Temporary wellpoints and observation wells installed by: Hand auger[a] *In situ* sampling (direct-push) technology[a] -Drilling technology	 X X X	 X X	 X	 X	Samples can be characterized physically and chemically by laboratory analytical methods. Laboratories can be mobile or fixed.
	Dissolved	Temporary wellpoints and observation wells installed by: Hand auger[a] *In situ* sampling (direct-push) technology[a] -Drilling technology	 X X X	 X X	 X	 X	Samples typically are collected using bailers or pumps. Samples can be screened effectively in the field using indicator and portable laboratory analytical equipment.
		In situ sampling using: *In situ* sampling (direct-push) technology[a] -Packer assemblies	 X	 X	 X	 X	Laboratory analytical methods are commonly used to characterize contaminants and to verify results of field screening efforts.
		Permanent monitoring wells (installed by drilling technology)	X	X	X	X	Close support laboratories can be used on larger projects for rapid turnaround of final laboratory results.

[a] Indicates a field-screening method that can be applied quickly and cheaply to rapidly obtain data.

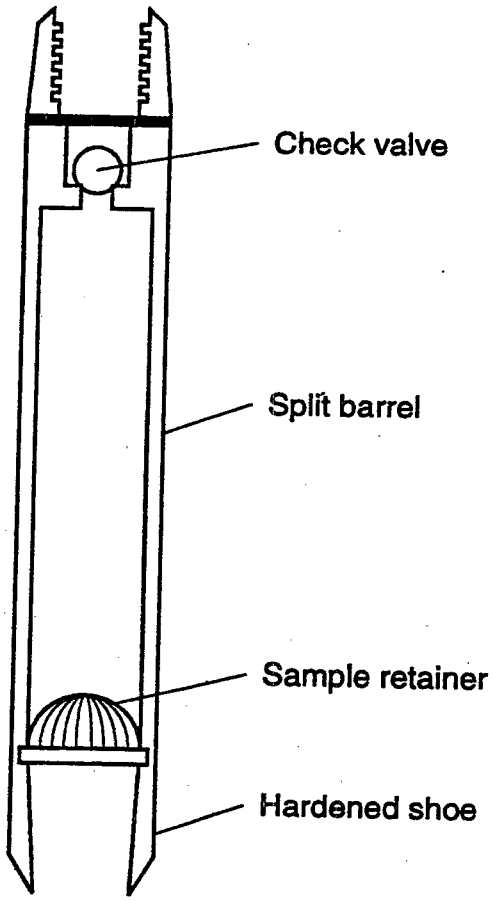

Figure 2-3. Split-spoon sampler.

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contains several brass sleeves with metal fingers to retain less-cohesive sandy soils. Brass sleeves can be used in either sampler to maintain sample integrity for laboratory determination of volatile organic compounds. Both samples are suitable for either cohesive or noncohesive soils. Although they can be used for soils with gravels, large gravel or cobbles can obstruct the sample and affect recovery.

As shown in Figure 2-4, the thin-walled tube sampler (also known as a push tube or a Shelby tube) is a long, thin cylinder typically constructed of stainless steel or brass. A sample is obtained by hydraulically pushing the tube under constant pressure for 24 to 30 inches. The thin-walled sampler is not suited for soils with cobbles that could be obstructions because the device will tend to collapse or otherwise bend from the resistance. This sampler will provide an undisturbed sample suitable for all analytical and physical testing.

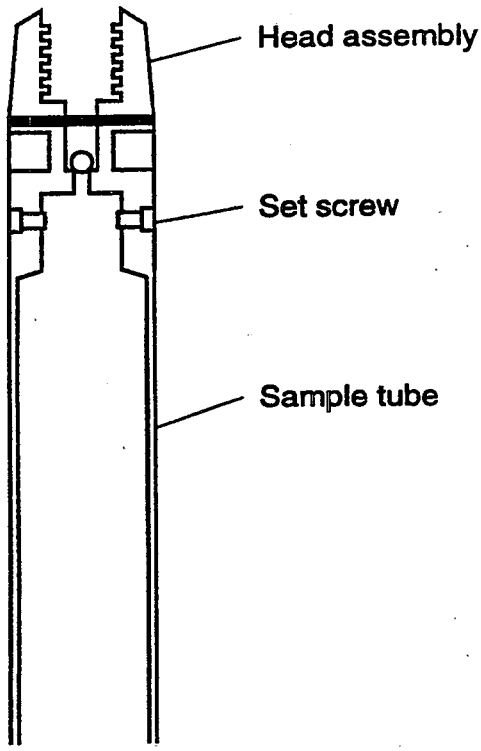


Figure 2-4. Thin-wall sampler.

Other investigative and sampling techniques that have gained popularity in recent years are the cone penetrometer and hydraulically or mechanically driven probe samplers. Driven probes consist of a cone tip or probe tip attached to a series of push rods driven into the ground by a truck-mounted hydraulic drive system. A specially equipped truck or van is used to house, transport, and deploy the driven probe sampler or the cone penetrometer. Driven probe samplers are suitable to depths of up to 100 feet in soils free of cobbles. Several makes and models are available that are capable of sampling soils, soil vapors, and groundwater.

In poorly to moderately consolidated soil or sediment, hydraulically or mechanically driven probe samples should be used to collect soil samples for residual liquid hydrocarbon analysis. Soil samples for residual hydrocarbon analysis should be collected from both above and below the water table. The depth to the water table and the presence of liquid hydrocarbons should also be documented. These horizons are usually evident based on the texture, soil color, and odor of the soil. The presence of free-phase hydrocarbons in the soil boring is clear evidence that a free hydrocarbon plume has been penetrated.

Although not commonly undertaken, test pits and trenches may be excavated at some sites to allow visual inspection of, and access to, shallow subsurface soils. Test pits and trenches are open excavations that allow observation of the shallow subsurface conditions at a site. They are excavated manually or more commonly with the means of a backhoe, trench excavator, or other earth-moving equipment. An excavation is a relatively inexpensive method for exploring contamination to depths less than 15 feet; however, it is more suited to sites with cohesive soils that will be self supporting and able to maintain stable sidewalls. Test pits may require the use of contaminated soil handling, produce fugitive hydrocarbon vapor emissions, and have safety hazards requiring shoring in accordance with standards established by the Occupational Safety and Health Administration (OSHA).

2.2.2 Soil Vapor Sampling

The behavior of a contaminant in the subsurface is difficult to predict given the complexity of the soils and the chemical properties of the organic substances. Contaminants that have migrated through the soils or that have volatilized into the vadose zone can produce free and residual hydrocarbons in the soil. Soil vapor sampling may be required to define the presence and extent of vapor phase hydrocarbons in the soil pore spaces. Both static and dynamic techniques can be used to conduct soil vapor sampling. Static sampling is accomplished either with an in situ adsorbent (activated charcoal) sampler left in the ground to adsorb the volatile organic compounds or as a static grab sample from a soil sample taken from the ground (head space measurement). These techniques do not provide equivalent measurements and may not provide reliable and representative results, but they can be used as initial screening tools to focus the site characterization investigation. A vertical profile of soil vapor contaminants should be developed to properly evaluate the soil vapor distribution in the subsurface. Three-dimensional sampling will fix the zone of highest contamination in space and focus on remedial technologies.

Headspace is typically measured by placing a soil sample in a clean container and allowing the sample to equilibrate to the ambient air temperature. An organic vapor detector [i.e., photoionization detector (PID) or flame ionization detector (FID)] is then used to screen the air space of the container. The technique can be modified by placing the sealed soil container in a hot bath to volatilize the organic compounds prior to monitoring of the head space vapors. Analytical methods for making these measurements are discussed further in Section 2.3.1.

Dynamic samples may be collected from an air stream withdrawn from the soil pore space. The air is drawn from the soil by a vacuum applied to a probe driven into the soil. An inward gradient is created toward the probe by the vacuum, and the soil vapor is evacuated. A soil gas sample is then collected from the mobilized air stream. A total organic vapor detector or a gas chromatograph is used to analyze the sample.

2.2.3 Soil Pore Water Sampling

Contaminants moving downward through the subsurface will pass through the vadose zone. The contaminants migrate through pore spaces in the soil that are not filled with water or other fluids and may remain or be adsorbed to soil particles. The vadose zone intervals are monitored to characterize the site. The vadose zone pore water under negative pore pressure, or tension, will not readily flow to allow for sample collection. Soil pore water samples can be collected with suction lysimeters, however.

A suction lysimeter is a common vadose zone sampler comprised of a porous cup attached to a hollow tube. Flexible tubing attached to the sampler allows sample collection at the surface. A vacuum is applied to the tube and held for a specified period. A vacuum greater than the negative pore pressure will cause a gradient on the tube, and pore water will accumulate in the sampler or be pulled to the surface via sample tubing depending on the configuration of the lysimeter used. The porous cup is constructed of ceramics, nylon, PFTE, or fritted stainless steel, depending on sample-specific requirements. The sample tube is either PVC or stainless steel (Fetter, 1993).

The vacuum-pressure lysimeter is a modified version of the suction lysimeter. This device is configured with two tubing lines: one for application of a vacuum to draw the pore water into the sampler and a second to drive the fluid to the surface for collection. Once the fluid is drawn into the tube sampler, the vacuum line is then pressurized and the fluid sample is driven through the second line. Part of the sample may be driven back through the porous cup into the formation when pressure is applied to the sampler (Everett, et al., 1984).

2.2.4 Groundwater Sampling Techniques

Because some of the components of hydrocarbons are soluble in water, groundwater sampling is required to characterize the site and determine the nature and extent of contamination in the subsurface. Groundwater is sampled at permanent or temporary sample locations by using a variety of extraction pumps, sampling devices, or sensors. The sampling techniques used to collect samples for measuring hydrocarbon releases in groundwater differ depending on the sampling depths and the volume of sample required. Sample locations are permanent, as in the case of constructed screened wells, or temporary one-time sample points, as are utilized with driven probe samplers.

The number and location of sampling points required for an assessment are site specific. A minimum of three spatially distributed wells are required to define the piezometric or potentiometric surface. One point is generally required upgradient to provide background information. The number of downgradient wells depends on site-specific conditions and the nature of the contaminant including but not limited to the following:

- Contaminant properties (solubility, density, reactivity)
- Groundwater system influences (pumping, migration pathways)

- Media properties
- Location of receptors.

In addition, it may be necessary to assess conditions at variable depths and to develop a three-dimensional image of the subsurface. This situation could require the use of cluster, or nested wells. Nested wells are grouped wells that are screened at individual horizons in one immediate area to monitor vertical gradients and groundwater quality. Seasonally saturated intervals or water table fluctuations also should be considered in defining the horizons and spatial distribution of sampling points.

The following discussions will present temporary and permanent sampling point techniques available for groundwater characterization. These techniques are summarized in Table 2-2.

2.2.4.1. Conventional Sampling Methods

A conventional groundwater sampling approach utilizes constructed wells completed at specific horizons. A wide choice of well construction materials, including fluoropolymers, metallics, and thermoplastics, is available that should be matched for compatibility with known contaminants. It should be noted that each material has its clear advantage for application to specific contaminant classes.

Wells typically consist of a well casing, a filter pack consisting of a specified gradation of sand to prevent infiltration of fine-grained formation soils, and an annular seal that includes expansive clay to isolate a discrete monitoring horizon or prevent vertical migration of surface water down the well casing (Figure 2-5). Screens may be of the same construction material as the well casing or, if appropriate for the contaminant, a hybrid construction with different materials to reduce the cost of construction materials. Where wells are constructed such that the screen extends across the water table and contaminants are not likely to contact the well casing, different materials may be used than those used for the screen interval in order to reduce costs or improve construction efficiency.

Once the wells are constructed, samples are collected by manual or mechanical techniques. Manual techniques consist primarily of bailers and are most effective for the sampling of shallow wells of less than 100 feet. Mechanical techniques consist of a variety of electrical and air-driven pumps. Pumps generally are used on wells requiring the removal of large volumes of purge waters or for deep wells over 100 feet. Bailers are better suited for shallow wells or for those requiring only limited purge water extraction.

Appropriate sampling equipment should be matched to the objectives of the analytical program. Sample devices are constructed of inert materials suitable for the analytes of interest, typically Teflon® or stainless steel. If samples are to be collected for volatile organic compounds, bailers or positive displacement pumps such as bladder pumps

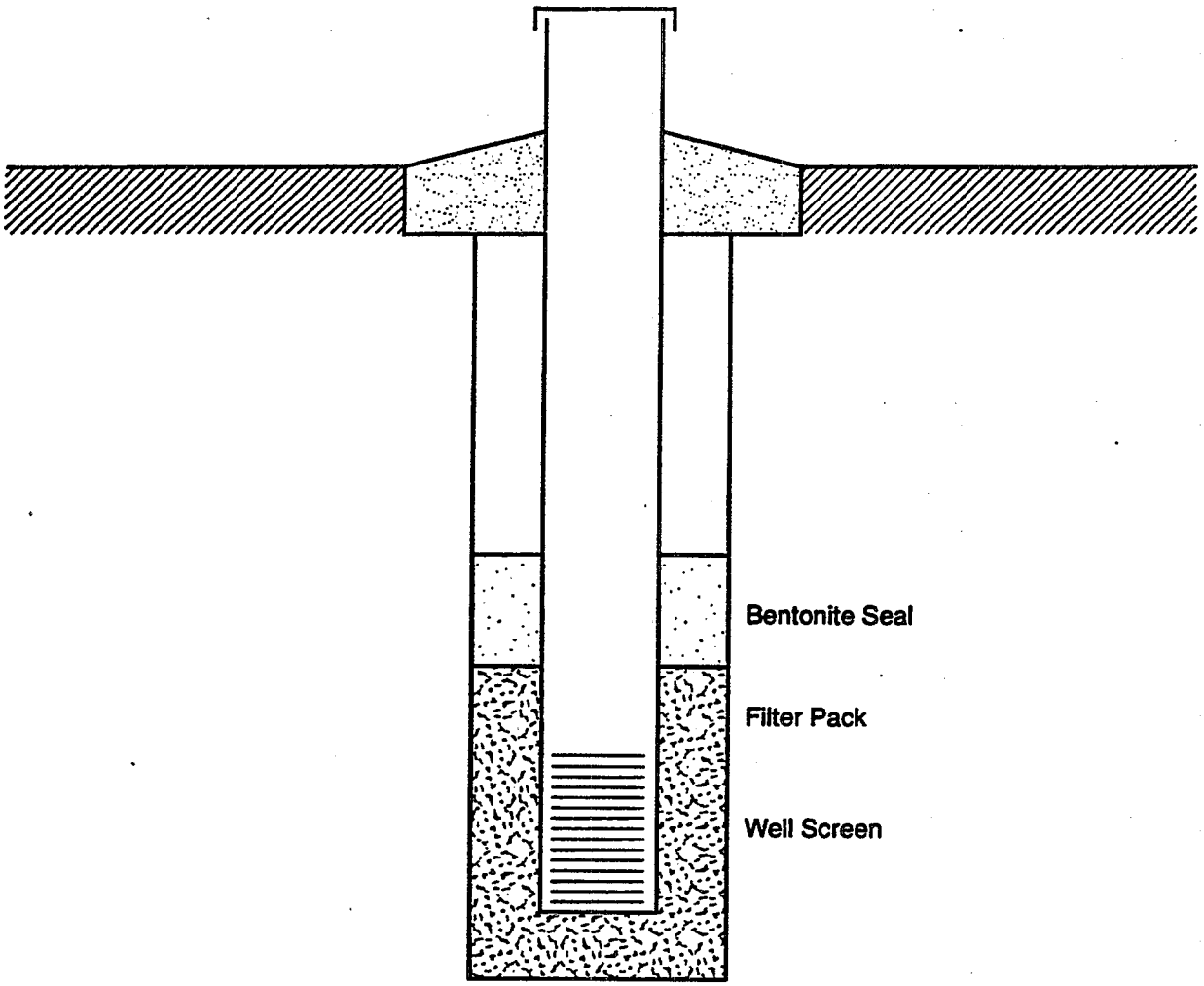


Figure 2-5. Typical monitoring well.

should be used to prevent loss of volatile components. Suction lift (peristaltic and centrifugal) and some electrically driven impeller pumps suitable for purging and sampling of other compounds should be avoided for VOC sampling because they may cause volatiles to be lost due to degassing of the water or turbulent sample flow.

Bailers are the simplest and most portable of the sampling devices. They consist of a rigid tube that fills with water when lowered into a well. As the device is retrieved, one or both ends of the tube are sealed by a check valve to prevent loss of water back into the well casing. Bailers are constructed of PVC, Teflon®, or stainless steel. Normally it is best to dedicate one bailer to a well to prevent cross-contamination. When a bailer is not dedicated to a single well, it must be thoroughly decontaminated between sampling

of individual wells. The representativeness of the sample depends on the user's technique when using a bailer and could vary between users (Driscoll, 1986).

Bladder pumps or gas-driven piston pumps are simple technical devices that operate as the name suggests. Water enters a bladder pump through the bottom and is forced under a continuous column to the surface through contraction of the bladder by compressed air. Water samples are separated from the air by individual bladders, and cross contamination is avoided. Pumps of this design can maintain very low flows (i.e., 100 ml/minute) suitable for sampling. Decontamination is difficult and pumps dedicated to individual wells are recommended (EPA, 1993b).

In a gas-driven piston pump, gas is injected through one of two tubes to lower the piston in the gas chamber, thereby allowing water to fill the upper chamber. Air under pressure is applied via a separate tube to push the piston upward to drive the sample to the surface. These pumps may operate at great depths but at lower flow rates than submersible pumps discussed below. The pumps' valves and pistons are sensitive to sediment and require thoroughly developed wells (EPA, 1993b).

The suction lift pump lifts the sample to the surface by applying a vacuum at the surface. Negative pressure is applied by a portable pump through a tube lowered into the well. Because of limits in the physics of fluid flow, these pumps have a practical lift limit of 23 to 26 feet. Only the tubing need contact the sample, and decontamination is minimal. These pumps are portable and relatively inexpensive. Negative pressures may promote degassing and loss of volatiles.

Electric pumps operate with a submerged, motorized pump that drives impellers to deliver water to the ground surface. A variety of pumps are available, but few are designed specifically to collect groundwater samples. (The Grundfos® Rediflo II is one such sampling pump.) Turbulent flow and water agitation within the pump can promote degassing and volatilization. Although pump designs are changing to reduce agitation, the user is cautioned to select the appropriate pump. Submersible pumps are capable of greater pumping heads than most other pump types (in excess of 150 feet) and at high flow rates. The initial costs of these pumps are greater than for other designs, and decontamination can be difficult.

2.2.4.2 Driven Probe Sampling Methods

A relatively new type of groundwater sampling technology that has developed in recent years is the in situ sampling probe or driven method. This technique allows rapid collection of samples without the installation of permanent wells. These methods are developed from variations of the conventional cone penetrometer drive devices. They are best employed in the preliminary site characterization stages where shallow and rapid sampling options best suit the objectives.

The soil-probe-type samplers include but are not limited to the Geoprobe®, Hydropunch®, and the BAT system samplers and are variations of the cone penetrometer method originally developed to measure soil physical properties. The probes are typically hydraulically driven to the horizon of interest, where a sample is collected via a bailer type device in the push rods or with an evacuated vial configured with a septum. The Geoprobe and Hydropunch use a sacrificial drive point that remains in the subsurface and provides a one-time sample (no additional samples can be collected from the driven location). Additional samples require additional points to be driven. The BAT system may be used as a temporary sample point or can be used to construct a permanent sample point that may be revisited for additional samples.

The cone penetrometer test (CPT) is used to stratigraphically log soils and to determine various hydraulic parameters. Soil permeability, groundwater head, and water-bearing zones can be derived from the pore pressure data generated during the CPT run. As the push rods are driven into the ground, excess pore pressure is produced. When steady penetration is stopped, the excess pore pressure will decrease over time and provide the information needed to calculate hydraulic conductivity. This method is not as accurate for clean sands and coarser materials because the excess pore pressure generated during the penetration of these materials is dissipated almost as soon as it is produced.

Driven probe samplers may be successfully employed in soils to depths of 100 feet. Devices that rely on groundwater suction for sampling will be limited to depths of approximately 25 feet. Success depends on the nature of the soils and the potential for obstructions to limit penetration. These devices may be used to sample groundwater for all analytical constituents; where suction-type pumps are used, however, caution should be exercised. Positive displacement pumps or bailers are best suited for VOC sampling.

2.3 Analytical Methods

State regulatory programs require laboratory analyses of soil samples as part of the site assessment and corrective action plan pertaining to soils containing petroleum hydrocarbons; however, properly applied and performed field measurement techniques can provide results more rapidly and useful for making on-site decisions. On-site analytical methods are capable of providing chemical-specific quantitative data in the field or in a nonlaboratory setting. Results from laboratory analyses provide quantitative data on petroleum hydrocarbon concentrations. The following sections present the techniques and methods utilized in both the on-site and fixed-based laboratory analyses.

2.3.1 On-Site Analytical Methods

Properly applied and performed field measurement techniques provide faster results for making on-site decisions than do laboratory analyses. Because field measurements are proving to be useful, new and improved instruments and techniques are being developed. Table 2-3 presents performance information on currently available field

Table 2-3. Summary of Soil and Soil Vapor Field Measurement Procedures and Analytical Instrument Performance

Procedure	Measuring Device	Lower Detection Limits for Gasoline[a]		Estimated Time for Collection and Analysis (minutes)
		Soil and Water	Soil Vapor	
Drager tube	Colorimetric Tube	NA	b	5
General headspace analysis[c]	FID[d]/PID/colorimetric detector tube	10's-100's ppm	10's-100's ppm	10-20
	GC	ppb	ppb	
Polyethylene bag sampling system	FID/PID colorimetric detector tube	1 ppm	1-100's ppm	10-20
	GC	10's-100's ppb	ppb	20
Extraction-colorimetric procedure	NA	Soil: 1 ppm Water: 0.1 ppm	NA	Soil: 45-60 Water: 10-15
Soil vapor	FID/PID/colorimetric tube	NA	10's-100's ppm	10-30
	GC	NA	ppb	15-35

[a] Determined by spiked field standards.

[b] Parameter specific.

[c] General headspace analysis refers to dynamic and static headspace analysis.

[d] Notes: FID = flame ionization detector; PID = photoionization detector; GC = gas chromatograph; ppm = parts per million; ppb = parts per billion; NA = not applicable.

techniques. The advantages of field measurement procedures and instruments include the following:

- Reliable qualitative and semiquantitative data that is produced on site can be used to make immediate decisions regarding the need for further assessment and ongoing remediation.

- The lower cost of field measurements allows more sampling points to be included in the site assessment, which results in a more comprehensive set of data.

- Immediate sample analysis reduces sample handling and eliminates sample storage, thus minimizing the loss of volatiles.

The disadvantages of field measurement procedures and instruments include the following:

- Depending on the procedure or instrument used, the results are generally semiquantitative or qualitative.

- The age, degree of weathering, or type of petroleum hydrocarbons in a sample determines which field technique will be used. (Some techniques, such as headspace methods that are less sensitive to nonvolatile constituents, are not well suited for weathered products.)

- Field techniques are subject to procedural errors that can affect the reliability of the results.

- Several state underground storage programs currently do not accept field measurement results alone (i.e., laboratory results are also required).

Although information collected by field measurement procedures can save time and money, many state and local agencies require laboratory analyses to verify field information, to quantify benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations and total petroleum hydrocarbon (TPH) levels, or to test for less-volatile products (e.g., diesel fuel).
Comparing results obtained by field measurement procedures and instruments with those obtained by laboratory analyses is difficult. As indicators of the presence of hydrocarbons, both techniques can provide useful results (given proper performance of the field technique). The types of results differ, however. Most field procedures and instruments test for groups of constituents, whereas most laboratory methods can be selected to analyze for individual constituents or groups of constituents. Also, the different detectors used in the field do not always evaluate the same range of hydrocarbons as the laboratory methods.

A significant variability factor also enters into comparisons of field and laboratory analyses. Field measurement methods can yield variable results because of variable instrument response, variable conditions in the outdoor environment, inconsistent protocol, detector limitations, and inappropriate calibration. Laboratory analyses can be significantly influenced by sample collection method, holding time, and sample transport. For these reasons, it is important to have a well-thought-out Quality Assurance/Quality Control (QA/QC) program to help eliminate external influences on analytical results.

Both field and laboratory analyses provide useful information for investigating a release. Field data are most reliable when obtained by a competent, well-trained field analyst using properly calibrated and maintained field instruments.

A wide range of field analytical instruments is available for determining the presence of volatile petroleum hydrocarbons in soil. Some simply detect the presence or absence of unspecified groups of volatile chemicals, whereas other more-sophisticated tools can identify and quantify specific constituents. The instruments discussed below are those commonly used to detect volatile organics.

2.3.1.1 Colorimetric Detector Tubes

A colorimetric detector tube is one of the simplest field analytical tools. Each tube is designed to monitor a specific vapor or gas in air. They consist of tubes packed with admixtures to react with the chemicals of interest. Although these tubes have some limitations in terms of accuracy and detection range, they have the advantages of being inexpensive and easy to transport, use, and interpret.

2.3.1.2 Photoionization Detector

Portable photoionization detectors (PIDs) are relatively easy to use in the field and particularly sensitive to aromatic hydrocarbon constituents. The PID utilizes an ultraviolet light to ionize the vapor sample in order to detect and measure the presence of organic vapors. The detection range for these instruments is about 0.2 to 2000 parts per million (ppm). Accuracy varies with the concentration level being measured, type of constituents present in the sample, and amount of moisture drawn into the instrument.

Because PIDs do not detect alkanes such as methane, they can be useful in detecting aromatic constituents released in areas containing natural methane (such as in septic fields, sewer lines, and bogs). The responsiveness of PIDs decreases in moist conditions when the relative humidity of the sample or ambient air is high (above 90 percent).

2.3.1.3 Flame Ionization Detector

Flame ionization detectors (FIDs) are commonly used to measure the presence of organic gases and vapors. This instrument uses a hydrogen flame to ionize molecules of volatile organic constituents (VOCs) in the vapor sample. The ionized molecules produce a current proportional to that of the sample. The FID will detect the presence of volatile vapors, including methane, that may yield high readings (false positives) in

areas where methane levels are higher than normal (for example, wetlands, sewers, septic fields, and bogs). A direct-reading colorimetric detector tube specific to methane can be used in conjunction with an FID to evaluate methane concentrations. The FIDs are less sensitive than PIDs to environmental conditions such as relative humidity and temperature; however, winds, excess carbon dioxide, and depleted oxygen can extinguish the flame in the instrument. These instruments are also more sensitive than PIDs to alkanes such as hexane and butane, which make up a higher fraction of gasoline than do the aromatics.

2.3.1.4 Portable Gas Chromatograph

A portable gas chromatograph (GC) uses a separation column to isolate and analyze specific constituents in either a liquid or vapor phase in conjunction with a PID or an FID detection system. A portable GC consists of a sample injection system, a separation column, an output detector, and a detection system. A GC/FID system contains a combustible gas supply for the flame; a GC/PID system contains an ultraviolet (UV) lamp. Although this GC is portable, it still requires a stable field location (i.e., air conditioned/ heated office trailer) and it is not suited for hand carrying to individual site locations. The instrument is fairly accurate with reproducible results.

2.3.2 Laboratory Analytical Methods

State regulatory programs require laboratory analysis of soil and groundwater samples for confirmation sampling as part of the site assessment and corrective action program for media containing or having the potential for containing petroleum hydrocarbons. Laboratory analytical results provide quantitative data for determining the presence of hydrocarbon compounds in soil or groundwater. The methods generally are performed in accordance with EPA Method SW-846, Test Method for Evaluating Solid Waste; however, a broader ranger of methods may be applied because of the complex combination of constituents with different physical and chemical properties (e.g., Methods 418.1, 8020, etc.). Table 2-4 presents a general overview of the analytical methods and their application.

Analytical methods range from the generic Total Petroleum Hydrocarbon (TPH) methods to the highly selective and sensitive Gas Chromatograph (GC) methods used to analyze constituents. Indicator parameter methods (i.e., TPH) focus on the common characteristics of several petroleum hydrocarbon constituents and are used as a screening method for identifying gross amounts of TPH. These methods specify the use of organic solvents to remove hydrocarbons from the soil matrix. Such methods neither accurately measure the lighter fractions nor identify any natural soil organics derived from biological activity (API, 1993). API has developed a method to prevent the loss of volatile compounds between sample collection and analysis using either methanol or methylene chloride as a preservative. Table 2-4 lists the methods commonly used to detect, identify, and quantify indicator parameters and specific constituents in soils. Table 2-5 lists the methods commonly used for analyzing dissolved contaminants.

Table 2-4. Analytical Methods for Soil Samples

Parameter	Method[a]	Comment
Benzene, xylene, toluene, and ethylbenzene (aromatic volatile organics)	EPA 5030A EPA 8020a[b] EPA 8021A[b] EPA 8240A[a]	Purge-and-trap extration Method GC-PID, ignores MTBE GC-ECD/PID in series GC/MS (typically used for gasoline)
Polynuclear aromatic hydrocarbons (PAHs)	EPA 3550A EPA 8270A	Ultrasonic extraction method GC/MS (typically used for used-motor oil and unknown)
Total petroleum hydrocarbons	EPA 418.1[b,c] EPA 8015A[b]	Does not distinguish between naturally occurring oils and petroleum-based oils Does not measure lighter fractions, such as BTEX
Naphthalene	EPA 8100	
Benzene and 1,2-dichloroethane (TCLP)	EPA 1311[d] EPA 8240A[b]	Zero headspace extraction GC/MS analysis
Lead (TCLP)	EPA 1311[d] EPA 6010 EPA 7421A EPA 7420A	TCLP leaching method Inductively-coupled plasma (ICP) Graphite furnace AA Flame AA
Ignitability/flash point	EPA 1010A EPA 1020A	Applies to liquids only, but is used on soils
Oil and grease	EPA 9071A	
Percent moisture	ASTM D2216	
pH	EPA 9045A	Soil pH method
Organic matter concentration (total organic carbon)	EPA 9060A	High-molecular-weight oils
Grain size analysis	ASTM D422	Sieve and hydrometer analysis

[a] EPA, Test Methods for Evaluating Solid Waste.

[b] The method cannot distinguish between soil matrix interferences and the target compounds or constituents.

[c] EPA Methods for Chemical Analysis of Water and Wastes.

[d] 40 Code of Federal Regulations Part 261, Appendix II.

Table 2-5. List of Dissolved Hydrocarbons and Corresponding Methods of Analysis (From U.S. Air Force, 1993)

Analytical Group	Constituent	Analytical Method[a]
Gasoline (motor gasoline, aviation gasoline, and gasohol)	1,2-dichloroethane	EPA Method 8010
	Benzene	EPA Method 8020
	Toluene	EPA Method 8020
	Ethylbenzene	EPA Method 8020
	Total xylenes	EPA Method 8020
	Total volatile organic aromatics	All detectable compounds by EPA Method 8020
	1,2-dobromoethane	EPA Method 8010 with ECD[b] substituted for Hall detector; 2-column confirmation
	Methyl-*t*-butyl ether	EPA Method 8020
	Total petroleum hydrocarbons	EPA Method 418.1 or 8015
Middle distillates (kerosene, diesel fuel, jet fuel, and light fuel oils)	Naphthalenes and other semivolatiles	EPA Method 8270
	Benzene	EPA Method 8020
	Toluene	EPA Method 8020
	Total xylenes	EPA Method 8020
	Ethylbenzene	EPA Method 8020
	n-propylbenzene	EPA Method 8020
	Total volatile organic aromatics	All detectable compounds by EPA Method 8020
	Total organic halocarbons	All detectable compounds by EPA Method 8020
	Total petroleum hydrocarbons	EPA Method 418.1 or 8015
Other or unknown	Priority pollutant Metals	Typically atomic adsorption; particular method dependent on metal analyzed
	Priority pollutant Volatile organics	EPA Method 8240
	Priority pollutant Extractable organics	EPA Method 8270
	Nonpriority pollutant Organics (with GC/MS peaks greater than 10 ppb)	EPA Methods 8240 and 8270
	Total petroleum hydrocarbons	EPA Method 418.1 or 8015

[a] Alternative methods, such as the EPA 500 and 600 series, exist and can be used in lieu of the EPA 8000 series. These methods have other detection limits or varying quality assurance/quality control criteria or both.

[b] Notes: ECD = electron capture detector; GC/MS = gas chromatography/mass spectrometry; ppb = parts per billion; *n*- = normal; *t*- = tertiary.

Chapter 3
Free Product Migration and Recovery

3.1 Introduction

Groundwater contamination from hydrocarbon spills or leaks is a widespread problem. The first step in assessing a spill site is to determine the areal and vertical extent of the contamination and to estimate the spill volume. The spilled product is defined as follows:

- *Residual hydrocarbons* retained in the unsaturated zone for small-volume releases or for a large depth to the groundwater surface.
- *Free product* for larger spill volumes or shallower water tables.

For larger spill volumes or shallower water tables, *nonaqueous phase liquid* (NAPL) may reach the groundwater where it will spread laterally if its density is less than water. Light nonaqueous phase liquids (LNAPLs) include most crude oils and common refined hydrocarbons including various aromatic solvents, gasoline, jet fuel, and various grades of fuel oil.

Common techniques for determining LNAPL volumes in the subsurface involve the use of shallow wells that intercept the water table to delineate the areal extent of free product floating on the water table or measurement of the total petroleum hydrocarbon (TPH) on soil cores. To quantitatively interpret monitoring well data, the product thickness measured in the wells must be converted to hydrocarbon-specific volume, i.e., hydrocarbon volume per unit area in the soil. The hydrocarbon-specific volume will typically be less than the well product thickness. A disadvantage of TPH measurement is that it yields a single measurement that is not suitable for long-term monitoring.

A theoretically based method for estimating hydrocarbon-specific volume from well product thickness was developed and reported by Lenhard and Parker (1990) and Farr et al. (1990). The method is based on the assumption that vertical equilibrium pressure distributions in the water and LNAPL phases close to the water table can be inferred from fluid levels in a well. An estimate of the volume of free product is determined on the basis of the hydrocarbon-specific volume at each monitoring well.

Initial remediation steps involve controlling and removing free product by pumping it from trenches or wells in order to limit the spread of the plume. Pumping rates should be selected to maintain hydraulic gradient control. Higher rates will lead to lower overall product recovery as NAPLs are smeared over a larger cone of depression in the water table and become trapped by capillary forces as residual hydrocarbons. The volume of free product that is recoverable will rarely reach 50 percent and may be less than 10 percent in unfavorable cases. Careful placement and design of free product recovery systems can have a major impact on recovery efficiency.

This chapter will present a discussion of the basic concepts of fluid movement and retention in multiphase porous media systems along with a discussion of the analytical tools available for assessment and remedial design of hydrocarbon spills as well as practical aspects of employing these methods to leaking UST sites. An overview will also be presented of the applications, limitations, and design considerations for different NAPL recovery systems.

3.2 Basics of NAPL Movement and Recovery

Theory of immiscible flow in porous media is not included in groundwater hydrology textbooks. However, knowledge of relationships between fluid pressure (P), saturations (S), and permeabilities (M) for the fluids of concern is required to predict advective velocities and saturations. In this section basic equations for multiphase flow and S-P relations are presented.

3.2.1 Continuity and Darcy Equations for Multiphase Flow

The following equations are used to describe the basic concepts of multiphase fluid movement and retention in porous media and thereby properly assess and remediate hydrocarbon spills.

3.2.1.1 Darcy Equation

The Darcy equation for any phase α (for water, α = w; for hydrocarbon, α = o; and for air, α = a) is given by:

$$q_{\alpha_i} = -\frac{k_{r\alpha}\, k_{ij}}{\mu_\alpha}\left\{\frac{\partial P_\alpha}{\partial x_j} + \rho_\alpha\, g\, u_j\right\} \qquad (3\text{-}1)$$

where:

q_{α_I} = volumetric flux of phase α in the *I*-th direction ($L^3\, L^{-2}\, T^{-1}$)
$k_{r\alpha}$ = *relative permeability* of the soil to phase α (-)
k_{ij} = *intrinsic permeability* tensor of the soil, *i,j* = x,y,z, (L^2)
μ_α = α-phase dynamic viscosity (MLT^{-1})
P_α = α-phase pressure ($ML^{-1}T^{-2}$)
χ_j = *j*-direction coordinate (L)

ρ_α = density of phase α (ML^{-3})
g = gravitational acceleration (LT^{-2})
u_j = $\partial z/\partial x_j$, a unit gravitational vector (+ upward) (-).

In groundwater hydrology, water-height equivalent heads rather than pressures are commonly used, and the equation may be written equivalently as:

$$q_{\alpha_i} = -\frac{k_{r\alpha}\, K_{sw_{ij}}}{\mu_{r\alpha}} \left\{ \frac{\partial h_\alpha}{\partial x_j} + \rho_{r\alpha}\, u_j \right\} \tag{3-2}$$

where:

$K_{sw_{ij}}$ = $k_{ij}\rho_w g/\eta_w$, the saturated conductivity for water (L/T)
$\mu_{r\alpha}$ = μ_α/μ_w, relative viscosity of phase α (-)
h_α = $P_\alpha/g\rho_w$, the water-equivalent pressure head of phase α (L)
$\rho_{r\alpha}$ = ρ_α/ρ_w, the specific gravity of phase α (-).

The generalized Darcy law can be used to describe the flow of water, NAPL, and air in soils when one, two, or three phases coexist within the pore space.

3.2.1.2 Mass Conservation Equation

Continuity equations can also be written for each phase. These equations require mass conservation for each phase; i.e., within a fixed soil volume, the change of mass within a phase equals the net difference of mass entering or leaving the phase.

For an incompressible fluid and porous medium, the continuity equation for bulk phase α is:

$$-\frac{\partial}{\partial x_i}\left(\rho_\alpha\, q_{\alpha_i}\right) = \frac{\partial}{\partial t}\left(\rho_\alpha \phi\, S_\alpha\right) \tag{3-3}$$

where:

q_{α_I} = volumetric flux of phase α in the *I*-direction (LT^{-1})
ρ_α = density of phase α (ML^{-3})
S_α = fraction of pore space filled with phase α (saturation) (-)
t = time (T)
ϕ = soil porosity (-)
x_i = *I*-direction coordinate (L).

In order to make use of these equations, the relations between fluid pressures, fluid saturations, and fluid relative permeability must be understood.

3.2.2 Capillary Retention and Relative Permeability Relations

3.2.2.1 Two-Phase Capillary Pressure Relations

Two-phase capillary pressure relations define the *capillary pressure*, P_c, between two phases (e.g., air and water or oil and water) by:

$$P_c = P_{nw} - P_w \tag{3-4}$$

where P_{nw} and P_w denote *nonwetting* and *wetting* phase pressures, respectively.

The *capillary head,* h_p, is similarly defined by:

$$h_p = h_{nw} - h_w \tag{3-5}$$

where h_{nw} and h_w denote nonwetting and wetting phase *pressure heads*, respectively.

The schematic shown in Figure 3-1 of a hypothetical pore cross section illustrates the difference between the wetting phase and the nonwetting phase in a two-phase system. The wetting phase may be water, and the nonwetting phase may be oil or air. The interface curvature is related to the capillary pressure by the Laplace equation of capillarity, which is given by:

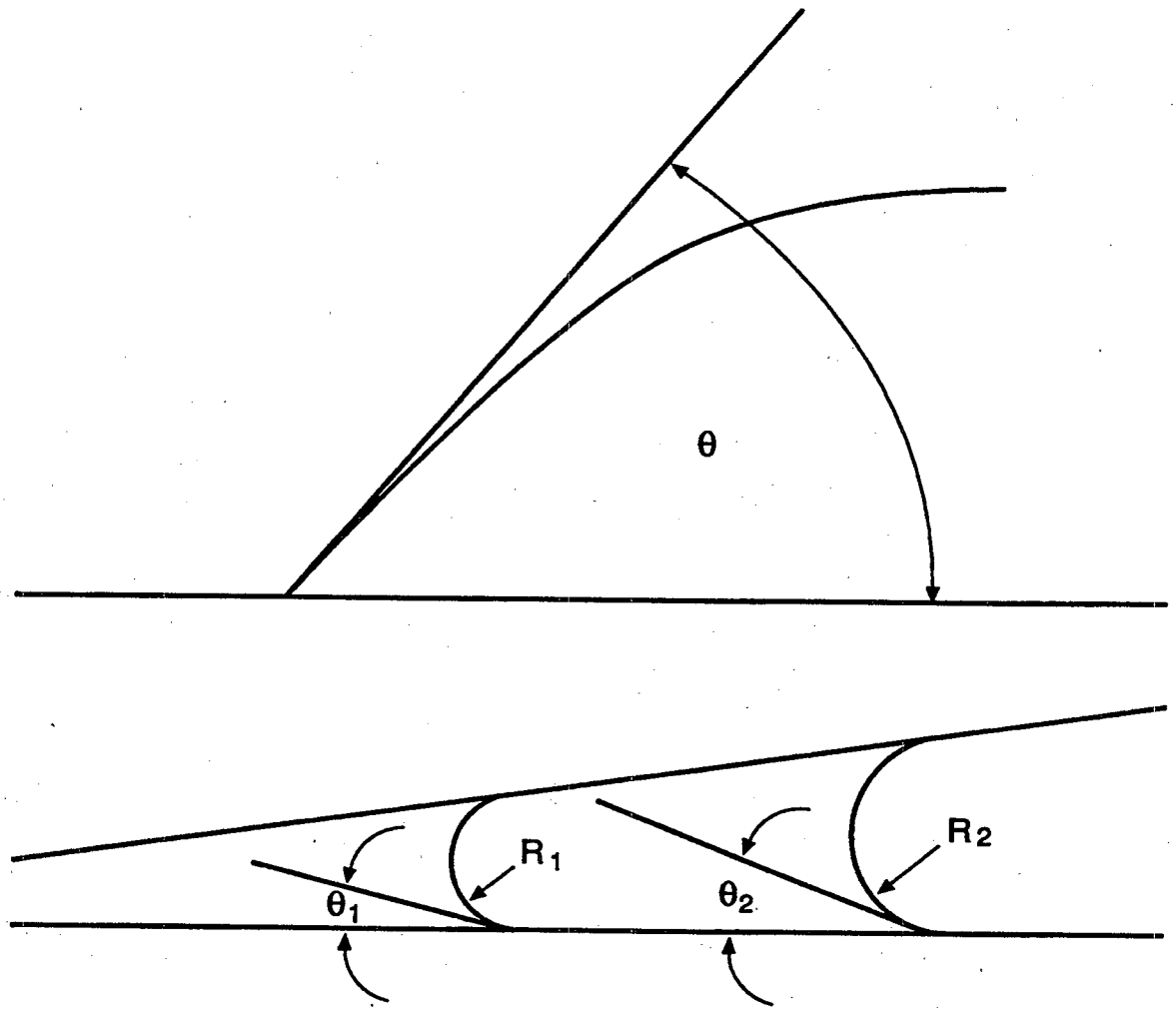
$$P_c = \frac{2\,\sigma}{r} \cos\theta \tag{3-6}$$

where:

θ	=	contact angle
r	=	radius of interface curvature (L)
σ	=	interfacial tension between the fluids (MT^{-2})
P_c	=	capillary pressure ($ML^{-1}T^{-2}$).

Note that the capillary pressure, P_c, will increase as the fluid retreats into smaller pore cross sections when the wetting phase saturation diminishes.

Consider an idealized representation of soil as a bundle of variously sized capillary tubes (see Figure 3-2) at equilibrium with the water table. At the water table, the water and air pressures are equal, so the capillary pressure is zero. The air-water capillary pressure head will increase linearly above the water table, and the capillary rise will depend on the radius of each "pore." The degree of saturation with the wetting phase



θ is the contact angle

Figure 3-1. Hypothetical pore cross section with two fluids.

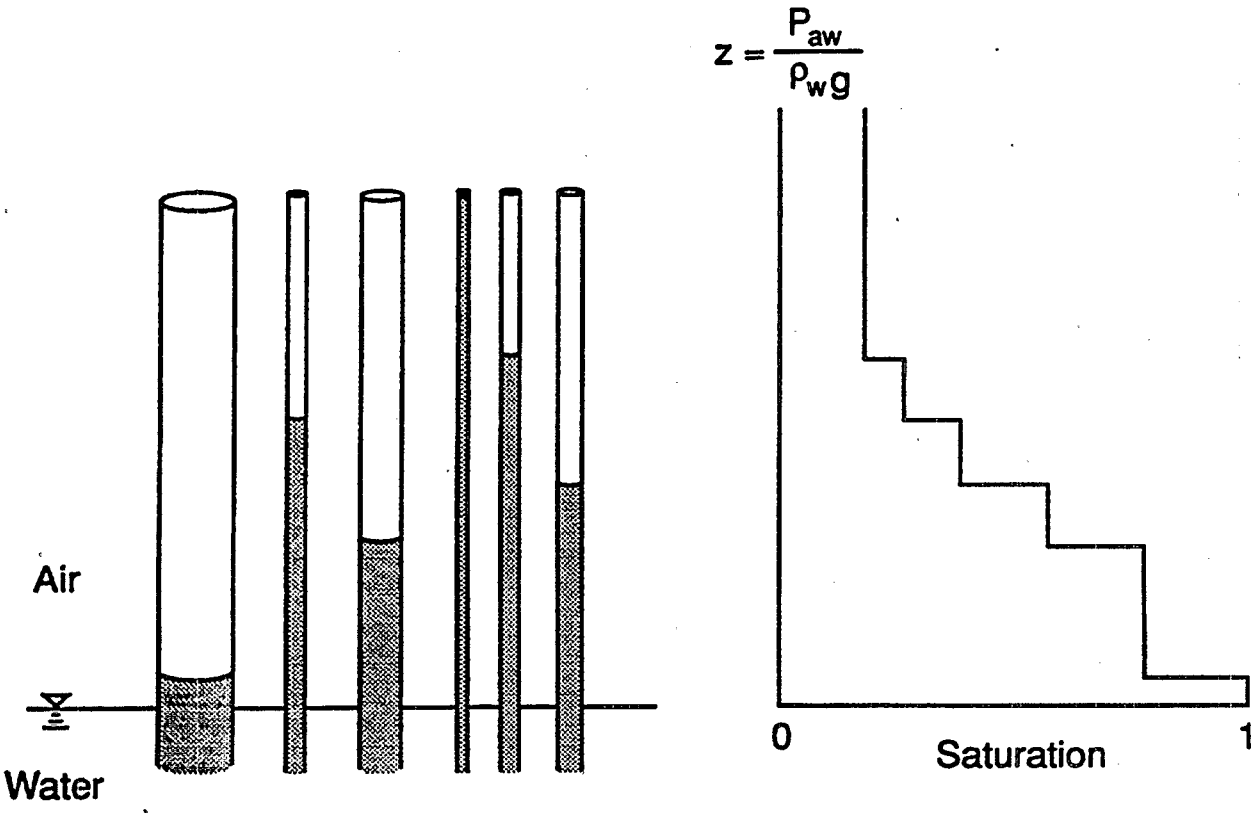


Figure 3-2. Capillary bundle model of soil pores and corresponding saturation-capillary pressure curve.

will diminish as the elevation above the water table increases in a manner that depends on the pore size distribution as shown in Figure 3-2.

Actual soil pores are a mixture of shapes and sizes interconnected in a complex manner that is better represented as a network of pore bodies connected by a system of pore throats. It is this pore network, rather than a system of capillary tubes, that gives rise to the phenomenon of hysteresis, which is the variation in the relationship of capillary pressure to saturation depending on whether wetting phase saturation is increasing (imbibition) or decreasing (drainage). A pore network with fluid distribution is presented in Figure 3-3; the network shown in Figure 3-3a is filled with wetting fluid--for example, water. Nonwetting fluid--for example, gasoline--is introduced from the upper surface by in-creasing the nonwetting phase pressure (or decreasing the wetting phase pressure) thereby increasing the oil-water capillary pressure. The oil will penetrate into any pores having a diameter larger than a certain value, which may be computed from the Laplace equation for the applied capillary pressure. Because the wetting phase is decreasing, the process is normally referred to as drainage. At the end of the drainage event, the fluid distribution in the pores may look like that shown in Figure 3-3b.

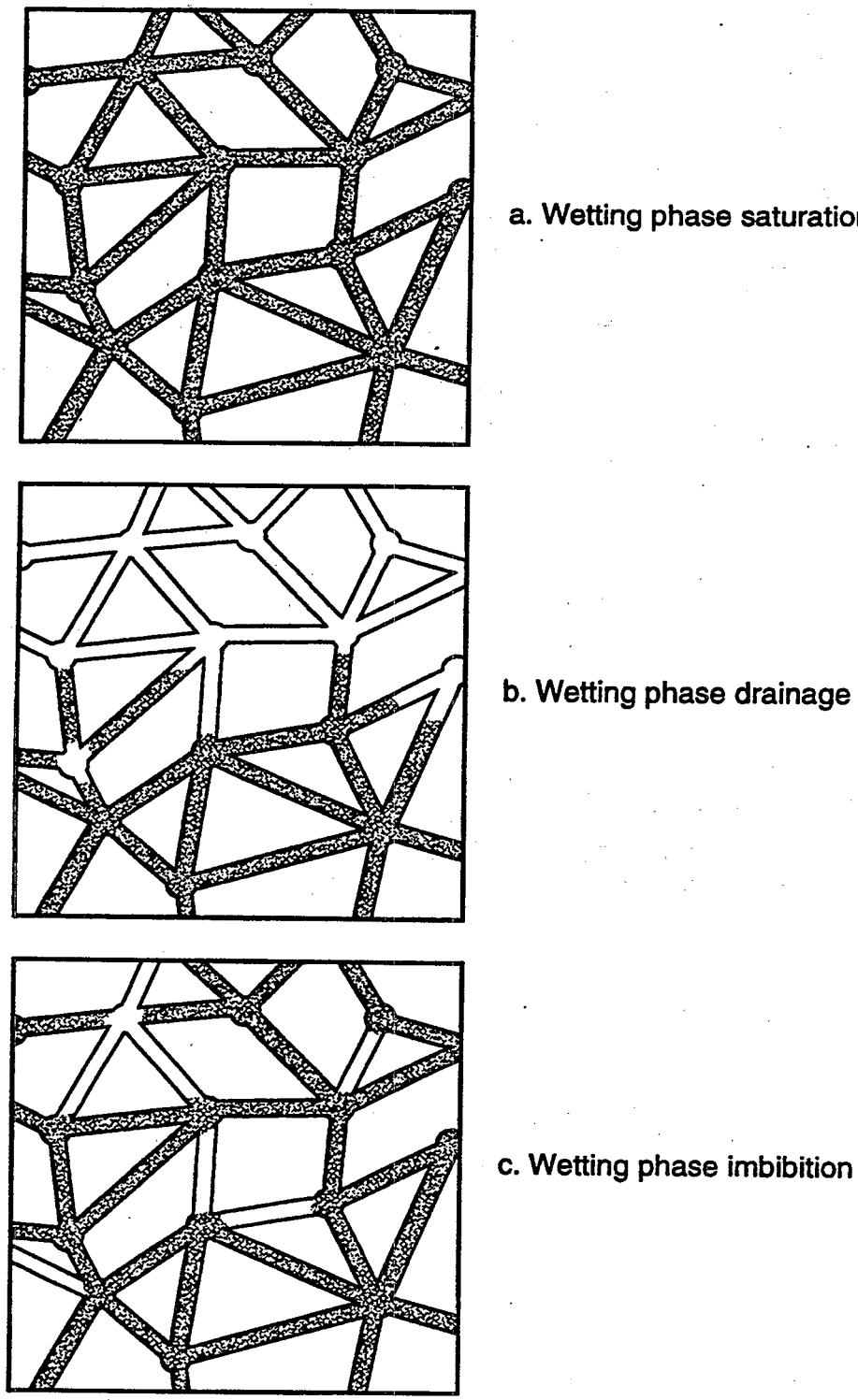


Figure 3-3. Network model of soil pores.

A decrease of the oil-water capillary pressure decrease in oil pressure or increase in water pressure) will cause water to displace oil from pores if the capillary pressure is less than the Laplace threshold. When the wetting phase saturation increases, the process is referred to as imbibition. The distribution of pore body and throat sizes will inevitably cause some of the oil-filled pores to get cut off because of the water displacement of oil in the surrounding larger pores. The net effect is a trapped nonwetting phase. Now, even when the capillary pressure returns to zero, some of the oil will remain at a residual saturation. The different path followed during drainage and imbibition is referred to as hysteresis. In addition to nonwetting phase entrapment, other factors such as variations in contact angles during wetting and drainage may lead to macroscopic hysteresis. Typical main drainage and imbibition curves are shown in Figure 3-4. The nonwetting phase saturation when the main imbibition curve reaches zero capillary pressure is referred to as the maximum nonwetting phase residual saturation, S_{nr}. Note that an infinite number of scanning paths can occur between the main drainage and imbibition paths.

3.2.2.2 Parametric Models for Saturation-Capillary Pressure (S-P) Relations
Measured capillary pressure data are commonly fit to the van Genuchten or the Brooks-Corey model. Equation 3-7 shows the van Genuchten model.

$$\bar{S}_w = [1 + (\alpha\ h_c)^n]^{-m} \qquad for\ h_c > 0 \tag{3-7}$$

where:

$\bar{S}_w$ = apparent wetting phase saturation (L^0)
α = parameter proportional to mean pore size (L^{-1})
h_c = air-water capillary head (L)
n = a parameter inversely related to width of pore size distribution (L^0)
m = $1 - 1/n$.

The Brooks-Corey model is presented below:

$$\bar{S}_w = (h_d/h_{nw})^{\lambda} \qquad for\ h_c > h_d \tag{3-8}$$

where:

h_d = nonwetting fluid entry pressure (L)
λ = pore size distribution parameter (L^0).

As the mean pore size increases (coarser grain size), the displacement pressure h_d decreases and the parameter α increases. The parameters n and λ are pore size

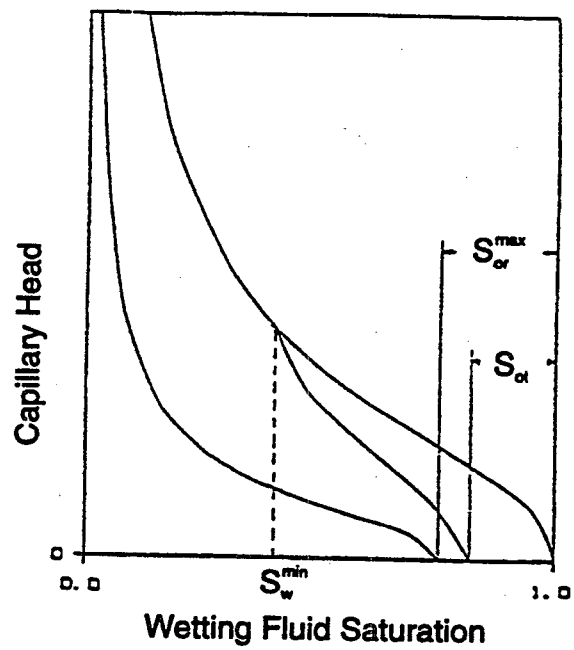


Figure 3-4. Typical two-phase saturation-capillary pressure curves.

distribution indices. Narrower pore size distributions are indicated by larger values of n and λ, which will result in sharper, more step-like capillary pressure curves (Figure 3-4).

3.2.2.3 Capillary Pressure Curves for Different Fluids

The air-water capillary pressure curve, which is measured for a given soil, can be related to the oil-water capillary pressure through application of the Laplace equation. This equation indicates that for the same radius, capillary pressure will vary inversely with the interfacial tension. The following equation assumes that water is used in the wetting phase:

$$S_w(\beta_{ow} h_{ow}) = S_w(h_{aw})(9) \tag{3-9}$$

where:

$$\beta_{ow} = \frac{\sigma_{aw}}{\sigma_{ow}} \tag{3-10}$$

β_{ow} = oil-water scaling factor (L^0)
σ_{aw} = surface tension of water (MT^{-2})
σ_{ow} = oil-water interfacial tension (MT^{-2}).

Air-oil capillary pressures can also be estimated by assuming that oil is the wetting phase in the air-oil pair. Thus, a similar method is produced, as shown in the following equations.

$$S_o(\beta_{ao}h_{ao}) = S_w(h_{aw}) \tag{3-11}$$

where:

$$\beta_{ao} = \frac{\sigma_{aw}}{\sigma_{ao}} \tag{3-12}$$

where: σ_{ao} = air-oil interfacial tension.

Figure 3-5 presents wetting fluid saturation-capillary head relationships for air-water, air-NAPL, and NAPL-water fluid pairs.

3.2.2.4 Three-Phase Capillary Pressure Relationships
The three-phase capillary systems show the behavior of a porous media with three fluid phases: air, water, and oil. It is assumed that water is the wetting fluid for the water-oil pair and that oil is the wetting fluid for the oil-air pair.

The idealized pore cross section for the three phases is shown in Figure 3-6. The oil-water interface radius varies depending on the amount of water saturation in the pores, which will control the oil-water capillary pressure. The degree of air-oil interface curvature depends on total liquid saturation (oil plus water), which controls the air-oil capillary pressure. The three-phase capillary pressure relationships are represented by two functions: S_w vs. h_{ow} and S_t vs. h_{ao} (where $S_t = S_w + S_o$). Note that the pristine air-water curve may vary from the contaminated air-water capillary pressure curve because of a change in the surface tension of contaminated water.

3.2.2.5 Relative Permeability Relationships
A complete description of fluid dynamics in multiphase systems is needed to understand the relative permeability changes under various conditions. The relative permeability of a porous media (k_{rd}) to the wetting phase depends on the media used and the degree of wetting phase saturation. As saturation decreases, the flow path becomes longer and more circuitous, thus resulting in a decrease in permeability as saturation diminishes. Capillary network models of the soil indicate:

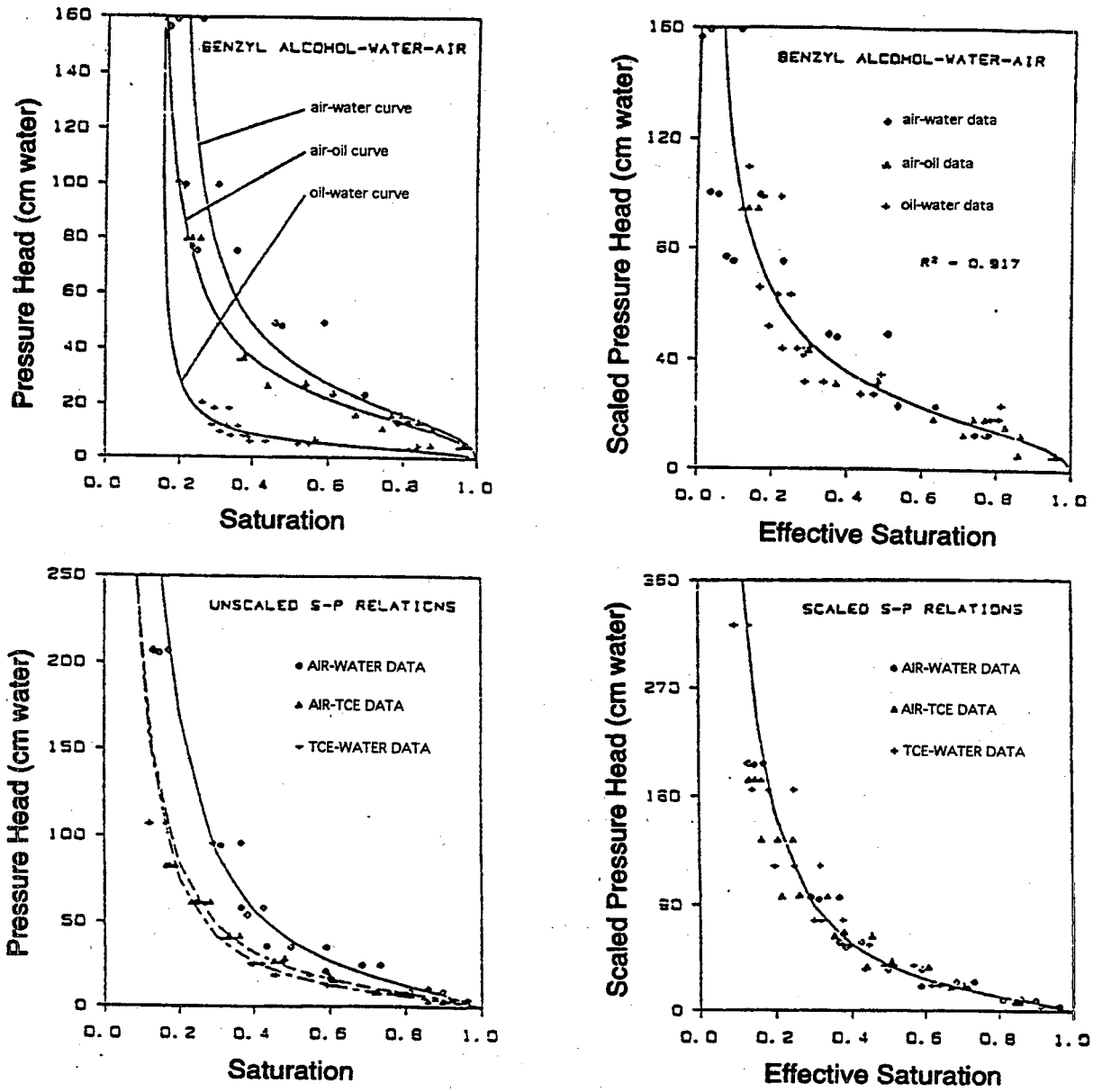
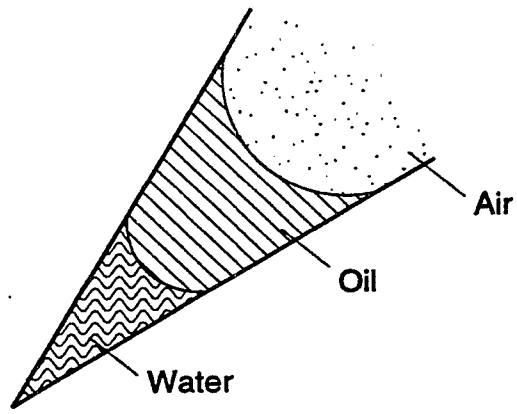


Figure 3-5. Measured S-P_c drainage curves for two soils and three fluid pairs.



Assume wettability in order: water → oil → air

Figure 3-6. Schematic of idealized pore cross section with three fluids.

Source: after Parker, 1989.

$$k_{r\alpha} = \tau \left(\frac{\overline{R}_\alpha}{\overline{R}_{sat}} \right)^2 \tag{3-13}$$

where:

$\overline{R}_\alpha$ = mean radius of pores filled with α-phase (L)
$\overline{R}_{sat}$ = mean radius of all pores (L)
τ = tortuosity coefficient (L^0).

Theoretical and experimental studies indicate:

$$\tau = \overline{S}_w^{\,b} \tag{3-14}$$

where *b* is an empirical exponent (L^0).

The van Genuchten model shows that water relative permeability is only a function of water saturation, and that air relative permeability is only a function of air saturation; the model further shows that oil relative permeability is a function of both water and air saturation, if both phases are present.

$$k_{rw}(\overline{S}_w) = \overline{S}_w^{1/2} \left(1 - (1 - \overline{S}_w^{1/m})^m\right)^2 \tag{3-15}$$

$$k_{ro}(\bar{S}_w,\bar{S}) = (\bar{S}_t - \bar{S}_w)^{1/2} \left\{(1 - \bar{S}_w^{1/m})^m - (1 - \bar{S}_t^{1/m})^m\right\}^2 . \tag{3-16}$$

$$k_{ra}(\bar{S}_t) = (1 - \bar{S}_t)^{1/2} (1 - \bar{S}_t^{1/m})^{2m} \tag{3-17}$$

The effects of hysteresis were not considered in the preceding equations (3-15, 3-16, 3-17). Experimental studies indicate that water relative permeability is minimally affected by saturation history. Nonwetting-phase relative permeabilities, however, can be markedly affected by nonwetting fluid entrapment because trapped fluid is hydraulically discontinuous and essentially contributes nothing to phase permeability.

Typical relative permeability curves for a two-fluid phase system are shown in Figure 3-7 for wetting phase drainage and imbibition. Note the small degree of hysteresis in the wetting-phase relative permeability curve. Also, note that wetting-phase permeability decreases several orders of magnitude as the wetting-phase saturation decreases from 100 to 50 percent, whereas the nonwetting-phase permeability decrease is roughly proportional to the saturation decrease. This change occurs because the nonwetting phase, by definition, occupies large pores that contribute disproportionately to permeability.

3.2.3 NAPL Movement and Residual Saturation in the Unsaturated Zone

The behavior of water alone will first be considered before any discussion of the movement of NAPL in the unsaturated zone. Following a rainfall or other event that brings the soil surface to a high degree of water saturation, water will continue to move vertically downward under the influence of gravity in a process referred to as redistribution. As redistribution proceeds, water saturation in the initial wetted zone decreases and relative permeability decreases proportionately. With time, redistribution essentially ceases and water content reaches a quasi-static state referred to as field capacity. It should be noted that this is not a true hydrostatic equilibrium condition.

NAPL spills or leaks in the unsaturated zone will move downward under the force of gravity and capillary pressure as well as laterally because of capillary forces. As the release migrates, the following occurs:

- The rate of advancement will be controlled by oil conductivity, which varies directly with intrinsic permeability, relative permeability, and NAPL density and varies inversely with NAPL viscosity.

- At high degrees of saturation, oil relative permeability will be near unity; at lower saturation, the relative permeability will be lower.

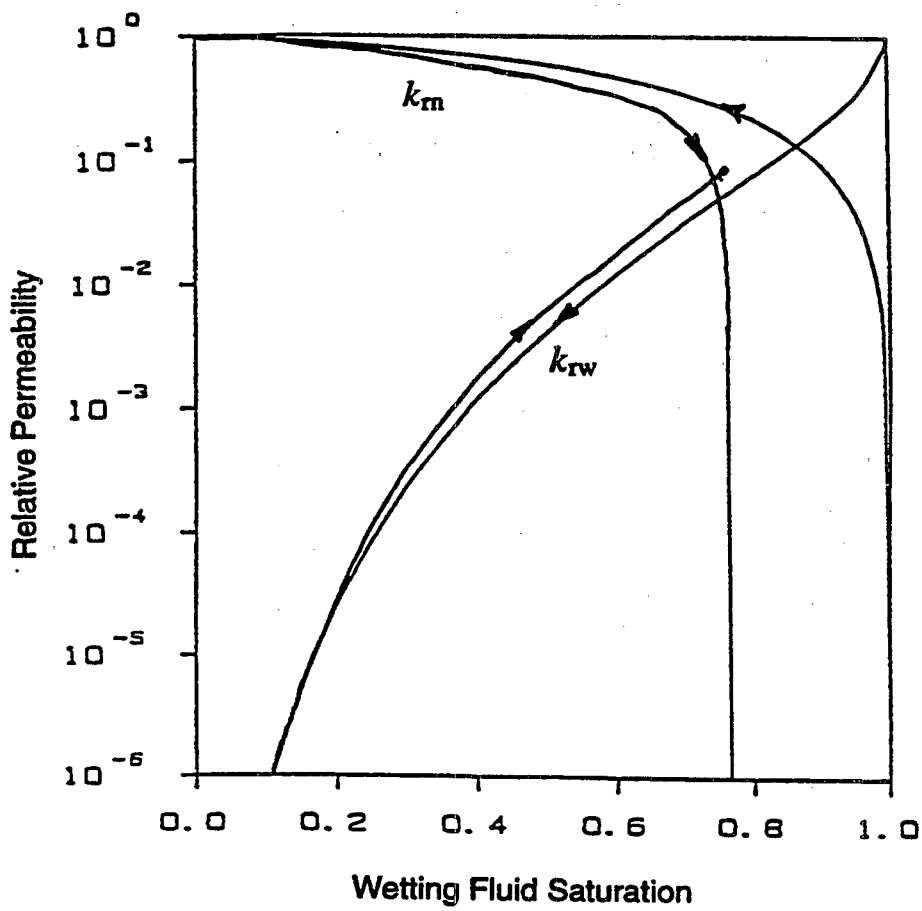


Figure 3-7. Typical wetting and nonwetting phase relative permeabilities for wetting phase imbibition and drainage paths.

- For slow leaks, the saturation will adjust to a low value. After the leak ceases, the front will continue to advance, but at an increasingly slow rate because the relative permeability begins to diminish as a result of the gradual reduction in NAPL saturation as the spill volume distributes over a greater soil volume. Because the NAPL relative permeability decreases approximately exponentially as saturation decreases, the rate of redis-tribution tends to decrease exponentially with time. As a result, after a period of weeks or months of redistribution after a spill event, NAPL fluxes in the unsaturated zone near the source may be essentially zero and the NAPL saturation is apparently static. Although a true equilibrium condition does not exist because oil will not exhibit a hydrostatic pressure distri-bution, a *quasi-static* state is maintained by negligible fluxes under the ambient gradient (due to gravity).

- Residual NAPL saturation occurring behind the draining oil front is referred to as pendular residual oil saturation or unsaturated zone residual saturation, not to be confused with trapped or insular residual saturation caused by an NAPL being occluded by water imbibition.

An example of the separate and combined effects of oil entrapment and unsaturated zone residual saturations is presented in Figure 3-8 for LNAPL redistribution after a spill at the ground surface. The case considered assumed a sloping water table from left to right that gradually rose over a 20-day period by 1 meter. The oil distribution 20 days after the spill event, simulated without consideration of oil entrapment (see Figure 3-8a), shows pendular residual oil of about 10 percent of pore space near the ground surface. Downgradient movement of oil over the water table is much greater than the case when oil entrapment is considered (see Figure 3-8b) because oil transmissivity is diminished as a result of the large volume of oil trapped (see Figure 3-8c).

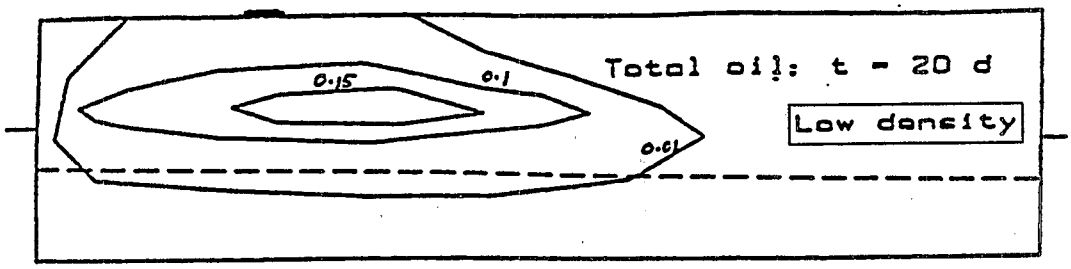
The findings based on this example are summarized as follows:

- LNAPL spreads laterally after reaching the water table.
- Oil entrapment markedly affects NAPL plume movement.
- Diminishing oil permeability near the ground surface leads to unsaturated zone residual oil ("pendular" residual oil).

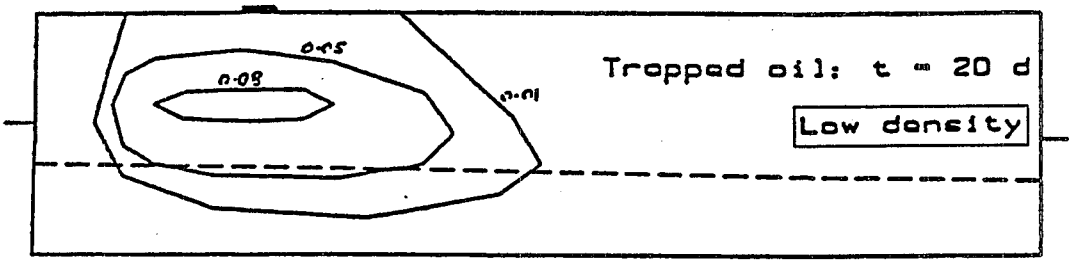
3.2.4 Relationship Between Well Product Thickness and Soil Distribution

After an LNAPL spill, product moves vertically downward through the unsaturated zone until it encounters a fine soil layer whose nonwetting fluid entry pressure precludes further downward movement, it reaches residual saturation, or it encounters a water table. In this section, the behavior of LNAPL that has reached a water table will be considered.

a. Without oil entrapment



b. With oil entrapment



c. Trapped oil

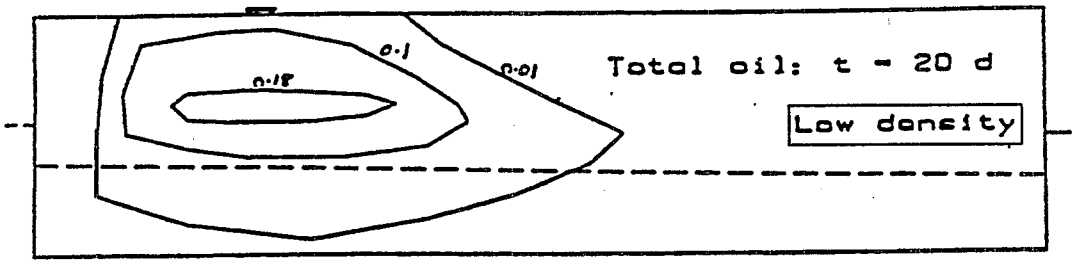


Figure 3-8. Oil saturation distributions twenty days after an LNAPL spill. a) Total oil saturation without considering oil entrapment, b) Total oil saturation with oil entrapment, c) Trapped oil saturation for case b. Units on contours are fractions of pore space.

3.2.4.1 Vertical Capillary Pressure Distribution

Water and oil flow are controlled by their piezometric heads. The *piezometric heads* for water (ψ_w) and oil (ψ_o) are as follows:

$$\psi_w = h_w + z \tag{3-18}$$

$$\psi_o = h_o + \rho_{ro}\, z \tag{3-19}$$

where:

h_w = water pressure in units of water height (L)
h_o = oil pressure in units of water height (L)
z = elevation above an arbitrary datum (L)
ρ_{ro} = oil-specific gravity (L^0).

The following equations were derived from the fluid table definitions defined in Figure 3-9:

$$\psi_w = z_{aw} + h_a \tag{3-20}$$

$$\psi_o = \rho_{ro}\, z_{ao} + h_a \tag{3-21}$$

where:

h_a = air pressure in units of water height (L)
z_{aw} = air and water pressure elevation (L)
z_{ao} = air and oil pressure elevation (L).

Note: at constant h_a, areal water flow is controlled by z_{aw}, and areal oil flow is controlled by gradients in z_{aw}.

Assuming vertical fluid redistributions occur on a sufficiently short time scale so that vertical pressure distributions approximate hydrostatic conditions, then vertical capillary pressure distributions are given by:

$$h_{ao} = \rho_{ro}\,(z - z_{ao}) \tag{3-22}$$

$$h_{ow} = (1 - \rho_{ro})\,(z - z_{ow}) \tag{3-23}$$

Fluid table elevations are related by:

$$z_{aw} - z_{ow} = \rho_{ro}\, H_o \tag{3-24}$$

RELATIONSHIP BETWEEN SOIL AND WELL PRODUCT THICKNESS

VERTICAL EQUILIBRIUM ASSUMPTION

- If recharge/leakage fluxes are small compared to regional velocities, vertical water pressure distributions will approach hydrostatic
- After oil reaches the water table, oil flow is primarily horizontal and vertical oil pressure distributions will tend towards equilibrium

Fluid Table Definitions for an LNAPL

$z_{\alpha o}$ → elevation where air and oil pressure are equal

$z_{\alpha \omega}$ → elevation where air and water pressure are equal

$z_{o\omega}$ → elevation where oil and water pressure are equal

Fluid table elevations are detected by a monitoring well or piezometer

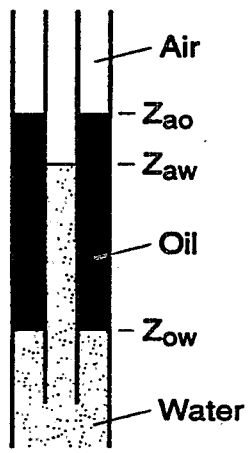


Figure 3-9. Fluid table definitions for LNAPLs.

where: $H_o = z_{ao} - z_{ow}$ is the well oil thickness (L).

3.2.4.2 Vertical Saturation Distributions

The following examples assume that two fluid table elevations or one elevation and the apparent oil thickness (H_o) completely define the three-phase static vertical head distributions.

- Knowing fluid table elevations z_{ao} and z_{ow} at a specified areal location, combined with the three-phase saturation-capillary pressure relationships, water and oil saturations may be computed as a function of elevation (Figure 3-10).

- An oil-water capillary fringe occurs above z_{ow} which is water saturated or at apparent water saturation if trapped nonwetting fluids are present. The thickness of the oil-water capillary fringe for the Brooks-Corey model is given by the following equation:

$$\delta_{ow} = \frac{\delta_{aw}}{\beta_{ow}(1-\rho_{ro})} \tag{3-25}$$

where:

δ_{aw} = thickness of air-water capillary fringe in oil-free system (L)
δ_{ow} = thickness of the oil-water capillary fringe (L)
β_{ow} = oil-water scaling factor (L^0).

- A narrower air-oil capillary fringe, which is also liquid-saturated (disregarding trapped fluids), will occur above z_{ao} and is defined by:

$$\delta_{ao} = \frac{\delta_{aw}}{\beta_{ao}\rho_{ro}} \tag{3-26}$$

where:

δ_{ao} = thickness of the air-water capillary fringe (L)
β_{ao} = air-oil scaling factor (L^0).

Because the oil-water capillary fringe thickness is greater than that of the air-oil capillary fringe, the actual soil thickness over which oil occurs will be smaller than the well oil thickness.

- Trapped oil is not in hydraulic contact with free oil and cannot be detected by a monitoring well. Computed oil saturation distributions based on

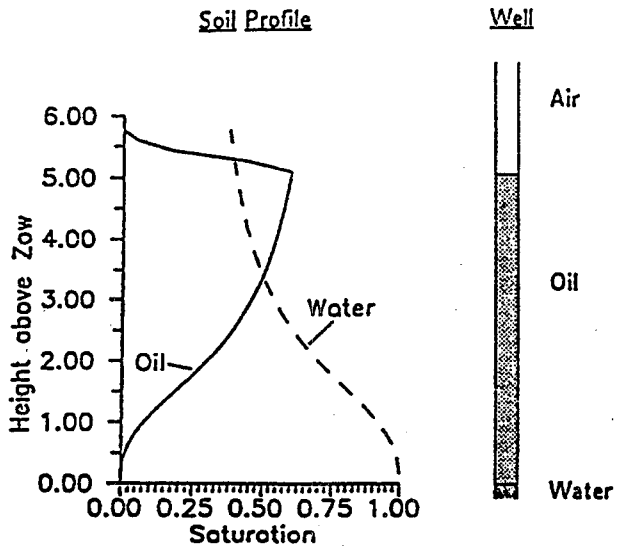


Figure 3-10. Oil and water saturation distribution in soil and relationship to fluid levels in a monitoring well.

nonhysteretic saturation-capillary pressure relationships will yield estimates of *free oil saturation* only. The maximum elevation (z_u) at which free oil will occur in equilibrium with an oil lens is:

$$z_u = z_{ow} - \frac{\rho_{ro}\beta_{ao}H_o}{\rho_{ro}\beta_{ao} - (1 - \rho_{ro})\beta_{ow}} \tag{3-27}$$

- The *free oil-specific volume* (V_{of}) or free NAPL volume per unit area can be computed from the vertical oil saturation distribution by the following equation:

$$V_{of} = \int_{z_{ow}}^{z_u} \phi \, S_{of} \, dz \tag{3-28}$$

where:

ϕ	=	soil porosity (L^0)
S_{of}	=	free oil saturation (L^0)
z_{ow}	=	oil-water table elevation (L)
z_u	=	maximum elevation where free oil occurs (L)
z	=	elevation above a datum (L).

Integration of Equation 3-24 yields V_{of} as a function of H_o as shown in Figure 3-11.

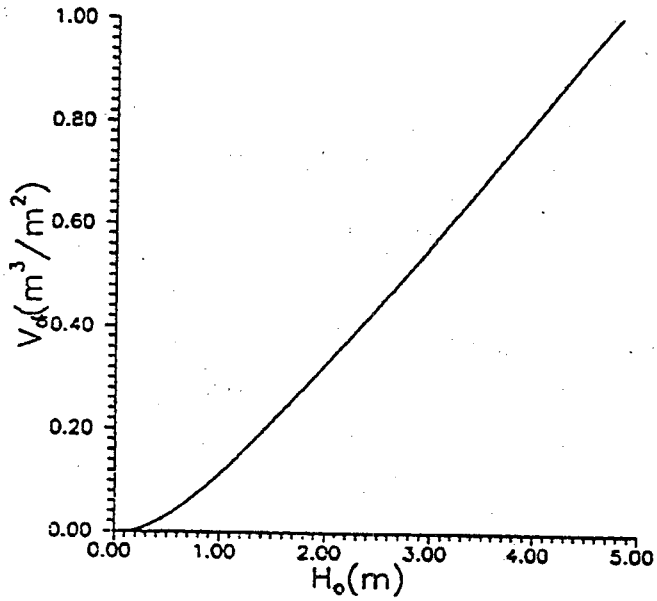


Figure 3-11. Free oil-specific volume versus well product thickness for a representative soil.

3.2.5 Areal Movement of Floating Product

3.2.5.1 Areal Water and Oil Flow Equations

Once LNAPLs reach the water table, further vertical movement will be limited by buoyancy effects. Flow will occur primarily in the areal (horizontal) direction. Under conditions of constant gas pressure, areal water flow occurs in response to gradients in the air-water table and oil flow occurs in response to air-oil table gradients.

- Assume approximate vertical equilibrium pressure distributions and uniform gas pressure. Integration of Darcy's law in the z-direction yields the following areal water and oil flow equations:

$$Q_{w_i} = - T_{w_{ij}} \frac{\partial z_{aw}}{\partial x_j} \tag{3-29}$$

$$Q_{\alpha_i} = - T_{\alpha_{ij}} \frac{\partial z_{ao}}{\partial x_j} \tag{3-30}$$

where:

Q_{α_I} = flow rate of α-phase (water or oil) in the I-direction per unit width ($L^3L^{-1}T^{-1}$)
$T_{\alpha_{ij}}$ = α-phase (water or oil) transmissivity tensor (i,j = 1,2), (L_2T_{-1})
$\partial z_{aw}/\partial x_j$ = air-water table gradient in the j-direction ($L\ L^{-1}$)
$\partial z_{ao}/\partial x_j$ = air-oil table gradient in the j-direction.

If the gas pressure is nonuniform, the gradient for water flow will be $\partial z_{aw}/\partial x + \partial h_a/\partial x$, where h_a is the water height equivalent air pressure. The gradient for oil flow will be $\partial z_{ao}/\partial x + (1/\rho_{ro})\partial h_a/\partial x$. Thus, if a vacuum is imposed at a recovery well, water and oil removal rates may be increased without resorting to a large drawdown in the fluid tables in the recovery well. This is commonly referred to as "vacuum-enhanced product recovery."

Mass conservation for water and oil requires:

$$\frac{\partial V_w}{\partial t} = -\frac{\partial Q_{w_i}}{\partial x_i} + \bar{J}_w \tag{3-31}$$

$$\frac{\partial V_o}{\partial t} = -\frac{\partial Q_{o_i}}{\partial x_i} + \bar{J}_o \tag{3-32}$$

where:

V_w and V_o = water and oil volume per unit area (L)
$\bar{J}_w$ and $\bar{J}_o$ = vertically integrated source-sink terms ($L^3L^{-2}T^{-1}$).

The preceding equations can be solved by examining the expressions presented in Figure 3-12 for specific volumes and transmissivities as functions of fluid table eleva-tions.

Oil relative permeability must be determined as a function of elevation. For a given well oil thickness, vertical oil and water saturation distributions may be evaluated as previously discussed and oil relative permeability may then be calculated. Figure 3-13 presents oil transmissivity versus free oil-specific volume for gasoline in a sandy soil.

Characterization of water-specific volume

$$dV_w = \phi_c dz_{aw}$$

where ϕ_c is the unconfined aquifer specific yied.

Characterization of oil specific volume

$$V_o = V_{of} + V_{ot} + V_{og}$$

where

V_o = total oil per unit area
V_{of} = free oil per unit area
V_{ot} = trapped oil specific volume
V_{og} = pendular residual oil specific volume.

Characterization of water transmissivity

$$T_{w_{ij}} = \int_{z_l}^{z_u} k_{rw} K_{sw_{s,ij}}\, dz$$
$$= (z_{ow} + \delta_{ow} - z_l)\, K_{sw_{ij}}$$

where

z_{ow} = oil-water table elevation
δ_{ow} = oil-water capillary fringe thickness
z_l = aquifer effective lower elevation

Characterization of oil transmissivity

$$T_{o_{ij}} = \int_{z_l}^{z_u} \frac{\rho_{ro}\, k_{ro} K_{sw_{ij}}}{\eta_{ro}}\, dz$$

where

ρ_{ro} = oil specific gravity
η_{ro} = oil specific gravity
k_{ro} = oil relative permeability

Figure 3-12. Vertically integrated relationships.

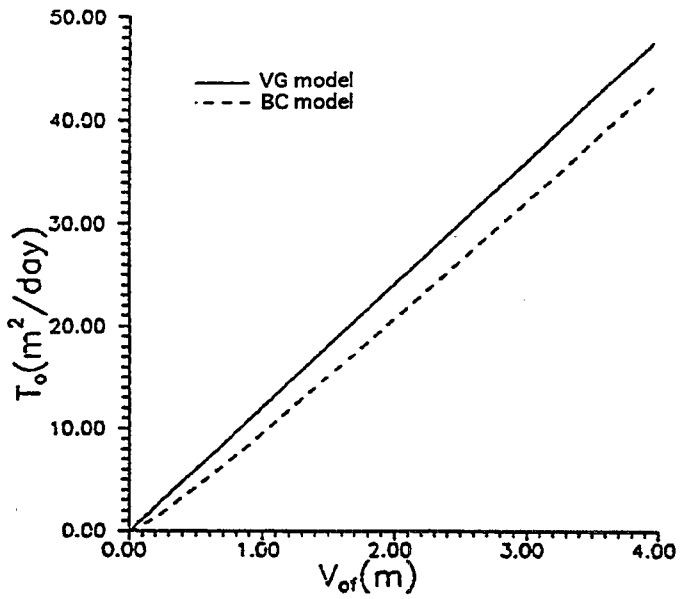


Figure 3-13. Oil transmissivity versus free-oil-specific volume for a sandy soil based on the van Genuchten (VG) and Brooks-Corey (BC) models.

3.2.6 Effects of Oil and Water Table Elevation Changes on Free Product

It is important to distinguish between free product (oil) that is mobile and may be detected in monitoring wells, as opposed to residual oil that is not free to move. Residual oil occurs as both oil trapped within pores during imbibition (insular residual oil) and as pendular oil held in the unsaturated zone by capillary forces.

- *Oil-specific volume* (V_o) is the total of V_{of}, free oil-specific volume, plus V_{ot}, insular (trapped primarily in the saturated zone) residual oil, plus V_{og}, pendular residual oil. V_{of} may be estimated from well oil thickness.

- The *residual oil-specific volume* in the saturated zone (V_{ot}) results from oil entrapment when the oil-water table rises, thereby causing water imbibition as the oil-water capillary pressure decreases. The magnitude of V_{ot} is controlled by:

  - The magnitude of the rise in the oil-water table (Δz_{ow}) relative to its historical minimum

- Maximum residual oil saturation (S_{ot})

- Maximum historical oil thickness (H_o^{max}).

An illustrative V_{ot} function is shown in Figure 3-14.

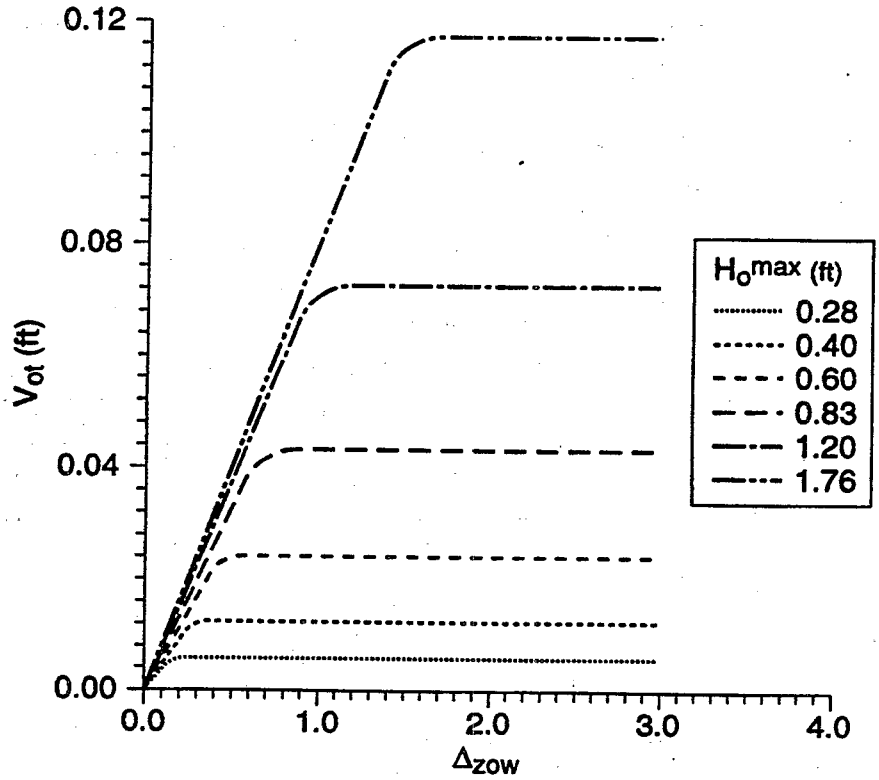


Figure 3-14. Trapped oil-specific volumes as a function of the oil water table elevation increase (Δ_{zow} historical maximum well oil thickness [H_o^{max}]).

- *Unsaturated zone residual oil-specific volume* is another source of residual oil. During periods of falling z_{ao}, downward oil redistribution eventually becomes negligible under gravitational forces as oil saturation reaches a critical value called the pendular or unsaturated zone residual saturation. The residual oil-specific volume in the unsaturated zone, V_{og}, is described by:

$$V_{og} = Min(V_{of} - V_{ot}, \phi\, S'_{og}\, \Delta z_{ao}) \qquad (3\text{-}33)$$

where

Δz_{ao}	=	downward change in the air-oil table as a result of pumping and/or seasonal fluctuations
S'_{og}	=	Min (S_{og}, S_o^{max}) in which S_{og} is the maximum unsaturated zone residual saturation after drainage from a high oil content
S_o^{max}	=	maximum oil saturation at an elevation $z=z_{ao}$ for the current well oil thickness H_o

Depending on the direction of water table fluctuations, water table elevations can affect well product thickness in various ways.

Fluctuations in the water table also have an effect on the thickness of the product observed in a monitoring well because of deviations from vertical equilibrium. When water flow is downward, water pressure increases more gradually with depth, and oil-water capillary pressure will be lower. At a given free oil saturation, this means the well oil thickness must become greater. Conversely, when water flow is upward, the well oil thickness will become compressed (Figures 3-15 and 3-16 from Ground Water, 1990). These effects produce the same trend as that produced by changes in product thickness; such changes are due to changes in residual saturation associated with fluctuating water tables and will usually be indistinguishable in practice.

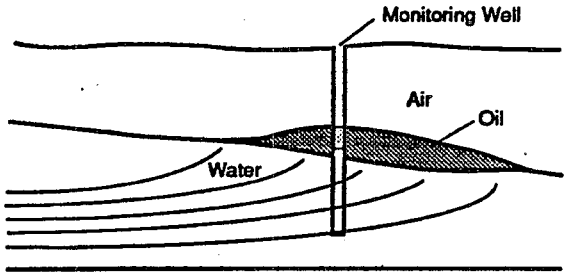


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Figure 3-15. Hydrocarbon thickness decrease for rising interface (Ground Water, 1990).

3.2.7 Characterization of Soil and Bulk Hydrocarbon Properties

NAPL flow is governed by the fluid and the media through which it is migrating. The fluid and soil properties that govern NAPL flow are shown in Table 3-1. In this chapter, a brief discussion will be presented of the methods used to characterize these properties.

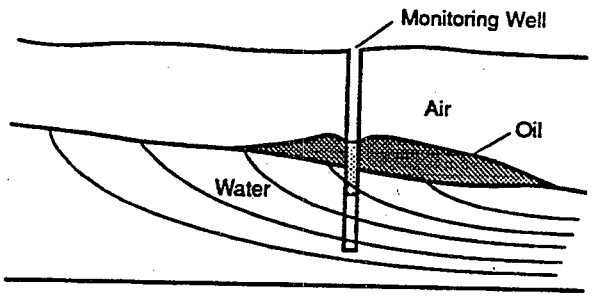

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Figure 3-16. Hydrocarbon thickness increase for falling interface (Ground Water, 1990).

Table 3-1. Fluid and Soil Properties Governing NAPL Flow

Fluid properties:	
ρ_{ro}	Ratio of oil to water density [L°]
β_{ao}	Ratio of water surface tension to oil surface tension [L°]
β_{ow}	Ratio of water surface tension to oil-water interfacial tension [L°]
Soil properties:	
K_{sw}	Saturated conductivity principal values [L T^{-1}]
ϕ	Total porosity [L°]
S_m	Water saturation at field capacity [L°]
S_{og}	Maximum unsaturated zone residual oil saturation [L°]
S_{or}	Maximum saturated zone residual oil saturation [L°]
α	VG mean pore size parameter [L^{-1}]
n	VG pore size distribution exponent [L°]

3.2.7.1 Estimation of Fluid Properties

Product-Specific Gravity Oil-specific gravity, ρ_{ro}, will vary significantly for different petroleum hydrocarbons depending on the specific chemical composition (see Table 3-2). Product-specific gravity can be determined as follows:

- Determine a laboratory measurement of the fluid sample collected. Measurements should be made within 5° to 10°C of the temperature expected in the field.
- Calculate product-specific gravity from fluid level data.

Table 3-2. Fluid Properties for Various Hydrocarbons

Product	ρ_{ro}	μ_{ro}	β_{ao}	β_{ow}
Crude oil	0.70-0.98	8-90	2.0-3.5	1.4-2.0
Diesel fuel	0.80-0.85	1.1-3.5	2.8-3.2	1.4-1.6
Gasoline	0.70-0.80	0.4-0.8	3.0-3.4	1.4-1.5
Fuel oil No. 1[a]	0.81-0.85	1.5-2.5	2.5-3.0	1.5-1.7
Fuel oil No. 2[b]	0.86-0.90	4-9	2.5-3.0	1.5-1.7
Fuel oil No. 4	0.88-0.92	5-24	2.5-3.0	1.5-1.7
Fuel oil No. 5	0.92-0.97	53-175	2.5-3.0	1.5-1.7
Fuel oil No. 6	0.94-1.05	60-150	2.5-3.0	1.5-1.7

[a] Fuel oil No. 1 ≈ kerosene
[b] Fuel oil No. 2 ≈ diesel.

A simple field procedure to determine product density in wells with free product is to measure the water piezometric elevation (z_{aw}) by use of a tube inserted through the oil layer in the monitoring well and to measure the air-oil and oil-water table elevations under static conditions. The product density may be computed by:

$$\rho_{ro} = \frac{z_{aw} - z_{ow}}{z_{ao} - z_{ow}} \tag{3-34}$$

where it is assumed that equilibrium conditions exist within the well bore and it is best to wait until fluid levels are stable following the insertion of the piezometer tubes.

Fluid Scaling Factors Air-oil and oil-water scaling factors (β_{ao} and β_{ow}) must be determined in order to describe three-phase saturation-capillary pressure relationships. The scaling factors are estimated from oil surface tension and oil-water interfacial tension data (Lenhard and Parker, 1987) by use of the following equations:

$$\beta_{ao} = \sigma_w/\sigma_o \tag{3-35}$$

$$\beta_{ow} = \sigma_w/\sigma_{ow} \tag{3-36}$$

where:

σ_w = surface tension of water (72 dynes/cm)
σ_o = surface tension organic liquid
σ_{ow} = oil-water interfacial tension.

Because interfacial tension is more difficult to measure than surface tension, an alternative protocol for determining β_{ow} is to measure the surface tension of water saturated with dissolved hydrocarbon (i.e., water that has been shaken with hydrocarbon and decanted to remove all traces of free liquid) and to compute the interfacial tension via the following equation:

$$\sigma_{ow} = \sigma'_w - \sigma_o \tag{3-37}$$

where:

σ'_w = surface tension of water saturated with dissolved hydrocarbon.

In the absence of measurements of either σ_{ow} or σ'_w, an approximate value of β_{ow} can be obtained assuming $\sigma'_w \approx \sigma_w$, which indicates that:

$$\beta_{ow} \approx \frac{1}{1 - 1/\beta_{ao}} \tag{3-38}$$

Based on surface tension and interfacial tension data for gasolines, $\beta_{ao} \approx 3.2$ and $\beta_{ow} \approx 1.45 \pm 10$ percent (Weiss, 1990). Approximate values of the fluid properties for various hydrocarbon products are given in Table 3-2.

For unrefined petroleum hydrocarbons (i.e., crude oil), an estimate of the scaling factors can be obtained by determining the correlation between oil surface tension and specific gravity. This correlation is shown by Baker and Swerdloff (1956) as:

$$\beta_{ao} = \frac{1}{1 - 0.5/\rho_{ro}} \tag{3-39}$$

$$\beta_{ow} = 2\rho_{ro} \tag{3-40}$$

These equations provide a simple procedure for estimating scaling factors for unrefined hydrocarbons. The procedures used to estimate surface tension and interfacial tensions of fluid mixtures have been reviewed by Lyman et al. (1982).

3.2.7.2 Viscosity

Product viscosity can be determined from laboratory measurements of a fluid sample or it can be estimated based on the type of product present (gasoline, diesel, oil) and on published values (see Table 3-2).

3.2.7.3 Estimation of Soil Properties

Soil properties include parameters defining the fluid retention properties and soil permeability (see Table 3-3). If soil properties exhibit variations in the vertical direction, parameters relevant to the capillary fringe zone, where most oil occurs, can be used to accurately predict oil recovery. An under- (or over-) estimate of water transmissivity can be corrected by adjusting the effective and actual aquifer lower boundaries deeper (or shallower) in proportion to the error in the aquifer conductivity.

Table 3-3. Representative Soil Properties for Various Soils

Soil type[a]	K_{sw} [m/d]	ϕ [-][b]	S_m [-]	α [m^{-1}]	n [-]
Sand	7.1	0.43	0.13	14.6	2.7
Loamy sand	3.5	0.41	0.21	12.5	2.4
Sandy loam	1.06	0.41	0.24	7.6	2.0
Sandy clay loam	0.31	0.39	0.28	5.9	1.5
Loam	0.25	0.43	0.35	3.7	1.7
Silty loam	0.11	0.45	0.43	2.2	1.7
Clay loam	0.062	0.41	0.55	2.1	1.7
Sandy clay	0.029	0.38	0.66	3.2	1.8
Silty clay loam	0.017	0.43	0.68	1.2	1.9
Silty clay	0.0048	0.36	0.84	0.84	2.8

[a] U.S. Department of Agriculture (USDA) classification system.
[b] Dimensionless.

3.2.7.4 Field Capacity Water Saturation

The "Field Capacity" water saturation, S_m, can be determined by use of the following methods:

- Measuring water content above the capillary fringe.
- Using S-h_{aw} curves (measured in the laboratory) of soil cores.
- Using specific yield, ϕ_e, in a long-term pump test, to determine $S_m = 1 - \phi_e/\phi$.
- Estimating S-h_{aw} from grain size data and then estimating $S_m = S_w$ at $h_{aw} \approx$ 1-3 meters.

The parameter S_m represents the minimum water saturation that will occur in the soil under field conditions. It should be noted that the minimum saturation determined in the fitting of laboratory moisture retention data will invariably be much smaller than the minimum field water content because equilibrium conditions are only asymptotically approached in the field. Estimates of S_m may be made from direct measurements of the degree of saturation of the soil cores that are taken from the field at elevations above the "capillary fringe;" this elevation is above the air-water table (or air-oil table if oil is present) where water saturation drops more or less sharply.

If the specific yield of the unconfined aquifer is known, this parameter can be used to estimate S_m:

$$S_m = 1 - \phi_e/\phi \tag{3-41}$$

where ϕ is the total porosity of the soil and ϕ_e is the specific yield or effective porosity. Measured specific yields are often observed to increase in relation to the duration of the pump tests. Because long-term drainage is of concern here (e.g., weeks to months), specific yields from short-term pump tests may underestimate the "true" effective porosity.

If laboratory moisture retention data are available, an estimate of S_m may be made by evaluating the water saturation at an air-water capillary pressure head of 100 cm, which may be taken as a close approximation of "field capacity" in humid climates.

3.2.7.5 Unsaturated Zone Residual Oil Saturation

The unsaturated zone residual oil saturation, S_{og}, can be determined by the following methods:

- Laboratory column studies
- An estimate based on soil TPH data
- An estimate as a fraction of field capacity.

Laboratory column studies can be conducted to estimate unsaturated zone residual oil saturation where water in the soil column is drained to the "field capacity" and then the column is flooded with oil and allowed to drain freely. The oil saturation is then measured near the top of the column. For columns less than one meter in length, suction may have to be applied.

Unsaturated zone residual oil saturation can be estimated from the soil TPH data z_{ao} as:

$$S_o = TPH \times \frac{(1-\phi)\ 2.65 \times 10^{-6}}{\rho_{ro}\phi} \tag{3-42}$$

where TPH is given in mg/kg.

Oil saturation can also be estimated as a fraction of field capacity in the following empirical relationship:

$$S_{og} \approx f_{og} S_m (1 - S_m) \tag{3-43}$$

where f_{og} may range from 0.2 to 0.5.

Fluids with higher viscosities and soils that are more heterogeneous will tend to have larger f_{og} values. Theoretical analyses indicate that residual saturation will increase in approximate proportion to the fourth root of product viscosity; i.e., $f_{og} \propto \eta_{ro}^{1/4}$ where η_{ro} is the oil-water viscosity ratio.

3.2.7.6 Saturated Zone Residual Oil Saturation

The saturated zone residual oil saturation, S_{or}, can be determined by the following methods:

- Laboratory column studies
- An estimate based on soil TPH data
- An estimate as a function of effective porosity.

Laboratory column studies can be conducted to estimate saturated zone residual oil saturation where the soil column is saturated with water and then is flooded with oil. The column is then water-flooded to displace the oil. The oil saturation present in the column would then be measured.

Typical values of S_{or} are given by:

$$S_{or} \approx f_{or}(1 - S_m) \tag{3-44}$$

where f_{or} ranges from 0.2 to 0.5 with a median of about 0.3.

Fluids with higher viscosities and soils that are more heterogeneous will tend to have larger f_{or} values.

3.2.7.7 Capillary Pressure Parameters

Air-water capillary pressure parameters α, n, and S_m can be determined by the following methods:

- Estimation from soil cores
- Estimation from grain size data
- Correlation with saturated conductivity
- Estimation from TPH data
- Estimation from product recovery data.

Capillary Pressure Parameters From Soil Cores Air-water capillary pressure curves are often characterized by fitting model parameters (i.e., α, n, and S_m) to the water content versus capillary pressure data obtained in the laboratory on soil cores, which will yield true equilibrium parameters. In the field, however, equilibrium is never truly attained because fluid drainage is impeded by low relative permeabilities as wetting phase saturations diminish. To correct for the deviation from equilibrium conditions, quasi-static model parameters should be used that yield the correct water saturation distribution under field conditions when a hydrostatic water pressure distribution is assumed. Procedures used to estimate quasi-static retention parameters from the laboratory data are described by Lenhard and Parker (1990). The simplest approach is to fix S_m at a value corresponding to the minimum field saturation, discard moisture data below about $S_w = 1.1 \times S_m$, and then fit the parameters α and n to the reduced data set by using a nonlinear regression method. Typical quasi-static parameters for various soil types are given in Table 3-3.

Capillary Pressure Parameters From Grain Size Data A theoretical procedure to estimate air-water capillary pressure parameters (i.e., α, n, and S_m) was derived by Arya and Paris (1981) based on the proposition that capillary pressure relationships are related to the pore size distribution of the soil, which may in turn be inferred from the grain size distribution. The method was calibrated and implemented by Mishra et al. (1988) in the program SOILPROP (ES&T, 1990). The user may either specify S_m as known (computed, for example, from specific yield), or S_m may be estimated by the

program to correspond to "field capacity" for the soil defined operationally as the water saturation at which the air-water capillary head is 100 cm.

Capillary Pressure Parameters From Saturated Conductivity Correlation Another method of estimating the mean pore size parameter α is to employ a correlation with saturated hydraulic conductivity:

$$\alpha \approx (K_{sw}/A)^{1/2} \tag{3-45}$$

Laboratory analysis of vertical conductivity has shown A ≈ 0.5 m^3d^{-1} (±50%). Because field-measured horizontal conductivities (e.g., from slug or pump tests) are generally much higher than vertical laboratory values, estimates of α using A=0.5 m^3d^{-1} and field-measured conductivities may be higher than values estimated from grain size distribution data. The true field parameter values will probably lie between these estimates.

Capillary Pressure Parameters From TPH Data The most critical parameter in estimating oil saturation distributions and spill volume is generally the capillary curve parameter α. If independent data are available on oil saturation at points in the field, these can be used to calibrate the value of α. Because oil saturation can be inferred from total petroleum hydrocarbon (TPH) data, if the latter measurements and monitoring well data are available, they may be used to calibrate α. The method is based on the premise that oil saturation distributions computed for given well fluid levels from three-phase saturation relationships should agree with TPH data if the capillary model is properly calibrated. The method requires as input well product thicknesses H_o, and oil-water table elevations, z_{ow}, in monitoring wells at specified coordinates (x_w,y_w), TPH measurements from a given depth interval for specified coordinates (x_T,y_T), and estimates of total porosity ϕ, irreducible water saturation S_m, the van Genuchten parameter n, oil-specific gravity ρ_{ro}, and fluid-dependent scaling factors β_{ao} and β_{ow}.

The major steps of the algorithm can be summarized as follows:

1. Interpolate z_{ow} and H_o at locations (x_T,y_T) where TPH is measured.

2. Calculate an average oil saturation $\bar{S}_o$ from the interpolated fluid levels over the interval of TPH measurements and use this $\bar{S}_o$ to calculate the corresponding TPH value.

3. Compare measured and calculated TPH values and iteratively adjust the value of α to minimize the sums of squares.

$\bar{S}_o$ is calculated by averaging S_o computed at midpoint, lower, and upper limits for TPH measurement intervals. TPH (in ppm) is calculated as:

$$TPH = \frac{\rho_o \overline{S_o} \phi}{\rho_b} \times 10^6 \qquad (3\text{-}46)$$

where ρ_o is the oil density and ρ_b is the soil bulk density.

In Step 3, measured TPH data are used only for intervals within elevations where free oil saturation is non-zero. This interval is defined by a lower limit z_l and an upper limit z_u'.

3.3 Free Product Control and Recovery

3.3.1 Introduction

The first requirement in spill remediation is to prevent further free product migration. This generally involves source removal or mitigation and installation of a system of trenches, sumps, or wells from which free product and sometimes water are skimmed or pumped.

The following methods are used to contain free product migration:

- Skimming or pumping free product from trenches, sumps, and wells without pumping groundwater can be an effective technique for use on layers of free product that are relatively static and remain in the vicinity of the spill or leak.

- Trenches installed on the downgradient side of the spill area that only skim or pump free product can also be effective in mitigating the migration of the free product layer.

- Pumping groundwater along with the skimming or pumping of free product is an effective approach when a hydraulic control is necessary to move the free product into the trench, sump, or well and/or to prevent migration of the free product layer.

- Pumping from trenches, sumps, or wells must be carefully controlled to limit contaminant migration. Increasing water pumping further will generally diminish recovery because of the increasing volume of residual product that will become smeared over the *cone of depression* of the water table drawdown. Thus, for a given well or trench configuration, water pumping rates should be determined in order to control product spreading.

Because various pumping configurations can be used to control the plume, additional criteria must be evaluated to determine the optimum system design. These criteria are the unit treatment costs and ultimate remediation objectives (removal of free product only, reduction of soil or dissolved concentrations below threshold values, etc.). The optimum design involves minimizing water pumping or the duration of the remediation period, maximizing total product recovery, or maximizing the product recovered per volume of water pumped (average oil-water cut).

Consideration also must be given to the total water pumping rate and total product recovery. The analysis of recovery system design involves two steps:

- For a given well configuration, pumping rates are determined to control free product layer movement.
- Recoverable product volume is estimated to determine the design that yields maximum recovery.

This chapter includes a description of the methodology used in each of these steps of the design process.

3.3.2 Design Considerations

3.3.2.1 Free Product Migration Control

In the absence of air-pressure gradients, water flow will occur in response to gradients in the air-water table, z_{aw}, also referred to as the corrected water table.

$$z_{aw} = z_{ow}\ \rho_{ro}\ H_o \tag{3-47}$$

Lateral flow of separate phase hydrocarbons occurs in response to gradients in the air-oil table elevation. Once the air-water surface is determined for a given well configuration, the air-oil table (z_{ao}) may be estimated.

$$z_{ao} = z_{aw} + (1-\rho_{ro})H_o \tag{3-48}$$

where:

z_{aw} = post-pumping water table elevation (L)
ρ_{ro} = oil-specific gravity (L^0)
H_o = oil thickness location prior to pumping (L).

If oil thickness is small compared to aquifer thickness, water transmissivity is slightly affected and water flow may be modeled independently of oil.

Equation 3-48 yields an approximation of the air-oil table after water flow approaches steady-state conditions, but before significant oil redistribution has occurred. Because oil will tend to accumulate at the wells and will gradually diminish in thickness near the plume perimeter, the oil gradient around the edge of the plume computed by Equation 3-35 should be an upper estimate. If the gradient of z_{ao} is flat or inward at all locations around the plume perimeter, control of plume migration should be assured for the assumed pumping conditions. For effective plume control, the plume perimeter should first be delineated (e.g., minimum oil thickness contour of 0.01 ft). The first step is to plot the air-oil table gradient normal to the boundary. The direction and magnitude of the oil gradient plume control are indicated when all vectors disappear or point inward around the entire perimeter of the plume.

To determine the product capture zone, any suitable analytical or numerical groundwater flow model can be used to compute the water table (z_{aw}) distribution in response to water pumping at selected locations at specified rates. Flow vectors or streamlines can be computed from the water table gradients to determine the direction of groundwater flow throughout the region with free hydrocarbon. Inward pointing water velocities around the entire plume perimeter indicate control of the dissolved plume.

To ensure control of the free product plume, the air-water table is corrected for oil thickness to determine the air-oil table using Equation 3-48. Plotting flow vectors or streamlines of z_{ao} will enable an assessment of oil plume control. If vectors of z_{ao} are inward on the entire plume perimeter, free product plume control is indicated.

Figures 3-17a through 3-17c show a hydrocarbon plume (closed contours of H_o), air-oil table contours, and air-oil gradients for a site with a regional flow field (left to right) and with three wells pumping at 0.2, 0.5, and 0.75 gpm, respectively. Note that the 0.2-gpm case does not provide plume control on the downgradient (eastern) plume border. Control is obtained for the 0.5- and 0.75-gpm cases.

3.3.2.2 Estimation of Recoverable Product Volume

Estimates of the volume of free oil recovered from well oil thickness were discussed in previous subsections. Only a fraction of this volume is recoverable, however, because of the processes used that lead to the occurrence of *residual oil*. Residual oil has been distinguished as *in-solar residual oil* in the liquid-saturated zone, which occurs as hydraulically discontinuous blobs trapped within a continuous water phase, and as *pendular residual oil* in the unsaturated zone, which occurs as thin films and as pendular rings of oil at particle contacts. Recoverable volume, Σ_∞, is calculated by the following equation:

$$\Sigma_\infty = \Sigma_{of} - \Sigma_{ot} - \Sigma_{og} \qquad (3\text{-}49)$$

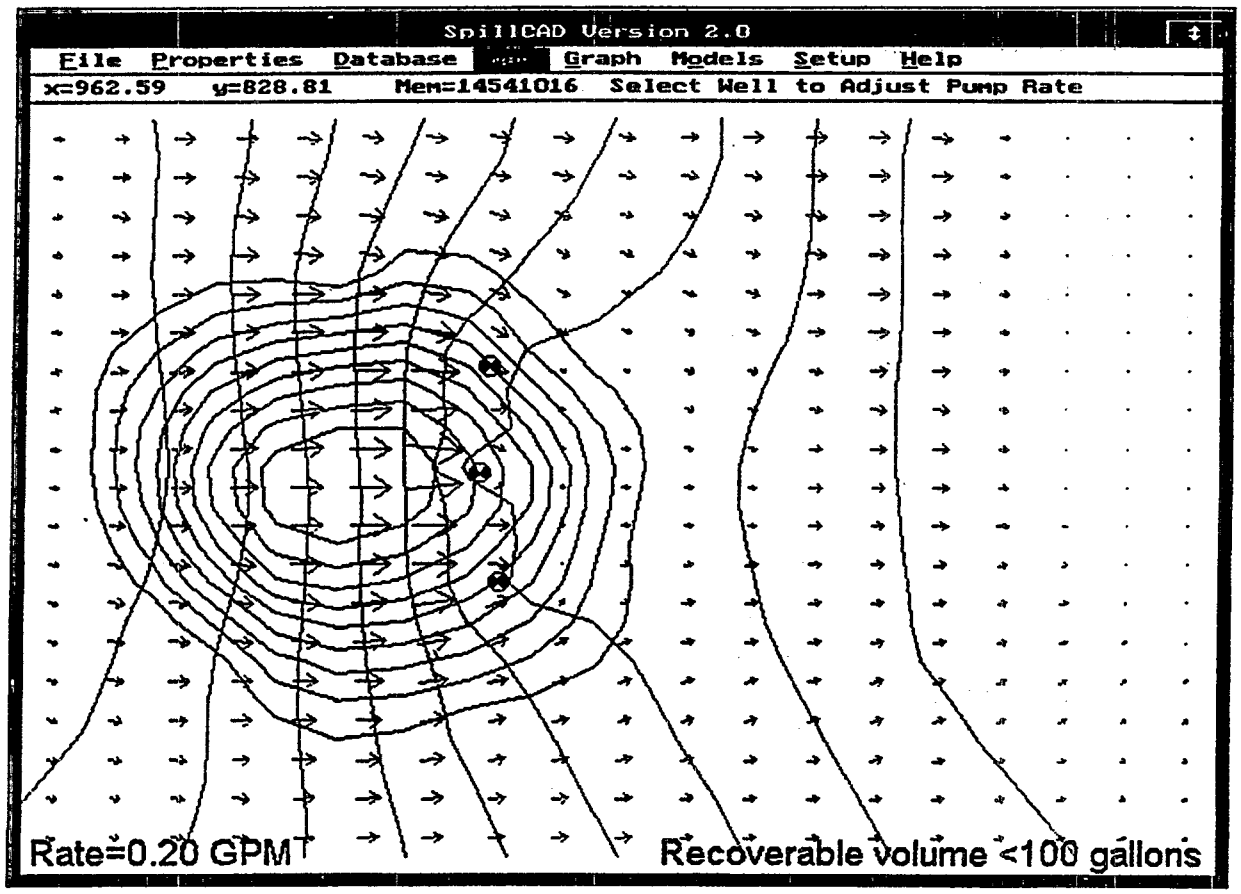


Figure 3-17a. Pumping rate of 0.20 gpm to control air-oil table gradient on plume perimeter.

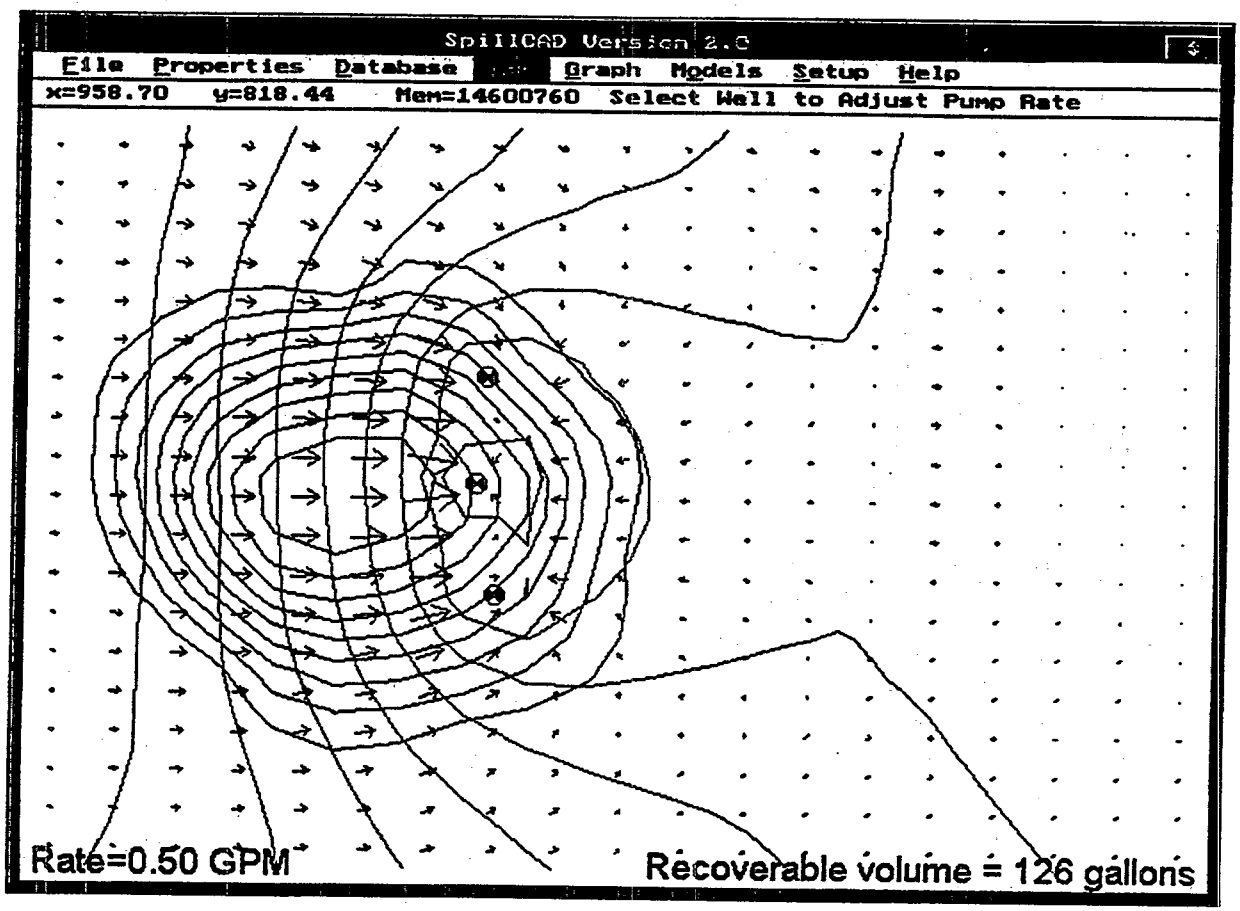


Figure 3-17b. **Pumping rate of 0.50 gpm to control air-oil table gradient on plume perimeter.**

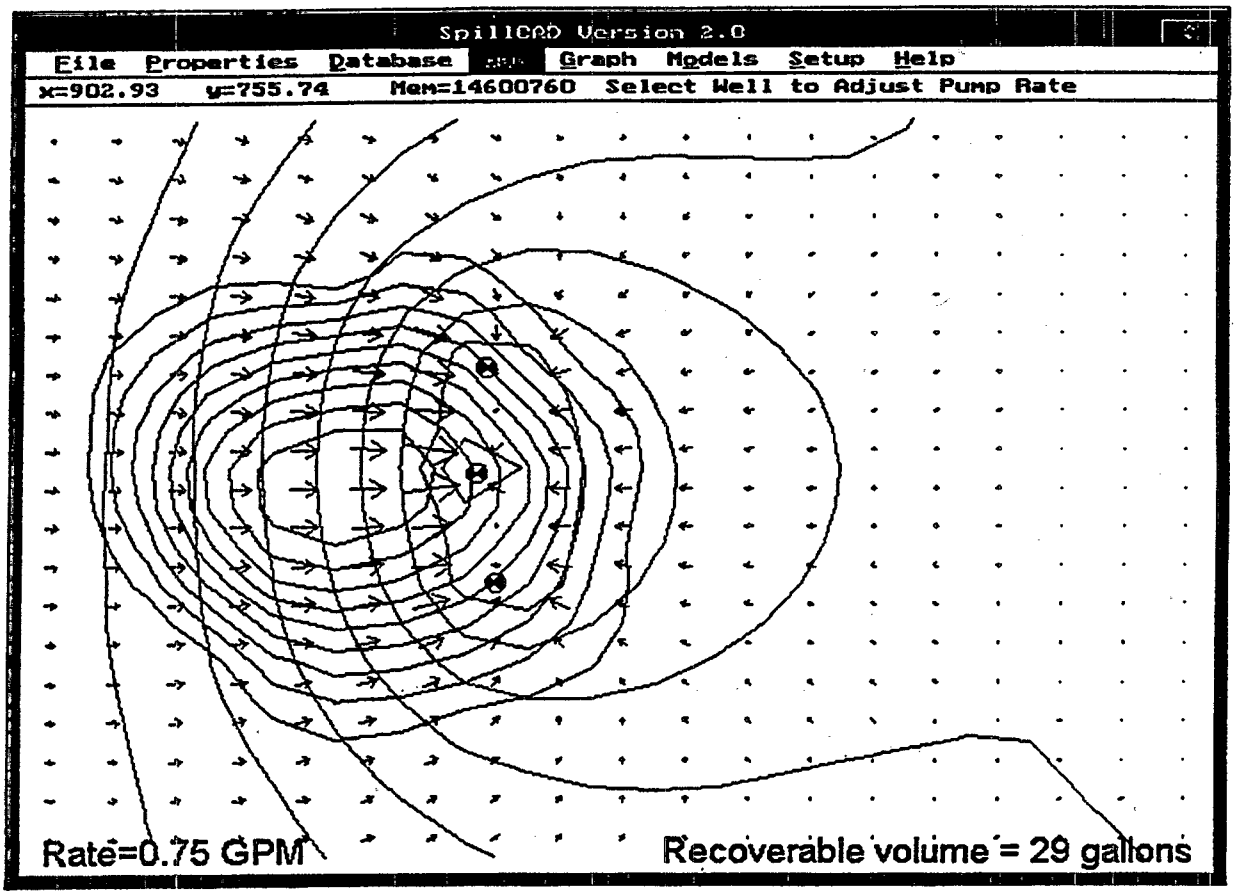


Figure 3-17c. Pumping rate of 0.75 gpm to control air-oil table gradient on plume permieter.

where:

Σ_{of} = initial free oil volume (L^3)
Σ_{ot} = volume of oil trapped in the unsaturated zone (L^3)
Σ_{og} = volume of residual oil in the unsaturated zone (L^3).

If the spill area is divided into a grid with *N* blocks of equal area *A*, the volumes may be computed as:

$$\Sigma_{of} = A \sum_{i=1}^{N} V_{of_i} \tag{3-50}$$

$$\Sigma_{ot} = A \sum_{i=1}^{N} V_{ot_i} \tag{3-51}$$

$$\Sigma_{og} = A \sum_{i=1}^{N} V_{og_i} \tag{3-52}$$

where:

V_{of_I} = initial free oil-specific volume at location *I* (L)
V_{ot_I} = residual oil-specific volume that may become trapped in the liquid-saturated zone at location *i* (L)
V_{og_I} = residual oil-specific volume held against gravitational drainage in the unsaturated zone at location *I* (L).

Free oil-specific volumes may be computed from well product thickness data as discussed in Section 3.2.4. The insular-specific volume is computed as described in Section 3.2.6 based on estimates of Δz_{ow} computed assuming that oil thickness does not change much within the period that water pumping reaches steady state. As product is removed from the formation during steady water pumping, the oil-water table will increase until well oil thickness (H_o) approaches zero. At this point $z_{ow} = z_{aw}$ and

$$\Delta z_{ow} = \rho_{ro} H_o \tag{3-53}$$

The value of H_o^{max}, also needed to compute insular residual-specific volume, is taken as the value of H_o prior to pumping. The pendular residual-specific volume may also be computed, as described in Section 3.2.6, assuming $\Delta z_{ao} = \Delta z_{aw}$, which is the water table drawdown.

The above estimates of asymptotic recoverable product volume are based on the assumption that lateral plume spreading is controlled. If this condition is not met, less product will be recovered because of increases in residual volumes as the plume spreads.

An example of different pumping rates for product recovery is illustrated in Figures 3-17a, 3-17b, and 3-17c. Note that at the lowest pumping rate of 0.2 gpm, plume control is not indicated, and thus the assumptions underlying Equations 3-51 through 3-53 are not met and the recoverable volume cannot be estimated. For cases b and c (pumping 0.5 and 0.75 gpm), the estimated recovery drops from 126 gallons for the 0.5-gpm case to only 29 gallons for the 0.75-gpm case, thus reflecting greater residual because of "smearing" in the larger cases of depression caused by pumping. The initial free oil volume for this problem was about 1,100 gallons prior to the start of recovery.

3.3.2.3 Free Product Migration to Trenches and Sumps

Trenches and sumps are effective in the control of free product migration and the recovery of free product. Previous sections covering vertically integrated flow equations can be used to estimate the rate of oil seepage into a trench. Flow into a large dug sump is analogous to that of a trench. Figure 3-18 illustrates water and oil distribution for the special case of a delta-function soil. For this soil, pore size distribution is narrow and saturation-capillary pressure relationships will be delta-functions resulting in an "oil pancake" on the water table. In this example, V_{of} is the free oil-specific volume, T_o is the oil transmissivity, and H_s is the oil-contaminated thickness of the soil.

If the pore size is narrow, S-P and S-z relationships will be delta-functions, resulting in an "oil pancake" on the water table.

For the VG model:

$$\delta_{aw} = 1/a \text{ and } n \to \infty$$

For the BC model:

$$\delta_{aw} = h_a \text{ and } \lambda \to \infty$$

For delta-function soil, soil hydrocarbon thickness and oil-specific volume are given, respectively, by

$$H_a = H_o + \delta_{ao} - \delta_{ow}$$

$$V_{of} = \phi(1 - S_m)H_s$$

Figure 3-18. "Oil pancake" approximation.

The special case of a *delta-function soil* is characterized by a step-function capillary pressure curve with an air entry head of h_d and a Brooks-Corey exponent $\lambda \to \infty$. (Note, this is the same as the van Genuchten model with $h_d = 1/\alpha$ and $\eta \to \infty$.) For this soil, oil saturation will equal $(1 - S_m)$ over the interval from $z_{ow} + \delta_{ow}$ to $z_{ao} + \delta_{ao}$ (see Equations 3-27 and 3-28), giving a thickness of $H_s = H_o + \delta_{ao} - \delta_{ow}$ in which effective oil saturation is unity $(S_o/(1 - S_m))$. The free-oil-specific volume V_{of} will be equal to $\phi(1 - S_m)H_s$, and oil transmissivity T_o will be equal to $\rho_{ro}K_{aw}H_s/\eta_{ro}$.

The oil flux into the trench per unit length will be equal to T_o grad z_{ao}. If oil is removed from the trench, the oil transmissivity on the downstream trench face will be controlled by the product thickness remaining in the trench. Note that free-oil-specific volume and transmissivity will be zero if the oil thickness in the trench is less than δ_{ow}. Thus, if a trench is used to recover product, and the product level in the trench is maintained below δ_{ow}, product will not enter the trench on the downgradient side.

3.3.2.4 Example Calculations

Example 1 To illustrate the calculations discussed above, soil concentration data for samples taken from a soil boring to a depth of 45 feet are used in a spreadsheet form given in Table 3-4 to compute total hydrocarbon-specific volume, benzene mass per area, and volume of soil per area with TPH greater than 1000 mg/kg. Given multiple soil borings, similar calculations using Equations 3-50 through 3-52 can be repeated for other locations and the results interpolated over a spatial domain to determine total hydrocarbon volume, benzene mass, and contaminated soil volume within the sampled region. Interpolation may be carried out using commercial or public-domain software (e.g., GEO-EAS or on a regular grid Surfer). The soil under consideration is assumed to have a porosity of 0.35 and a bulk density of 1.72 g/cm^3. The hydrocarbon density is assumed to be 0.80 g/cm^3. Values in Table 3-4 were computed as follows:

Column A. Sample depth is the distance from the ground surface to the center of the core sample.

Table 3-4. Example Spreadsheet Calculations from Soil Boring Data

A	B	C	D	E	F	G	H	I
Depth (ft)	dZ (ft)	TPH (mg/kg)	θ_0 (-)[a]	V_0 (ft^3/ft)	Y_e (mg/kg)	$f\rho_b Y_e$ (g/ft^2)	$\delta(Z)$ (-)	$\delta(Z)dZ$ (ft^3/ft)
5	5.5	542	0.0012	0.006	5	1.3	0	0.0
15	8.0	1180	0.0025	0.020	9	3.5	1	8.0
21	6.5	3937	0.0085	0.055	37	11.7	1	6.5
28	8.0	6836	0.0147	0.118	53	20.7	1	8.0
37	8.5	678	0.0015	0.012	6	2.5	0	0.0
45	4.5	27	0.0001	0.000	0	1.2	0	0.000
				0.206		39.8		22.5

[a] Dimensionless.

Column B. The sample interval, dZ, is half the distance from the current sample to the next shallower sample, plus half the distance from the current sample to the next deeper sample, except for the shallowest and deepest samples, in which case, the interval is half the distance from the sample center to the next sample, plus 0.5 ft to account for one half of the actual length of the sample core.

Column C. Measured TPH in the soil core is given as mg hydrocarbon per kg dry soil.

Column D. The average volumetric oil content in the sample interval is computed from Equation 3-46.

Column E. Each entry in the column is calculated as $\theta_o dZ$, and the entire column is summed to obtain the oil-specific volume, V_o = 0.206 ft^3 per ft^2.

Column F. Measured soil benzene concentration is expressed as mg benzene per kg dry soil.

Column G. The average benzene mass per area in g/ft^2 in the sample interval is computed from:

$$m_\alpha = \int_{z_l}^{z_u} \frac{\rho_b \, Y_\alpha}{10^6} \, dz \tag{3-54}$$

where Y_α is the soil concentration of species α, z_l and z_u are the lower and upper elevations where the contaminants occur, and the factor f = 0.0283 is inserted to make the proper unit conversions. The column is summed to obtain the mass of benzene per area over the boring depth, m_{benz} = 39.8 g/ft^2.

Column H. The indicator variable is 1 if TPH ≤ 1000 mg/kg and 0 if TPH is smaller.

Column I. The volume of contaminated soil per area in each sample interval is calculated as $\delta(Z)dZ$. The column is summed to obtain the contaminated soil volume of 22.5 ft^3 per ft^2.

Example 2 An example calculation is shown in spreadsheet form to compute free-oil-specific volume, V_{of}, from well product thickness, H_0, in a monitoring well. The well product thickness for the example is 3 feet and the air-oil and oil-water table elevations are 93 and 90 feet, respectively. Assumed oil and fluid properties for the problem are given in Table 3-5. Vertical integration is performed from a lower elevation of Z_{ow} = 90 feet to an upper elevation of Z_u = 93.4 feet, computed from Equation 3-27. Calculations are performed at 35 equal-depth intervals of 0.1 foot to numerically integrate for oil-

specific volume. To compute total free-oil-volume, calculations of oil-specific volume must be repeated at various areal locations. Because well product thickness must be a smooth function in space (discontinuities in the piezometric gradients cannot occur), while oil-specific volume may be discontinuous as a result of soil heterogeneity, it is preferable to interpolate H_o from monitoring wells onto a computational grid and to compute V_{of} on the grid from interpolated apparent thickness values. The values in Table 3-6 were computed as follows:

Table 3-5. Soil and Fluid Properties for Example Problem

$\rho_{ro} = 0.8$	$K_{sw} = 8.0$ ft day^{-1}	$S_m = 0.15$
$\eta_{ro} = 0.6$	$\phi = 0.35$	$S_{og} = 0.06$
$\beta_{ao} = 3.2$	$\alpha = 2.5$ ft^{-1}	$S_{or} = 0.20$
$\beta_{ow} = 1.5$	$n = 2.0$	

Column A. The first value of Z is Z_u from Equation 3-27, the final value is Z_{ow}, and intermediate values are incremented in intervals of dZ = 0.1 ft.

Column B. The oil-water capillary pressure h_{ow} is calculated as $h_{ow} = (1-\rho_{ro})(Z-Z_{ow})$.

Column C. Air-oil capillary pressure is calculated using Equation 3-22 above Z_{ao}. At lower elevations, $h_{ao} = 0$ is employed to compute total liquid saturation.

Column D. Water saturation is calculated using Equation 3-7 given h_{ow} at the specific depth.

Column E. Free-oil saturation is calculated for each depth as $S_{of} = S_t - S_w$.

Column F. The free-oil volume per unit area for each depth interval is computed as $\phi S_{of} dZ$. A sum of all values in Column F gives the free-oil-specific volume of 0.309 ft^3/ft^2.

3.3.3 Systems and Equipment

The previous sections have dealt primarily with the soil, oil, and water characteristics in the aquifer or formation that affect the migration and recovery of free product. This section presents a discussion on the basic systems and equipment that are used to recover free product.

Free-product recovery techniques can be grouped into three basic approaches:

- Recovery of free product from open excavations
- Recovery of free product from trench and sump systems
- Recovery of free product from wells.

Each of these basic approaches is presented in this section. An overview of the different applications and design considerations for equipment commonly used in each approach will be discussed.

Table 3-6. Spreadsheet for Free-Oil-Specific Volume from Well Product Thickness

A	B	C	D	E	F
Z (ft)	h_{ow} (ft)	h_{ao} (ft)	S_w (-)[a]	S_{of} (-)	$\phi S_{of} dZ$ (ft^3/ft^2)
93.4	0.68	0.32	0.46	0.00	0.000
93.3	0.66	0.24	0.47	0.08	0.003
93.2	0.64	0.16	0.48	0.20	0.007
93.1	0.62	0.08	0.49	0.38	0.013
93.0	0.60	0.00	0.50	0.50	0.018
92.9	0.58	0.00	0.51	0.49	0.017
92.8	0.56	0.00	0.52	0.48	0.017
92.7	0.54	0.00	0.53	0.47	0.017
92.6	0.52	0.00	0.54	0.46	0.016
92.5	0.50	0.00	0.55	0.45	0.016
92.4	0.48	0.00	0.56	0.44	0.015
92.3	0.46	0.00	0.58	0.42	0.015
92.2	0.44	0.00	0.59	0.41	0.014
92.1	0.42	0.00	0.61	0.39	0.014
92.0	0.40	0.00	0.62	0.38	0.013
91.9	0.38	0.00	0.64	0.36	0.013
91.8	0.36	0.00	0.66	0.34	0.012
91.7	0.34	0.00	0.67	0.33	0.011
91.6	0.32	0.00	0.69	0.31	0.011
91.5	0.30	0.00	0.72	0.28	0.010
91.4	0.28	0.00	0.74	0.26	0.009
91.3	0.26	0.00	0.76	0.24	0.008
91.2	0.24	0.00	0.78	0.22	0.008
91.1	0.22	0.00	0.81	0.19	0.007

(continued)

Table 3-6. (continued)

A	B	C	D	E	F
Z (ft)	h_{ow} (ft)	h_{ao} (ft)	S_w (-)[a]	S_{of} (-)	$\phi S_{of} dZ$ (ft^3/ft^2)
91.0	0.20	0.00	0.83	0.17	0.006
90.9	0.18	0.00	0.85	0.15	0.005
90.8	0.16	0.00	0.88	0.12	0.004
90.7	0.14	0.00	0.90	0.10	0.003
90.6	0.14	0.00	0.93	0.07	0.003
90.5	0.10	0.00	0.95	0.05	0.002
90.4	0.08	0.00	0.96	0.04	0.001
90.3	0.06	0.00	0.98	0.02	0.001
90.2	0.04	0.00	0.99	0.01	0.000
90.1	0.02	0.00	1.00	0.00	0.000
90.0	0.00	0.00	1.00	0.00	0.000
					0.309

[a] Dimensionless.

3.3.3.1 Open Excavations

Free product is usually recovered from open excavations during tank, soil, or pipeline removal or replacement at a petroleum-handling facility. Free product is removed by one of the following ways:

- Vacuum truck
- Floating skimmers
- Portable trash pumps
- Absorbent booms
- Other direct removal techniques.

These techniques can effectively remove most of the spilled or leaked product at many sites. In addition, the excavation and treatment of accessible soil laden with product can significantly reduce the mass of petroleum remaining in the subsurface.

3.3.3.2 Trench and Sump Systems

Trench and sump systems can effectively recover free product that occurs as follows:

- At shallow depths(<15 feet)
- Pooled or floating on the groundwater table
- Perched above a low hydraulic permeability layer.

Sumps are often installed in the old tank pit excavations to recover NAPL not removed during initial excavation. In very permeable sands and gravel (>10^{-2} cm/sec) where there is considerable slope to the water table, trenches should be placed on the down-gradient edge of the free product area to intercept the migrating NAPL. In less-permeable soils, the sumps or trenches are often placed in the middle of the quasi-static layer to provide for the most efficient product recovery.

Trench Construction and Installation Trenches and sumps are installed in excavations of at least three to five feet below the top of the free product layer and several feet below the expected lowest seasonal fluctuation of the water table or to the geologic barrier that is perching the hydrocarbons. Care must be taken not to penetrate the geologic barrier, which would allow uncontrolled downward migration of liquid hydrocarbons. A typical trench system (Figure 3-19) consists of the following:

- One or more layers of perforated pipe, often installed at the water table/free product interface.
- One or more vertical standpipes or sumps installed with the trench to remove the product and water.
- Trench excavation backfilling with appropriate fill and cover material.

A sump recovery system, which is installed in an existing or excavated hole, consists of the following:

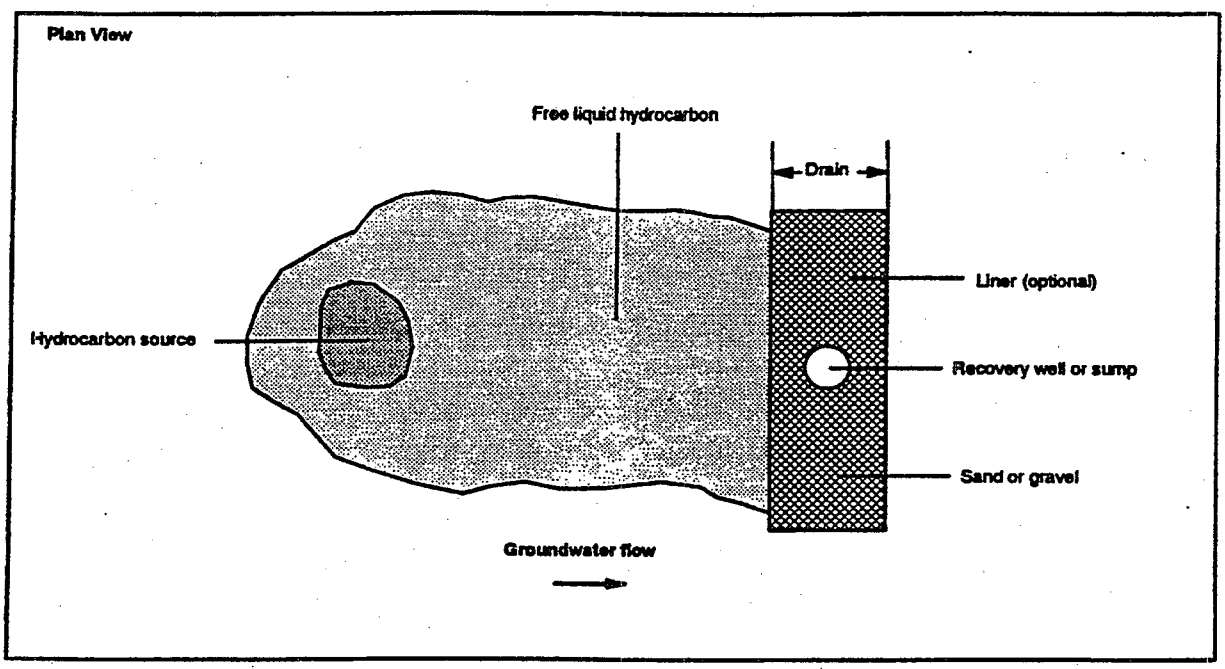
- Galvanized perforated pipe (24- to 36-inch-diameter) placed vertically in the excavation.
- Backfilling in the area around the pipe with gravel to above the upper elevation for the NAPL layer.
- Excavation backfilling with appropriate fill and cover material.

Product is removed from trenches or sumps by routine manual skimming or with the aid of various removal equipment.

3.3.3.3 Applications

Trench and sump systems are applicable to a wide variety of hydrogeologic settings, and the only major limitations are the depth to which they can be installed and the availability of space for the installation. Trenches can be used successfully for recovery in the following:

- Heterogeneous earth materials in which fluid migrates randomly through placed zones such as discontinuous layers of sand.



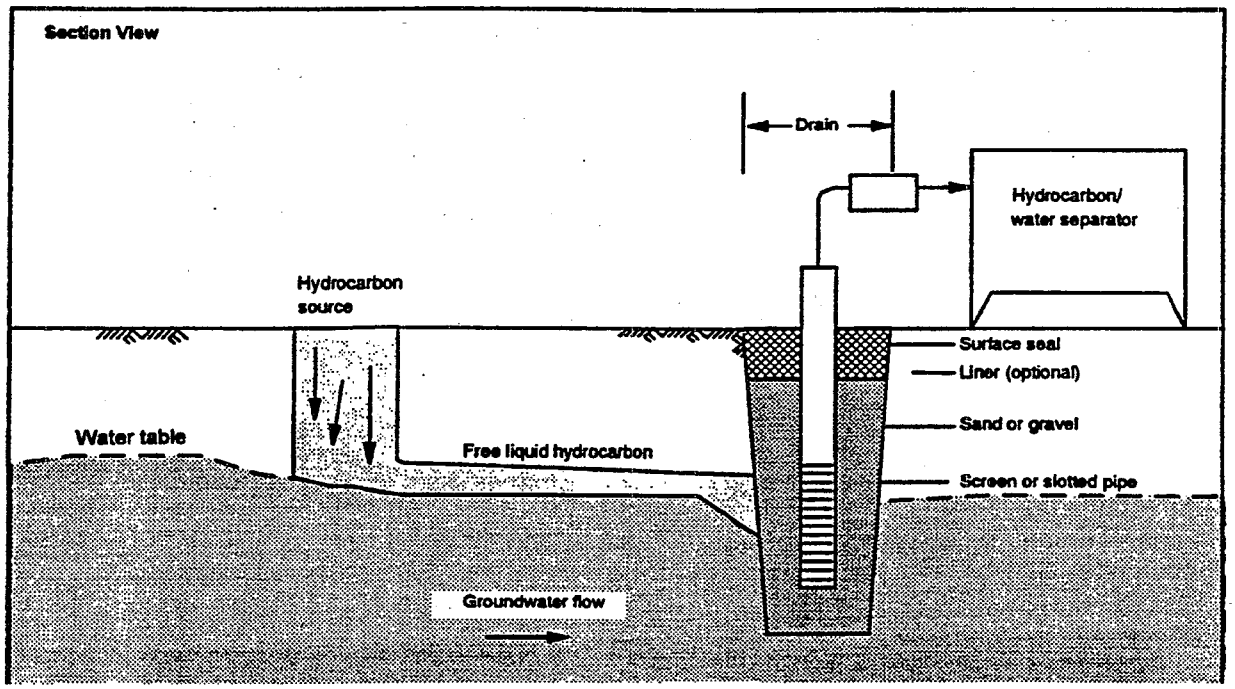


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Figure 3-19. Typical trench system.

- Areas with shallow water tables and relatively low hydraulic conductivity where interception of liquid hydrocarbon in trenches is a more practical alternative than numerous closely spaced recovery wells.

- Areas where the saturated thickness of the area aquifer is minimal, making wells ineffective, such as zones along rivers that may be dry during part of the year.

3.3.3.4 Recovery Well Systems

Recovery wells are useful for both shallow and deep free-product removal where long-term pumping or skimming is required. For depths greater than 10 to 15 feet, wells are generally a less-expensive and more flexible alternative to trenches and sumps. At a given site, if the initial recovery well or wells prove inadequate for controlling and removing the product layer plume, then additional wells can be added with less expense and site disruption than additional trenches or sumps. Basic component considerations include well diameter, placement depth, and pumping rates required for control and recovery of the product layer plume.

Well Diameter The recommended diameter of recovery wells is 4 inches, and a larger diameter is considered even more efficient. The effectiveness of a well for removing product, however, is often more related to the amount of silt and clay in the formation and the manner in which the well is installed. At some sites, more free product has been successfully removed from 2-inch diameter wells than from large 24-inch-diameter wells. Nevertheless, 4-inch or larger diameters are preferable simply because of the room required to install and adjust skimming or pumping equipment. Regardless of the diameter, though, care should be taken during well construction that the drilling process does not reduce the permeability of the product/water table zone. During well operation, the drawdown should be minimized to prevent fouling and plugging of the annular space around the well screen and the subsequent reduction in the flow of free product into the well.

Placement Depth Free product recovery wells are designed to remove free product with minimal water pumping because water treatment greatly increases the cost of the recovery system operation. Free product control and recovery is governed by the air-oil table gradient, which is in turn related to the air-water table gradient and product thickness. At a given pumping rate, the drawdown in the air-water table will increase as the fractional penetration of the well in the aquifer diminishes. Therefore, to maximize product recovery per volume of water pumped, product recovery wells should be screened over the shallowest depth possible to maintain plume control. In most cases, the bottom screen elevation should be less than 10 to 15 feet below the lowest anticipated level of the pre-pumping water table elevation. Groundwater models can be used to evaluate the effects of partial well penetration and pumping rate on water table draw-down. When dissolved plume control is a factor in system design, placement depth will be controlled by the depth of the soluble plume. Because greater well

placement depths may be required to achieve dissolved plume control, a well system that is optimal for product recovery may be inadequate for dissolved plume control, and a system that is adequate for dissolved plume control may not be ideal for free product recovery.

Areal Placement and Operation of Wells The optimal number and placement of wells will depend on the areal distribution and thickness of the free product plume, permeability of the aquifer, regional flow gradient, and the residual product saturations that will remain in the saturated and unsaturated zones. Maximum product recovery will be obtained by minimizing the total drawdown over the zone of the free product plume, while maintaining plume control around the plume perimeter. For the same total water pumping rate, product recovery will generally increase with the number of wells in operation. The economically optimum number of wells will depend on the tradeoff between the cost of well installation and operation versus the benefit gained by reducing the residual product volume. Regional flow gradients and soil anisotropy will distort the zone of influence to ellipsoids. A systematic approach to evaluating the effects of well placement and well numbers on product recovery was described in Section 3.3.2.

3.3.3.5 Recovery System Selection

The selection of an appropriate recovery well system will depend on a variety of interrelated factors:

- Depth to groundwater and free product
- Age, extent, and mobility of product
- Soil and fluid properties governing free product migration (see Table 3-1)
- Regional hydraulic gradient
- Physical setting (area available for trenches, wells, and pumps, etc.)
- Water and air handling and treatment requirements (oil/water separation, air stripping, carbon treatment, thermal treatment, etc.)
- Chemical properties of the water and product that affect the degree or potential for scaling, corrosion, or fouling of the system.

Recovery system selection also depends on the type of recovery program being implemented, and the equipment and facilities available at the location. For example, an acceptable and cost-effective alternative for an oil refinery with available hydrocarbon separation and water-handling facilities may not be acceptable at a retail service station where space and fluid-handling facilities are limited. The type of liquid hydrocarbon and

quality of the produced water will also have a major impact on the type of system selected.

3.3.3.6 Recovery Equipment

The following equipment is used to remove NAPL from excavations, trenches, sumps, and wells:

- Direct-removal equipment (skimming, pumping, absorbing)
- Skimming equipment
- Single-pump equipment
- Dual-pump equipment
- Vacuum-enhanced recovery equipment.

Table 3-7 provides a summary of these techniques along with design considerations, advantages, and disadvantages. The applications, limitations, and design considerations for each of these systems will be briefly discussed below. Common operating ranges of each pumping system are shown in Table 3-8.

3.3.3.7 Direct Removal

Direct-removal techniques can be used in many product recovery situations. The most common technique is the use of a vacuum truck to suck water and product from excavations, sumps, or wells. At some sites the existing wells are periodically pumped out by a vacuum truck until the free product is removed to a thin layer or sheen. Periodic hand bailing of wells or sumps is also a viable technique for use on small localized free-product layers. Absorbent pads and booms are often used in open excavations and to swab out wells with very thin layers of material. Dedicated product skimming bailers and absorbent tubes are used as part of a skimming system, which is discussed further below.

Skimming Equipment The three basic types of skimming equipment are:

- Floating (large saucer type or small float type)
- Floating inlet (floating filter intake within a pump body)
- Absorbent skimming (absorbent in a dedicated bailer and belt skimmer).

Skimming equipment, which is designed to remove product floating on the water table, operates at generally low removal rates and produces little or no water. Skimming equipment is available in the following designs.

<u>Large floating skimmers</u> These skimmers, which can remove product at a fairly high rate (up to 5 gpm), have a large oliophilic screen that allows product into the pump body but not water. They are generally limited to shallow (<20 feet) applications and require a 24-inch-diameter area or more.

Table 3-7. Free Product Recovery and Control Systems and Equipment[a]

	Recommended Minimum Well Diameter	Recommended Minimum Value for K (cm/sec)	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential for Product Removal	Advantages	Disadvantages
SKIMMING SYSTEMS								
• Floating							No water pumped, skims very thin layers, moves up and down with GW	Limited radius of influence, clogging of screen, generally limited to shallow (<25 ft) applications
- Large Saucer Type	36"	>1 x 10^{-4}	L	L	M	M		
- Small Float Type	4"	>1 x 10^{-4}	L	L	M	M		
• Floating inlet							No water pumped, skims very thin layers, low cost	Limited radius of influence, manually adjusted, clogging, low removal rate (different for bailers and pneumatic pumps)
- Bailer/Passive	2"	>1 x 10^{-4}	L	L	L	L		
- Pneumatic Pump	4"	>1 x 10^{-4}	L	L	L	L		
• Absorbent								
- Absorbent Bailer	2"	>1 x 10^{-4}	L	L	L	L		
- Belt Skimmer	2"	>1 x 10^{-4}	L	L	L	L		
SINGLE PUMP SYSTEMS								
• Diaphram Pump	2"	>1 x 10^{-4}	L	L	L	L	Low cost, low maintenance surface-mounted pumps, easy to maintain, low flows	Pumps water and product, requires o/w separator, shallow (< 20 ft)
• Centrifugal Pump	2"	>5 x 10^{-3}	L	L	L	L	Low cost and maintenance	Level sensor and o/w separator required (<25 ft)
• Submersible Pump	4"	>1 x 10^{-2}	M	M	L	L	No depth limitation, easy installation, removes water and product	Flow >5 gpm, o/w separator water treatment, emulsification
• Pneumatic							Can operate over wide range of flow rates, can pump from deep, low K aquifers	Requires air compressor system and water treatment, emulsification
- Top Filling	4"	> 1 x 10^{-3}	M	M	M	M		
- Product only	4"	> 1 x 10^{-4}	M	M	M	M		

Table 3-7. (continued)

	Recommended Minimum Well Diameter	Recommended Minimum Value for K (cm/sec)	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential for Product Removal	Advantages	Disadvantages
DUAL PUMP SYSTEMS								
• GWP and PP with separate levels and product sensors	8"	$> 1 \times 10^{-2}$	H	H	H	H	Cone of depression induces migration of product to well, high potential product removal rates, pump GW and product potential large radius of influence	High initial cost, high maintenance; recovery wells often become clogged and inefficient, works best in clean sands and gravels, cycling the GWP on and off with level sensor not recommended approach
• GWP running steady with PP and product sensor	6"	$>1 \times 10^{-2}$	H	H	M	H		
• GWP running steady with floating product skimming pump	6"	$> 1 \times 10^{-3}$	H	H	M	H		
DIRECT REMOVAL								
• Open Excavations or trenches	...	...	...	L	...	M	Good initial remedial action using vacuum truck absorbent pads, etc.	Not practical for removing product away from excavation area
• Routine skimming or bailing of wells	2"	$>1 \times 10^{-4}$	...	L	...	L	Inexpensive, works on small localized product layers	Very limited radius of influence and removal rate
VACUUM ENHANCED PUMPING								
• Drop tube suction lift	2"	$> 1 \times 10^{-5}$	M	H	L	VH	Works well with low to medium permeability soils, large radius of influence, increases water and product flow by 3 to 10 times; can significantly reduce site remediation time	Requires high vacuum pump or blower, usually requires thermal air treatment system and water treatment
• In-well pump augmented by vacuum on well	4"	$> 1 \times 10^{-5}$	H	H	L	VH		

a GW = Groundwater
GWP = Groundwater Pump
PP = Product Pump
K = Hydraulic Conductivity
GPM = Gallons Per Minute

L = Low
M = Medium
H = High
VH = Very High

Approximate cost ranges based on a unit single well system including water handling and treatment:

Capital Costs:
L = $3,000-10,000
M = $10,000-25,000
H = >$25,000

Operating Costs:
L = $500-1,000/mo
M = $1,000-3,000/mo
H = >$3,000/mo

Maintenance Costs:
L = <10% of capital cost/yr
M = 10 to 25% of capital cost/yr
H = >25% of capital cost/yr

Table 3-8. Pumping System Versus Common Operational Range

Pump Type	Fluid Production Rate per Well		
	Low (<5 gpm)	Medium (5-20 gpm)	High (>20 gpm)
Skimming			
Down hole	■		
Suction lift	■		
Vacuum-enhanced			
Shallow	■		
Deep	■		
Pneumatic single pump			
Submersible	■	■	
Suction lift	■	■	
Electric single pump			
Submersible	■	■	
Suction lift	■	■	
Two-pump systems			
Submersible electric		■	■
Submersible pneumatic		■	■
Suction lift		■	■

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Small float systems These systems, which can work in 4-inch or larger wells, are also limited to depths of 30 feet or less. The floating inlet skimmers use a floating screen inlet to capture the product and are contained in a pump device or a bailer. These generally require a 4-inch-diameter or larger well to operate.

Absorbent skimming bailers These bailers, which are very simple, are hung in the well across the free-product layer. The absorbent material is periodically removed and disposed of.

Belt absorbent skimmers These skimmers use a loop of material that slowly moves down into and out of the well, picking up product as it loops through the water level surface in the well. These systems are very simple mechanical systems that can work in 4-inch or larger wells, but are perhaps best suited for skimming sumps.

The following single-pump systems are designed to skim free product layers:

- *Pneumatic skimming systems with a top intake* that skims fluids from the liquid hydrocarbon/water interface (Figure 3-20).
- *Pneumatic skimming systems with a density-sensitive float valve* that allows water to pass before the valve seats.
- *Floating or depth-controlled skimming systems* with conductivity sensors that activate the surface-mounted pump when liquid hydrocarbons have accumulated to a sufficient thickness.
- *Filter skimming systems* with a filter material that preferentially passes hydrocarbons.

3.3.3.8 Applications

Because fluid is slowly extracted by a skimming system from the aquifer, only a minimal depression occurs in the air-oil table and the area of influence is minimal within which hydrocarbons are directed toward the well.

Skimming equipment is used in the following situations:

- In trenches, sumps, or wells
- In formations with low hydraulic conductivity ($<10^{-2}$ cm/sec)
- Where water table fluctuations are large (> 1 meter or 3 feet).

3.3.3.9 Design Considerations

The following factors should be considered for selecting or designing skimming equipment:

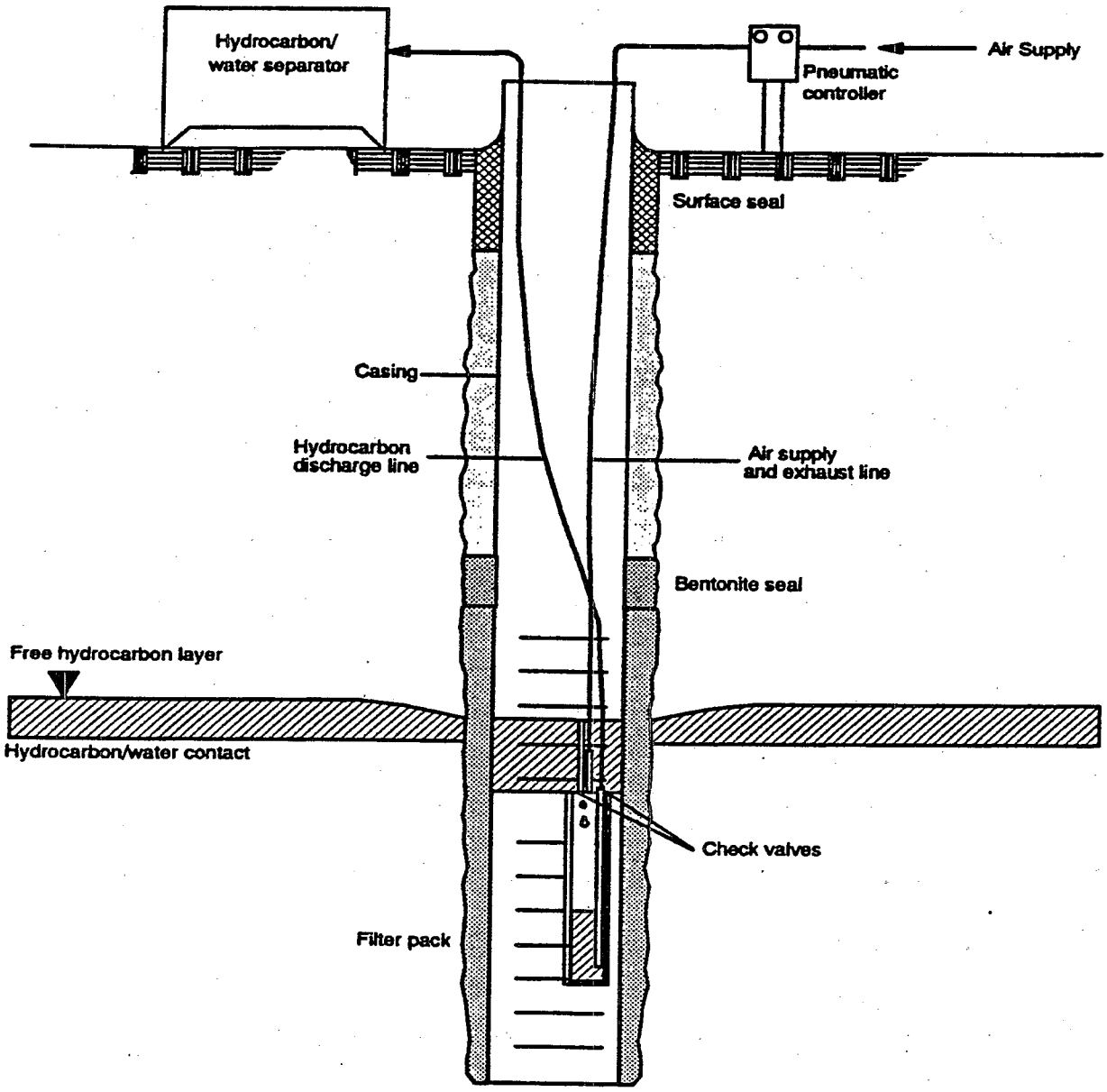

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Figure 3-20. Pneumatic skimming pump.

- Simple operation and maintenance
- Depth limitations on some of the skimming equipment
- Fouling of oliophilic or filter screens
- Little or no water produced
- Generally inexpensive to install and operate.

3.3.3.10 Single-Pump Equipment

Single-pump equipment produces both water and hydrocarbons from a single intake. In some cases, as discussed above, it can be used primarily to remove hydrocarbons. This equipment may consist of either single or multiple wells in which several wells are manifolded together to a single-surface-mounted pump or single common treatment area. The types of pumps that can be used include diaphragm, centrifugal, submersible, and pneumatic. Examples of single-pump systems are provided in Figure 3-21.

3.3.3.11 Applications

Because of the costs associated with the separation and treatment of dissolved hydrocarbons, single-pump equipment is normally limited to areas of medium- to low-hydraulic conductivity where the volume of produced water is small. The application and limitations of single-pump systems include the following:

- Creates a larger capture zone through depression of the water table.
- Useful in formations of low to moderate permeability (10^{-4} to 10^{-3} cm/sec).
- Less expensive to install than dual-pump equipment (total costs may be higher after installation of an air compressor, separator, and treatment system).
- Requires an oil-water separator at the surface.
- Increases the dissolved hydrocarbon component in the pumped water.
- Tends to emulsify hydrocarbons in the water.

3.3.3.12 Design Considerations

For the selection and design of single-pumps, the following factors should be considered:

- Simple operation and maintenance.
- Can operate at flow rates from as low as 0.1 gpm to over 20 gpm.

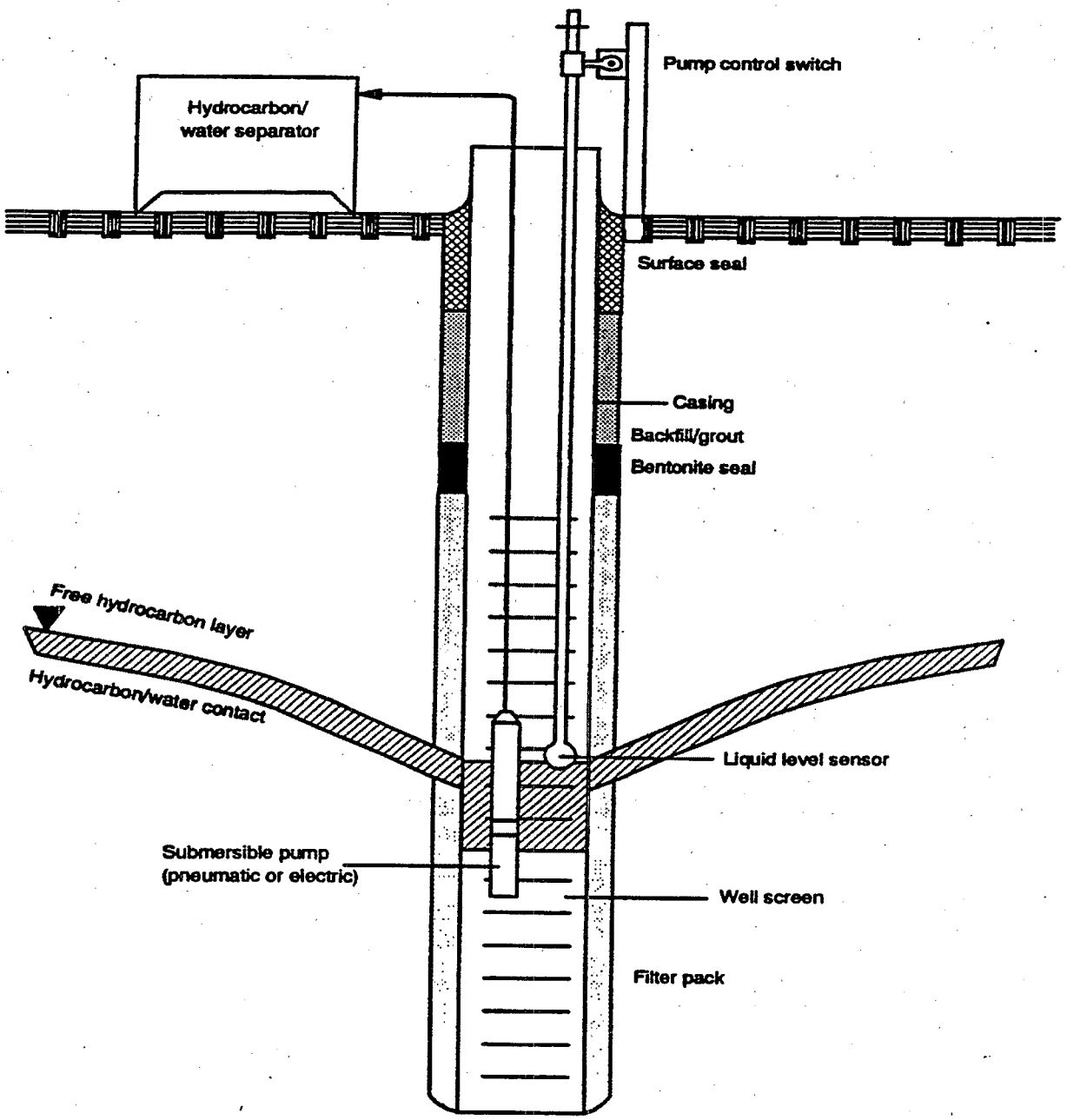

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Figure 3-21. Single-pump system.

- Pumps in contact with hydrocarbons require hydrocarbon-resistant seals and appropriate ratings for explosive environments.

3.3.3.13 Vacuum-Enhanced Recovery Equipment

Vacuum-enhanced recovery equipment use a surface-mounted vacuum pumping system (vacuum pump or blower) with an in-well pump to simultaneously remove soil vapors, NAPL, and water from a recovery well. Vacuum-enhanced systems are principally designed to operate in medium- to low-permeability soils (10^{-3} to 10^{-5} cm/sec), where high gradients may be necessary to achieve reasonable product recovery rates. To achieve such gradients by means of water pumping, large drawdowns at the well bore may be required. Large drawdowns, however, will result in large amounts of residual product becoming tied up in the cone of depression, thereby limiting the ultimate recovery. A means of overcoming this problem is to simultaneously pump water and soil air from the well (or from adjacent wells). The procedure is similar to operating a venting well (to be discussed in detail in Chapter 4) during the pumping of water and product, except that the system is designed to maximize product recovery rather than gas flow. The effect of the vacuum is to reduce the gas pressure to below atmospheric pressure for a radius around the well. Decreasing the air pressure has the effect of decreasing the air-oil capillary pressure, which will raise the plane of zero air-oil capillary pressure. Because liquid saturation is controlled by the air-oil capillary pressure, a large drawdown in the air-oil capillary fringe is implemented while the oil pressure gradient to the well is enhanced, thus increasing the oil recovery rate. Examples of vacuum-enhanced pumping equipment are shown in Figure 3-22.

3.3.3.14 Applications

The applicability of vacuum-enhanced recovery equipment can be summarized as follows:

- Can significantly speed up recovery rates and reduce the time for site remediation.
- May be used in hydrogeologic settings where the effectiveness of single-pump systems is limited.
- Useful in areas of medium- to low-hydraulic conductivity (10^{-3} to 10^{-5} cm/sec) or where saturated zones are thin.
- Can also be used in high-hydraulic conductivity (< 10^{-3} cm/sec) areas for controlled skimming.
- Used at depths greater than 5 feet.
- Can use 2-inch or larger wells and is easily adapted to the existing monitoring well network.

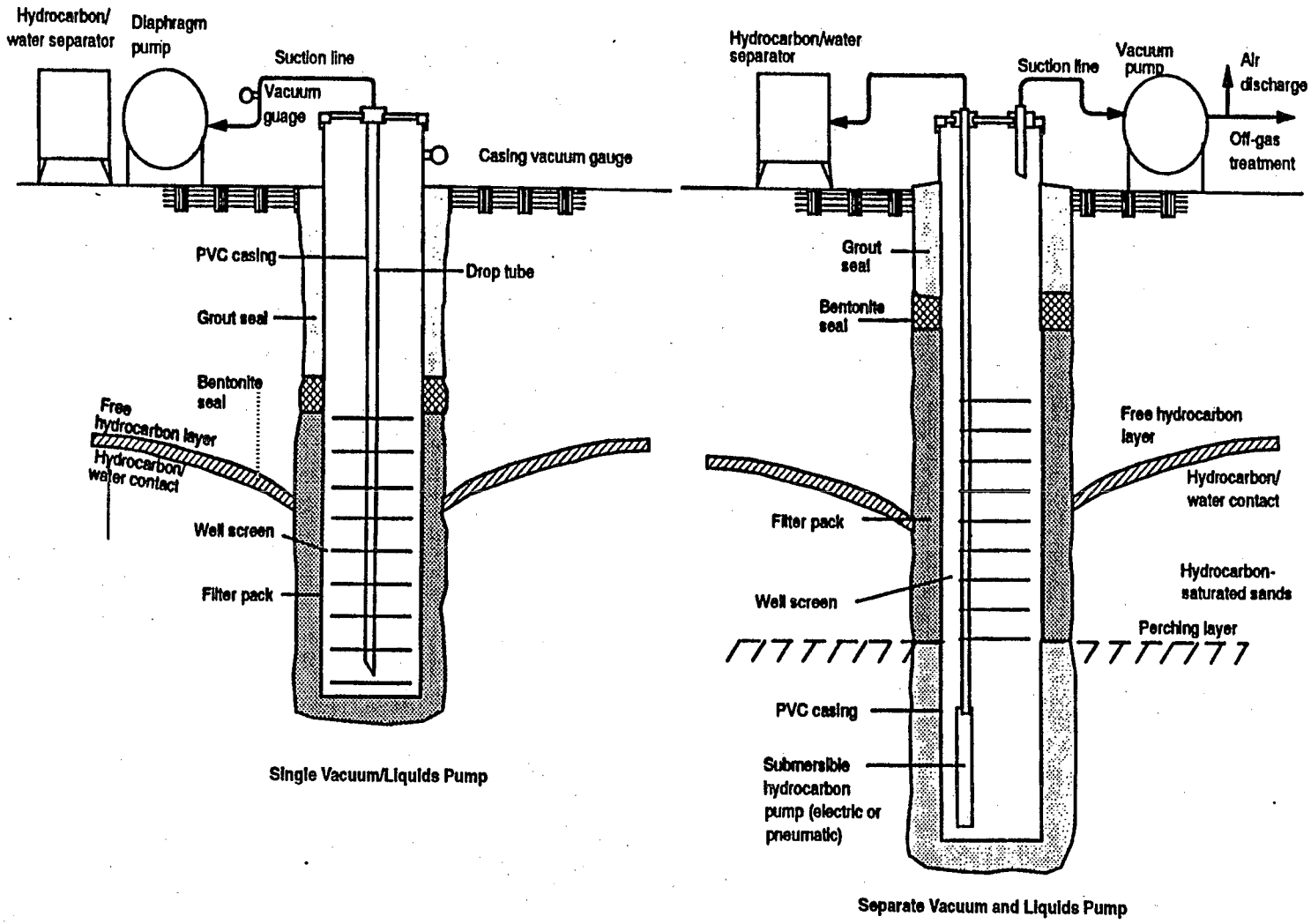

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Figure 3-22. Vacuum-enhanced single-pump options.

- Requires oil-water separator at surface.

- Higher initial capital cost than some alternatives, but shorter remediation time may result in lower overall life-cycle costs.

3.3.3.15 Design Considerations

When the use of vacuum-enhanced recovery equipment is evaluated, the following factors should be considered:

- May require permits and/or treatment for discharge air from vacuum system.

- Requires sealed well system.

- Requires optimization of vacuum and pumping rates to maximize radius of influence and recovery of product while minimizing total fluid requiring treatment.

- Proper screening interval is a minimum of 5 feet above and 10 feet below the water table.

3.3.3.16 Two-Pump Equipment

Dual-pump equipment employs separate pumps for product recovery and water table depression. Water is withdrawn from a pump placed near the bottom of the well to create a cone of depression as a capture zone, and the product is removed from a pump with an intake placed slightly below the hydrocarbon-water interface. Originally, two-pump systems were designed with a water level probe that turned the groundwater pump on and off to maintain a constant water level in the well. Field experience has shown, however, that this technique rarely works because of significant mechanical and electrical problems. Therefore, proper design and sizing of a continuously operating groundwater system is recommended. In place of a product pump, a skimming device such as a floating inlet pump float or floating skimmer can be used to remove the free product. An example of a dual-pump, dual-probe system is shown in Figure 3-23.

3.3.3.17 Applications

The following factors should be considered for dual-pump applications:

- Where water table depression is necessary for recovery.

- When hydraulic conductivities are high (> 10^{-2} cm/sec) and saturated thicknesses are large (> 1.0 m or 3.0 ft).

- Product and water are separated in the well.

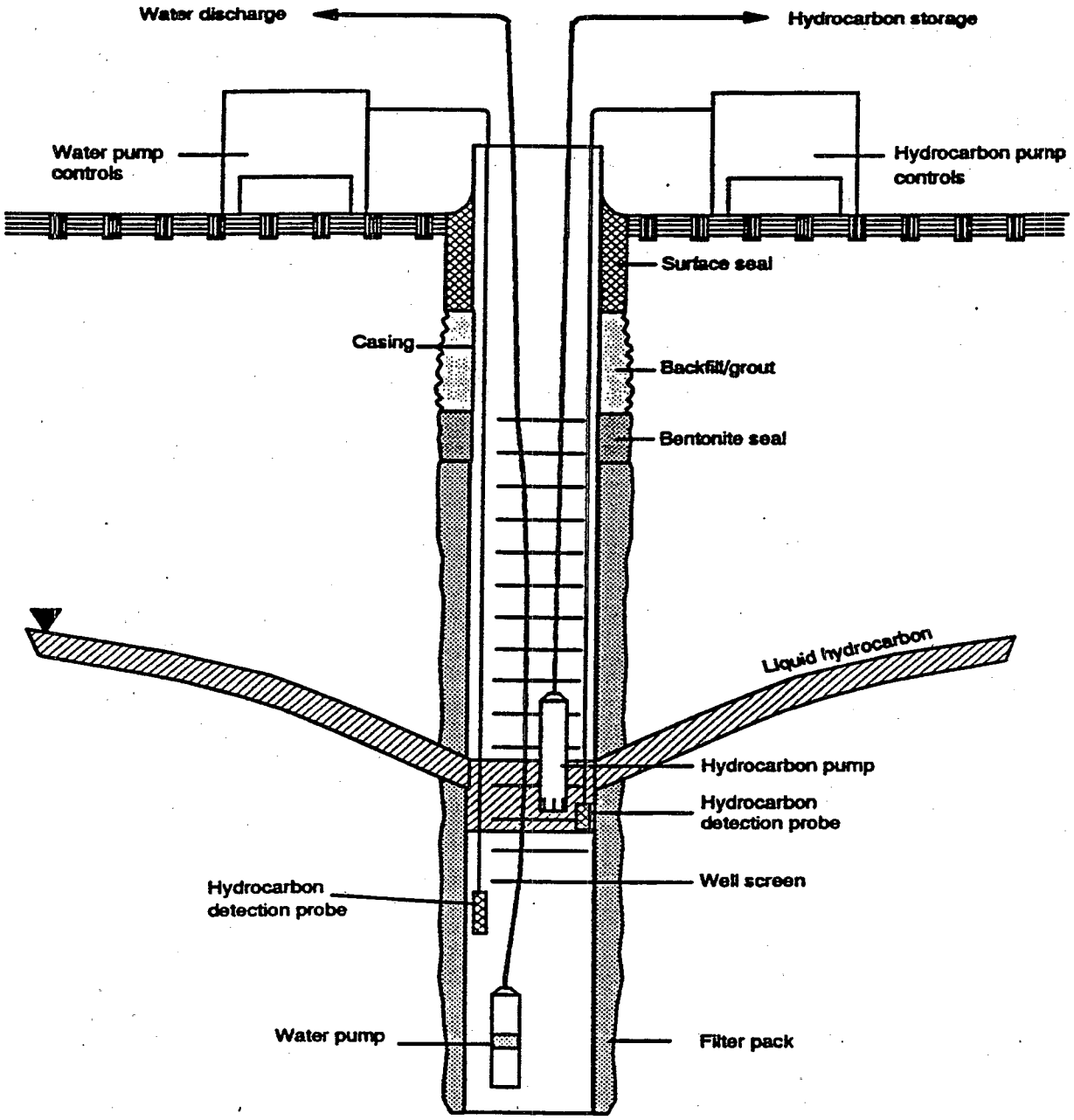

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Figure 3-23. Two-pump systems.

- Higher capital, operation, and maintenance costs.

- Initial startup and adjustments require experienced personnel.

- Systems require careful monitoring to maximize efficiency of removal and prevent mixing of water and oil wastes.

3.3.3.18 Design Considerations
For the design of dual-pump systems, the following factors impact system effectiveness and cost:

- Pump separation should be maximized to minimize dissolved hydrocarbon component.

- Pumping rates and placement in well must be balanced to maintain hydrocarbon-water interface at a constant level to the extent possible. Initial setup must be done by experienced personnel. Setting and running the groundwater pump at a constant rate is the preferred mode of operation.

- Requires larger diameter wells than single-pump systems.

- Figure 3-24 shows a typical recovery system capture zone for a two-pump system.

3.3.4 System Operation and Monitoring Requirements

After the design and installation of a recovery system, the operating system must be monitored to enable adjustments to be made to maintain system effectiveness. Periodic measurements should be made of the following parameters:

- Dissolved concentrations of influent and effluent from the water-treatment system to verify function of the treatment system.

- Oil and water levels in monitoring wells.

- Fluid levels (pump switch levels) in recovery wells and trenches.

- Total water and total product pumped for the period to determine recovery system effectiveness. Gradual reductions in product recovery and product thickness are indications that the system is functioning properly.

Table 3-9 lists potential problems and solutions encountered in the operation of recovery systems.

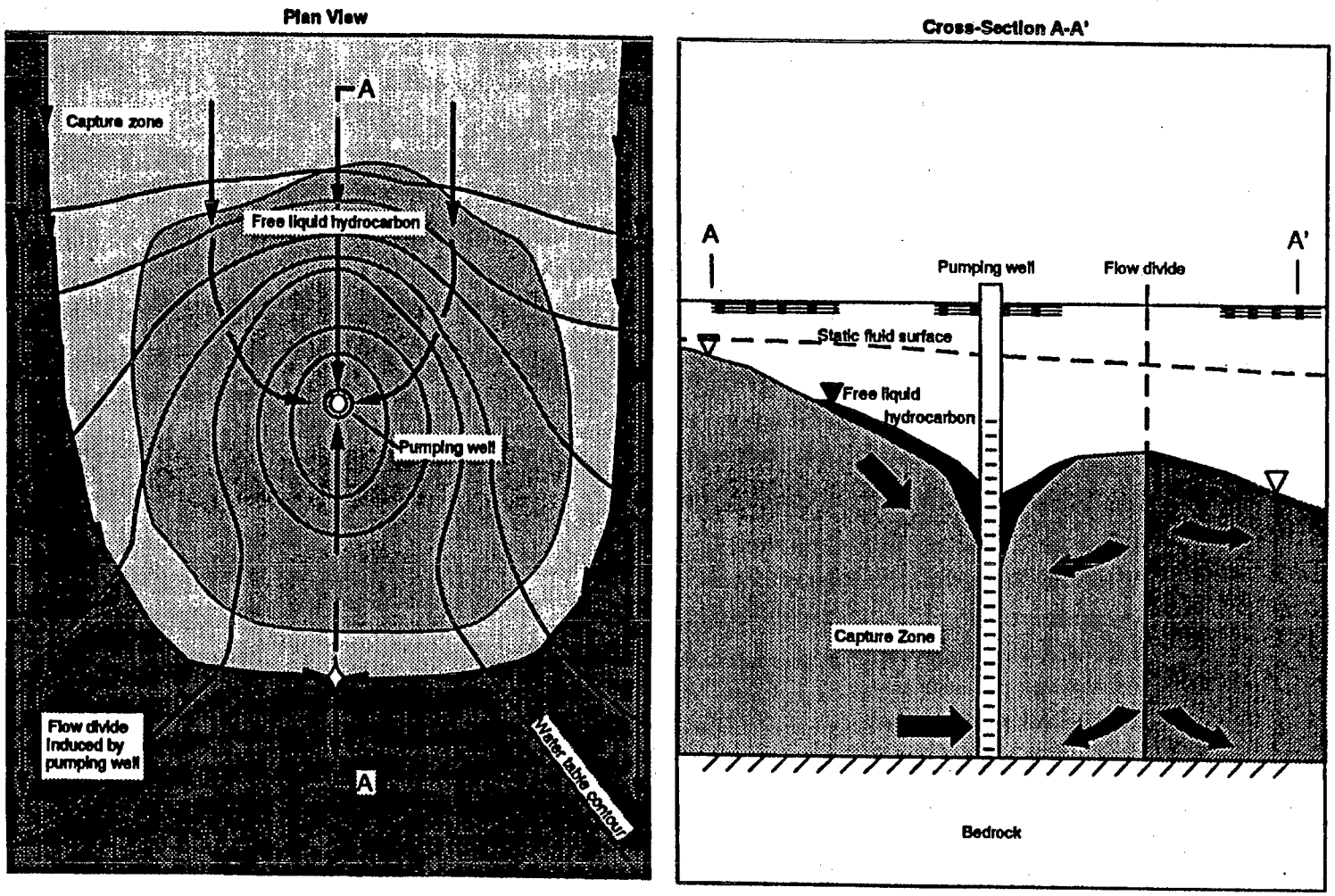

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Figure 3-24. Recovery system capture zone.

Table 3-9. Potential Problems and Solutions During Recovery System Operation

Problem	Verify	Solution
Physical/biological clogging of well resulting in low drawdown in formation due to large well loss and possible loss of plume control.	Check air-water table in monitoring wells to determine if there is adequate drawdown.	Lower pump level in well, recondition well using chemical backflushing, install new wells.
Regional rising or falling water table resulting in reduced free product and increased residual product.	Check changes in air-water table elevations for monitoring wells for measurement period.	Change pump levels to maintain plume control.
Pumping rate too high resulting in excessive drawdown tying up large amounts of residual product in the cone of depression.	Check air-water table in monitoring wells to determine if there is excessive drawdown.	Reduce pumping rates, install additional recovery wells if needed to maintain plume control.
Loss of gradient due to inadequate recharge to sustain pumping rates over area of influence of recovery system.	Check current air-water table distribution and changes over time to determine if gradient is becoming increasingly flat.	Install recharge galleries.

3.3.4.1 Regulatory Considerations

Regulatory constraints can delay the full operation of a recovery system. Some of these constraints involve federal, state, and local regulations pertaining to the following permits:

- *Permits for wells.* In states that require well permits, one of the primary purposes is to develop a database of existing wells and statewide hydrogeology. The permit process itself is generally straightforward, relatively simple, and rapid.

- *Discharge permits (National Pollutant Discharge Elimination System) [NPDES] for pump water.* Disposal of pumped water, on the other hand, can be a very difficult issue. Effluent concentrations must be less than either the Federal Maximum Contaminant Level, the applicable Method

Detection Limit, or a site-specific risk-based criterion. The specific criterion is dependent on the applicable Federal, State, or local regulations.

- *Permits for injection wells utilizing hydrodynamic control.* Injection well permits are in most instances subject to the same permitting issues as discussed above for disposal of pump water. Aquifer hydraulics (transmissivity, storativity, well yield, etc.) also need to be understood prior to the operation of an injection system.

- *Air discharge permits for air strippers and catalytic combustion.* For large systems, the air permitting process may be time-consuming and costly in order to meet requirements of the Clean Air Act of 1990. Some states do not require air discharge permits for smaller systems.

As an interim measure, skimming may be used to remove free product from recovery wells and thereby reduce the spread of contaminants. The successful removal of free product at many sites has been limited to technical difficulties encountered in locating free product in the subsurface and in removing product through recovery wells. At shallow depths, strategically located trenches may obviate the need for pumping. In addition, Resource Conservation and Recovery Act (RCRA) and other regulations may apply to the disposal of recovered product or residues from the treatment of contaminated water or air (e.g., spent activated carbon). If recovered free product can be recycled for reuse, it is not considered a RCRA hazardous waste under Subtitle C regulations. On-site storage of recovered product may also be subject to state or local fire codes.

3.3.5 Side Waste Stream Treatment

A partial list of available treatment systems for remediating spilled hydrocarbons includes:

- Separators
- Air stripping
- Bioreactors
- Carbon adsorption
- Catalytic combustion.

3.3.5.1 Separators

Hydrocarbon/water separators are often used in the initial treatment phase. Separators allow the free-phase NAPL to separate from the water and be skimmed off the top while the recovered water is pumped from the bottom. Most separators are equipped with vertical tube coalescing tubes designed to agglomerate small entrained oil particles to larger particles for effective gravity separation. After oil surfaces inside the separator, the oil is skimmed by a rotary skimmer and transferred to an external storage tank. The

greater the difference between the specific gravities of the oil and water, the faster the rate of separation. Nonemulsified oil is effectively removed down to about 10 mg/liter.

3.3.5.2 Air Stripping

Air stripping is a technique used to remove hydrocarbons from water by transferring contaminants to an air stream. Volatile organic compounds having Henry's law constants above 0.01 are readily air-strippable at ambient temperatures (EPA, 1993a). A stripping tower consists of a tall shell filled with either packing material or a series of perforated plates to promote contact between the air and water streams. The water stream is introduced at the top through a spray nozzle or distributor. Air is blown in from the bottom of the tower. As the streams pass each other, the hydrocarbons are transferred to the air stream, which exits the top of the tower. The cleaned water leaves from the bottom. If the required effluent concentration in the water is very low, a carbon bed may be needed to adsorb any remaining hydrocarbons from the exit water.

The primary factors affecting stripper design are:

- Characteristics of tower packing, typically 1 to 12 feet in diameter and 5 to 50 feet in height
- Expected water flow rate, typically 5 to 30 gpm/ft^2
- Contaminant type and concentration
- Required water effluent concentration.

3.3.5.3 Bioreactors

Bioreactors are used to microbiologically degrade hydrocarbons in a liquid or slurry. A typical bioreactor involves a suspended-growth activated sludge system, either as a continuous-flow system (CFS) or as a periodic process called a sequencing batch reactor (SBR). In either case, a controlled environment is created that is suited to the maximum degree of biodegradation obtainable. It is generally accepted that most "hazardous organics" can be treated biologically if a suitable substrate and group of organisms can be established. In a CFS, pretreated water enters a completely mixed bioreactor suitable for organism growth and substrate removal. Biomass is separated from the treated effluent in a clarifier and then returned to the bioreactor to maintain system operation. Excess biomass is processed as sludge. Clarified effluent is final treated if necessary. In an SBR, a single tank is used to accomplish the same functions that a conventional CFS carries out in a series of separate tanks. A typical SBR involves the use of two reactors, with wastewater flow alternating in cycles between the two reactors. An SBR is considered more flexible than a CFS because the adjustments are more easily made to the control system within the reactor tank in an SBR than are changes to the size of a tank in a CFS.

3.3.5.4 Carbon Adsorption

Carbon adsorption beds are used to remove hydrocarbons from air or water streams. They are capable of very high removal efficiencies from either carrier stream. Usually two or more beds are installed in series with a sample port between the first and second beds. When breakthrough occurs, the bed is removed from the process and the back-up bed is placed in the lead position. Because the adsorption process is reversible, the carbon bed is usually regenerated for reuse by thermal regeneration. Sizing a carbon system requires a knowledge of the concentration of contaminants and the process flow rate. Commercial manufacturers provide a range of sizes to accommodate a wide range of flow rates and loadings. Carbon use is only economical for relatively low mass removal rates. High mass-removal rates make the cost of replacing/regenerating the carbon prohibitive.

3.3.5.5 Catalytic Combustion

Catalytic combustion is a process that uses catalysts to increase the oxidation rate of wastes at lower temperatures than conventional thermal incineration processes. The use of a catalyst results in lower fuel requirements and reduced construction materials, but limited applications for liquid wastes. Catalytic combustion is typically used on vapor streams to burn contaminant materials as completely as possible prior to discharge to the atmosphere. The catalysts are normally metal compounds, such as a rodium-platinum alloy, distributed on the surface of a support or carrier. Carriers are inert metal oxides, such as alumina or porcelain, with large surface areas. Reaction data to assist in the choice of a catalyst is often based on pilot-plant testing of the site-specific waste materials. The exhaust is then discharged through a stack to the atmosphere.

This technique may be used in the following treatment applications:

- Vapor stream from air stripper
- Pump discharge from a soil venting system
- Other process off-gases.

3.4 Free Product Recovery Equipment Costs

3.4.1 Basic Cost Information

The areal extent and volume of the free product plume will dictate whether a small simple recovery system or a large high-volume system will be required. The characteristics of the soil matrix and/or the aquifer, such as permeability and heterogeneity, will guide the selection of either high-volume two-pump recovery systems or low-volume skimming systems. The expected recovery rate and the desired remediation time will, in many cases, dictate the number and spacing of trenches, sumps, or recovery wells. If expedited free product recovery is the preferred alternative, then a vacuum-enhanced pumping system might be selected over a gravity drainage pumping system.

The physical and chemical characteristics of both the free product and the groundwater can affect the initial selection and cost of equipment and the long-term operation and maintenance costs. High dissolved iron and solids can create significant maintenance problems and costs that must be factored in when recovery and treatment equipment is selected. The depth to water and free product will not only affect the selection of the type of skimming or pumping equipment, but will also affect the long-term operation costs. Deeper water will result in greater energy costs for water and product removal.

The site conditions, restrictions, and regulatory requirements can determine the location and size of equipment that can be used. The methods of storage, treatment, and disposal of water and free product are usually tightly regulated and will to some extent dictate system design and operation.

3.4.2 Unit Capital, Installation, Operation, and Maintenance Costs

In Section 3.3.2, the different types of free product recovery systems and equipment were described. In Table 3-7 the different types of equipment, requirements, relative costs, advantages, and disadvantages were listed. Each type of free product recovery equipment has associated water and product handling equipment such as holding tanks, oil/water separators, and transfer pumps. In addition, water and/or air treatment may be required that use air stripping and thermal treatment devices. Thus, the unit capital costs associated with a single type of recovery system has numerous components that need to be factored in along with installation, operation, and maintenance costs.

An example spread sheet showing the different basic components for the free product recovery systems is shown in Table 3-10. Example unit costs are shown for each of the different types of free product recovery equipment. Also provided are high and low estimates for each of the cost items, time intervals, and typical volume of product. The costs are presented in thousands of dollars for simplicity in presentation, and total system installation costs are subtotaled. Yearly estimated costs for operation and maintenance, disposal, and monitoring are provided along with typical duration of remediation in years. A high and low subtotal for estimated operational costs is provided along with a high and low total estimate for the life cycle of each type of free product recovery equipment. The last two columns in the table provide a very rough estimate of the estimated cost per gallon of free product recovered with each type of equipment.

This table and the basic approach discussed here are intended to provide the basic components that should be considered in the evaluation and selection of a free product recovery system. For each site, a detailed cost estimate needs to be developed that accounts for specific conditions and regulatory requirements. In the next section, an example of a detailed cost buildup for a free product recovery system installation is presented.

Table 3-10. Unit Cost ($1000) for Single Free Product Recovery System[a]

	Free Product Recovery Equipment		Product & Water Handling Eq.		Water Treatment		Air Treatment		Installation and Start-up		Subtotal System Installation		One-yr O&M		One-yr Disposal		One-yr Monitoring		No. Yrs. Typical Operation		Subtotal Operation		Total		Typical Volume (gal) Product Rec		Approx. Cost Range ($/Gal)	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
SKIMMING SYSTEMS																												
• FLOATING																												
- Large Saucer Type	7	9	3	5					2	4	12	18	8	12	1	3	0	1.5	3	5	27	82.5	39	101	1000	2000	19.5	101
- Small Float Type	3	5	2	4					1	2	6	11	6	8	0.6	1	0	1.5	3	5	19.8	52.5	25.8	63.5	200	400	64.5	318
• FLOATING INLET																												
- Bailer/Passive	0.5	1	0.1	0.1					0.1	0.2	0.7	1.3			0.2	0.3	0.5	0.5	3	5	2.1	4		5.3	1	4	700	5300
- Pneumatic Pump	3.5	10	0.3	2					0.3	3	4.1	15	0.5	6	0.4	1	0.5	2	3	5	4.2	45	2.8 8.3	60	200	400	20.8	300
SINGLE-PUMP SYSTEMS																												
• Diaphram Pump	2	3	3	5	8	10			5	7	18	25	6	8	1.5	2	6	8	3	5	40.5	90	58.5	115	200	400	146	575
• Centrifugal Pump	3	4	3	5	12	16			6	8	24	33	9	12	0.8	1	6	8	3	5	47.4	105		138	100	200	357	1380
• Submersible Pump	5	6	5	7	12	16			6	8	28	37	12	15	0.8	1	6	8	3	5	56.4	120	71.4	157	100	200	422	1570
• Pneumatic																												
- Top Filling	7.5	9	3	5	8	10			6	8	24.5	32	15	18	1.5	2	6	8	3	5	67.5	140	84.4	172	200	400	230	860
- Product Only	8.5	9.5	2	4	2	3			3	5	15.5	21.5	15	18	1.5	2	6	8	3	5	67.5	140		162	200	400	208	808
DUAL PUMP SYSTEMS																							92 83					
• GWPW/S & PP W/S	12	14	6	10	15	20			10	15	43	59	30	40	1.5	6	12	16	3	5	131	310	174	369	1000	5000	34.7	369
• GWP & PP W/S	10	12	6	10	15	20			10	15	41	57	25	35	1.5	6	12	16	3	5	116	285	157	342	1000	5000	31.3	342
• GWP & Skimmer	10	12	6	10	15	20			10	15	41	57	20	30	1.5	6	12	16	3	5	101	260	142	317	1000	5000	28.3	317
VACUUM ENHANCED PUMPING																												
• Drop Tube Suction Lift	8	12	6	10	15	20	30	40	8	10	67	92	20	30	1	2	12	16	0.5	1	16.5	48	83.5	140	1000	8000	10.4	140
• In Well Pump	10	15	6	10	15	20	30	40	10	15	71	100	20	30	1	2	12	16	0.5	1	16.5	48	87.5	148	1000	8000	10.9	148
DIRECT PUMPING																												
ABSORBENT SKIMMING																												
• Absorbent Bailer	0.5	1	0.1	0.1					0.1	0.2	0.7	1.3			0.2	0.2	0.5	0.5	3	5	2.1	3.5	2.8	4.8	1	4	700	4800
• Belt Skimmer	3.5	10	0.3	2					0.3	3	4.1	15	0.5	6	0.4	1	0.5	20	3	5	4.2	135	8.3	150	200	400	20.8	750

[a] Costs are for equipment and operational costs only. Trench, Sump, or Well costs are not included.
Costs for Engineering, Administrative Support, Permits and Reporting are not included.
A Unit Recovery System includes one skimmer or pumping system, flow rates between 1-40 gpm, extent of Free Product layer between within 50 feet radius from Trench, Sump, or Well.
1993 dollars.

3.4.2.1 Sample Cost Estimation

A typical free product recovery system installation involves many tasks and components. Table 3-11 provides a detailed list of these typical tasks and components. The quantities and costs for individual items in this table will vary between sites and depend on the specific brand and type of free product recovery equipment being installed. This table is intended to provide a guide as to the level of detail that should be considered when a cost estimate is developed.

Table 3-11. Typical Installation for Groundwater and Product Recovery

Description	Quantity	Cost
Material	50.00	101.25
4-inch PVC Pipe	260.00	526.50
2-inch PVC Pipe	260.00	526.50
1-inch Black Iron Pipe	520.00	171.60
.75-inch Elec. Cond.	10.00	7.50
.75-inch Elec. 90D	570.00	273.60
1.0-inch Elec. Cond.	15.00	18.00
1.0-inch Elec. 90 D	1.00	4.50
2-inch Ts	20.00	30.3
2-inch 90 Deg	20.00	18.00
2-inch 45 Deg	5.00	26.63
4-inch 90 Deg	35.00	330.12
12-inch Drain Pipe	2.00	18.26
12-inch Coupling	1.00	78.00
12-inch Manhole	10.00	39.00
2-inch PVC Screen	1.00	22.50
2-inch Lock Cap	1.00	690.00
3x3x3 Culvert	0.25	138.00
Geotex Fabric (6000)	110.00	805.20
Ballast Rock (Ton)	60.00	763.20
Fencing	0.25	17.40
Wire Mesh		
Forms	60.00	50.40
3000 PSI Concrete	8.00	480.00
Peagravel (Ton)	30.00	228.96
Glue (PVC)	1.00	13.80
Earth Anchor	3.00	84.28
Tower Anchor	3.00	9.68
Total		5,383.57
Outside Services		
Repaving (Per SqFt)	450.00	1,620.00
Trucking (Per Hr)	40.00	1,440.00
Disposal (Per Load)	10.00	1,140.00
Electrical	1.00	5,040.00
Total		9,240.00
Permits		
SFWMD Water Use	1.00	360.00
SPWMD Well Construction	2.00	240.00
Electrical	1.00	300.00
Building	1.00	60.00
Plumbing	1.00	60.00
Project Engineer (LC352)	24.00	1,824.00
Total		2,844.00

Table 3-11. (continued)

Description	Quantity	Cost
Equipment Rental		
Loader/Backhoe	9.00	2,106.00
Excavator (½ yd)	2.00	1,020.00
Crane Truck	1.00	390.00
Boom Truck	1.00	354.00
Air Compressor (185)	3.00	198.00
Hammer/Hose/Chisel	3.00	126.00
Concrete Saw w/Blades	3.00	360.00
Plate Compactor 24 inch	4.00	216.00
Barricades (each/day)	450.00	270.00
Utility Vehicle	20.00	1,700.00
Total Equipment		6,740.00
Recovery System		
Water Pump (Sub)	1.00	5,920.00
Product Pump (Sub)	1.00	4,480.00
Probes & Cable	2.00	1,170.00
Tank Full Probe	2.00	710.00
Product Tank (250 Gal)	1.00	375.00
Total		12,655.00
Air Stripper		
Tower	1.00	10,105.00
Extra Port	1.00	665.00
Demister	1.00	415.00
Skid	1.00	4,750.00
Pressure Switch	1.00	55.00
Flow Meters	3.00	1,350.00
Telemanager Tel-100	1.00	2,100.00
Multipanel	1.00	4,550.00
Fs Controllers	1.00	850.00
Power Disconnect	1.00	200.00
Float Switch	1.00	150.00
Freight	1.00	720.00
Total		25,910.00
Recovery Wells (Labor)		
Well Installation	2.00	7,140.00
Vault	2.00	1,200.00
Cutting Disposal	15.00	4,500.00
Project Engineer (LC352)	16.00	1,216.00
Total		14,056.00

Table 3-11. (continued)

Description	Quantity	Cost
MANPOWER REQUIREMENTS:		
Recharge Gallery		
Senior Field Technician	40.00	2,160.00
Field Technician	40.00	1,640.00
Technician Support	20.00	760.00
Project Engineer	10.00	830.00
Total		5,390.00
Trenching		
Senior Field Technician	60.00	3,240.00
Field Technician	60.00	2,460.00
Technician Support	30.00	1,140.00
Project Engineer	15.00	1,245.00
Total		8,085.00
Equipment Compound		
Senior Field Technician	20.00	1,080.00
Field Technician	20.00	820.00
Technician Support	8.00	304.00
Project Engineer	8.00	664.00
Total		2,868.00
Unload NEPCCO Equipment		
Senior Field Technician	8.00	432.00
Field Technician	8.00	328.00
Technician Support	8.00	304.00
Project Engineer	8.00	664.00
Total		1,728.00
Complete Hookup		
Senior Field Technician	30.00	1,620.00
Field Technician	30.00	1,230.00
Technician Support	15.00	570.00
Project Engineer	10.00	830.00
Total		4,250.00
Project Management		
Project Engineer	4.00	432.00
Project Engineer	4.00	388.00
Project Engineer	32.00	2,848.00
Total		3,668.00
Total Cost For Free Product System Installation		**$102,817.57**

Chapter 4
Remediation of Residual Organics Using Vapor-Extraction-Based Technologies

Soil vapor extraction (SVE) based technology primarily includes soil vapor extraction, bioventing, and a combination of soil vapor extraction and air sparging. This technology removes volatile contaminants and to a lesser extent semivolatile contaminants from the vadose zone and upper part of the saturated interval (primarily in the case of air sparging). This chapter will briefly discuss the physical processes involved, feasibility of application, system design, and monitoring requirements for effective SVE application.

4.1 Introduction To SVE-Based Technologies

SVE systems are used to induce airflow through hydrocarbon-contaminated subsurface soils. Vapors are withdrawn by applying a vacuum to wells, or trenches, which removes the contaminants from the subsurface. SVE systems are designed to remove residual contaminants from unsaturated soils and can be combined with groundwater pumping wells to remediate soils that were contaminated below the water table. Figure 4-1 depicts a typical SVE system.

SVE can be used to biovent the soil and to deliver oxygen for enhanced biodegradation. Bioventing systems utilize air movement induced by the vapor extraction system to deliver oxygen to normally anaerobic, hydrocarbon-rich areas. In many cases, an increased oxygen supply stimulates the activity of naturally occurring microorganisms that convert the hydrocarbons into water and carbon dioxide. Bioventing is further discussed in Chapter 5.

In-situ SVE/air sparging systems force air into the porous medium in the saturated zone in an attempt to aerate the water and strip volatile contaminants from this zone. The vapors move into the unsaturated zone, where they are removed by the vacuum created in the soil system. Air sparging and related technologies are discussed in Chapter 6.

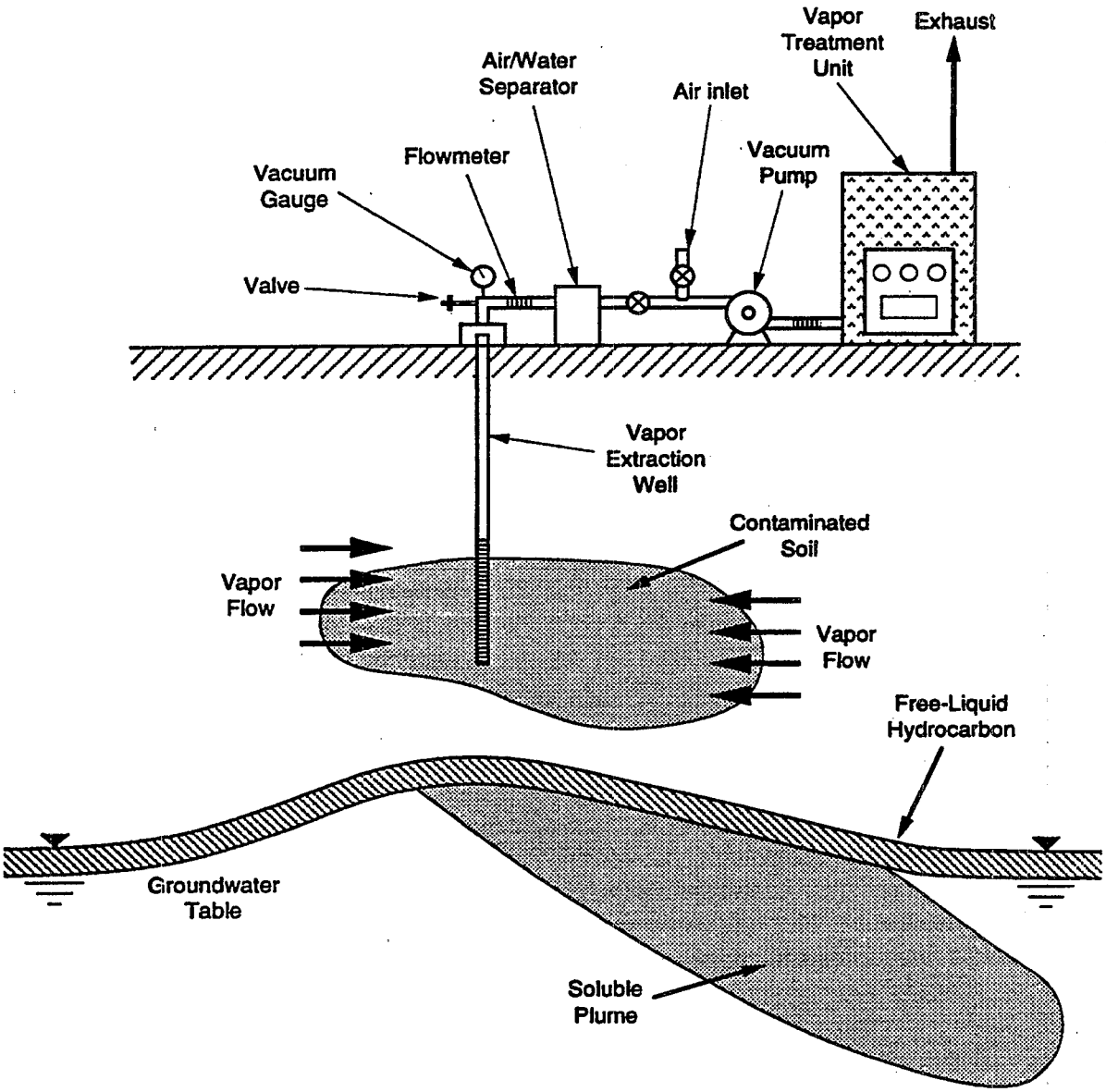


Figure 4-1. Components of an SVE system.

Source: after Hoag, 1991.

4.1.1 Typical Applications of SVE-Based Technologies

SVE-based technologies are typically used to achieve one or more of the following goals:

- Vadose Zone Source Mitigation - The removal and/or biodegradation of residual volatile and semivolatile contaminants that cannot be remediated by other means for technical or economic reasons, such as contaminants located underneath structures, excessive volumes of contaminated soils, etc.

- Vapor Migration Control - Creation of contaminant vapor intercepter system to prevent the movement of vapors into structures, utility conduits, or sewer systems. Alternatively, air inlet wells can be used to keep vapor-phase contaminants from migrating onto a site. Vapors from other sources may mobilize in response to an applied vacuum.

- Groundwater Dissolved Contaminant Plume Remediation - SVE/air sparging techniques may be used to reduce concentrations of volatile constituents in groundwater. Some SVE-only applications have also shown reduced concentrations of volatile constituents in groundwater.

The composition and distribution of contaminants in the subsurface at leaking UST sites will limit the available remedial options for immobile hydrocarbons. Coupling SVE with other technologies may prove successful in a broader range of applications. SVE is applicable to a broad spectrum of sites contaminated with gasoline, solvents, and other volatile compounds. SVE can be implemented with minor site disturbance, where normal business operations can often be continued throughout the cleanup.

The three main factors that influence the effectiveness of any in situ SVE operation are airflow rate, contaminant vapor concentrations, and the vapor flow path relative to the contaminant location (Johnson et al., 1990). These factors will be discussed later in this chapter.

The current practice for implementing SVE systems typically involves the following activities:

- Site Characterization - to collect soil samples and conduct analyses according to EPA or state protocols.

- Installation of Groundwater/Free-Product Recovery Systems - to remove dissolved and immiscible liquid hydrocarbons.

- Soil Gas Sampling - to determine residual contamination in the vadose zone or in the location of soil borings and groundwater/free product recovery systems.

- Air Permeability Testing - to determine vapor flow rates, airflow patterns in the subsurface, and the number of vapor extraction wells required to capture volatile constituents from contaminated soil.

- Estimates of Radius of Influence - to determine the number and spacing of vapor extraction wells for containment of hydrocarbon vapors.

- System Design - through intuition or empirical approach or may match existing site wells and other equipment.

- Permit Applications.

- System Installation and Operation.

- TPH and BTEX Monitoring - to evaluate the progress of the remediation and the system performance. Soil gas concentration and composition yields useful information about the residual composition and extent of contamination.

- Confirmation Testing - installation of soil borings to determine if contaminant concentrations in the soil have decreased. Decreases in vapor extraction well concentrations are not necessarily evidence that soil concentrations have decreased.

It should be noted that the current practice for SVE is not necessarily the most effective approach for remediation. Different approaches to SVE design and monitoring will be discussed later in this chapter.

4.1.2 SVE-Based System Components

An SVE-based system generally consists of the following major components:

- Extraction system

  - One or more vapor extraction wells or trenches
  - One or more air inlet or injection wells (optional)
  - Vacuum pumps and/or blowers
  - Vapor liquid separator (optional) (necessary when thermal gas treatment units are used)
  - Monitoring wells

- Monitoring equipment (flow meter, pressure gauges, valves, sampling ports, etc.).

- Off-gas treatment system.

These SVE system components will be briefly described below.

4.1.2.1 Extraction System Components

Vapor extraction wells usually consist of a pipe with the screened interval placed in permeable packing, typically coarse sand or gravel; the remaining portions of the well are grouted to eliminate short-circuiting of the system. The materials are selected to be inert and unaffected by the contaminants of concern. Vapor extraction wells are typically cased not less than 5 to 10 feet below the ground surface to prevent the short-circuiting of air near the well. Vapor extraction wells may be designed for vertical or horizontal installation to (1) penetrate the contaminated zone, and (2) allow sufficient airflow to be induced throughout the zone of contamination to remediate soils within an acceptable period of time.

Injection and passive inlet wells, when used, are typically constructed in a manner similar to the vapor extraction wells. Injection wells essentially inject air by means of blowers and are typically used to control subsurface airflow to specific zones. Passive inlet wells allow air to be drawn into the ground, but are limited to low airflow rates as a function of changes in barometric pressure. Passive inlet wells are relatively inexpensive compared with an injection system.

Vacuum pumps and blowers are used to induce subsurface airflow. The following vacuum pump or blower types are commonly used:

- Liquid Ring Pumps - to apply vacuums of up to 29 inches (786 mm) of Hg (395 inches of water).

- Rotor Lobe Blowers (similar to liquid ring pumps) - typically operate at lower vacuums and require periodic (monthly) maintenance.

- Rotary Vane Blowers - a maximum vacuum of 27 inches (685 mm) of Hg (368 inches of water) and, when equipped with carbon blades, require low maintenance.

- Regenerative Blowers - high vapor flow rates with low to moderate vacuums (<114 inches of H_2O) that require minimal maintenance.

- Centrifugal Blowers - very high flow rates, but operate at very low vacuum.

Vapor/liquid separators are used to remove groundwater hydrocarbon condensate from the vapor stream. This protects the vacuum and vapor treatment equipment. Separators generally consist of the following forms:

- Knockout drums or tanks - decrease vapor stream velocity due to their larger volume compared to the transfer piping. Gravity is used to separate dirt and liquid from the vapor stream. A demisting fabric is sometimes placed in the drum to collect separated waste.

- Condensers - using basically the same approach as knockout drums, are equipped with a refrigerant to condense additional moisture.

- Demisters - screen or mesh used to entrain and remove water from a vapor stream by mechanical removal.

4.1.2.2 Offgas Treatment

Vapor treatment units are used to remove contaminant from the vapor stream before it is discharged to the atmosphere. The selection of a treatment unit should be based on a balance between the amount of vapor concentrations extracted and economics (Figure 4-2). A wide variety of methods may be used, including thermal destruction units, carbon adsorption units, vapor condensate units, and bioreactors. Examples of these units include:

- Granular-activated carbon drums - Contaminant molecules are sorbed to carbon surfaces as the vapor stream passes through the unit. Because carbon adsorption is a transfer process rather than a contaminant destruction process, additional costs are incurred for carbon disposal or regeneration. Regenerated carbon may have a shorter useful life than fresh activated carbon because of the inability of some regeneration processes to liberate all carbon sites. Vapors may require cooling before entering canisters. Canisters may require cooling because of high heat generated during water absorption.

- Catalytic oxidation - The vapor stream is preheated and passed across a catalyst. Oxidation occurs between 120° and 650°C depending on the unit. Systems are available that can operate continuously at flow rates in the 100- to 100,000-scfm range. For vapor concentrations <200 ppmv, supplemental fuel is required or auxiliary heating (i.e., electrical bed heaters). Oxidation is self-sustaining with vapor concentrations greater than 3,000 ppmv. Vapor concentrations greater than 12,000 ppmv generally require dilution to prevent sintering of the catalyst. Catalysts can consist of metallic mesh, a monolithic ceramic honeycomb, or a packed bed of

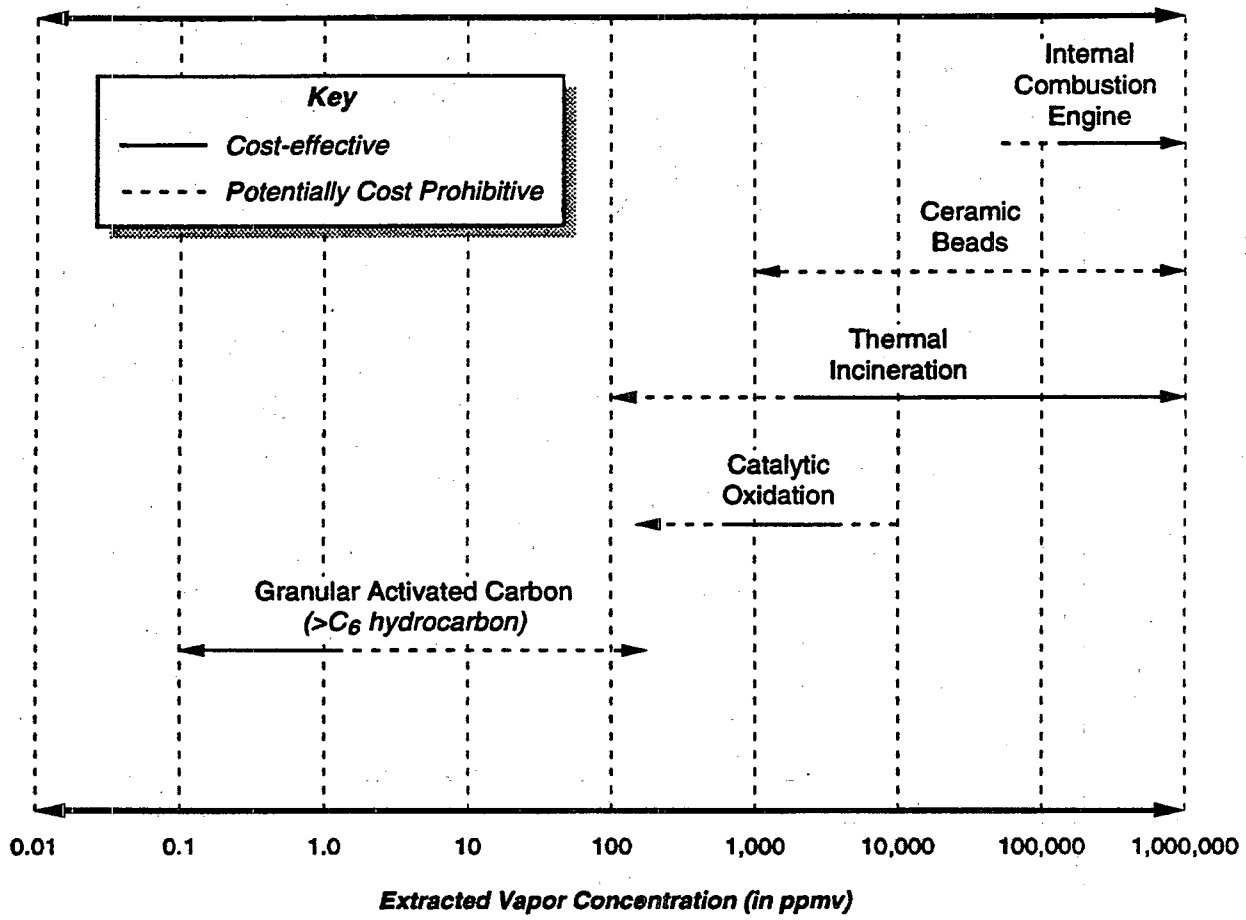


Figure 4-2. Selection of vapor treatment technology based on extracted vapor concentrations.

Source: after USEPA, 1991a.

catalyst-impregnated pellets. Metallic mesh can be poisoned by particulates blocking pore openings on the catalyst surface, chemical reactions between the metal catalyst and reactant in gas, or the chemisorption of gaseous material on metal. The average efficiency of these systems tends to be >90 percent.

- Thermal incinerators - These incinerators convert hydrocarbons to CO_2, H_2O, and NO_x at operational temperatures of 535° to 760°C in one second or less, either in a combustion chamber or a direct flame. Units can be constructed for any flow rate range available up to 1000 scfm for UST application. Flow rates are generally about 60 scfm. Incineration is self-sustaining for vapor concentrations greater than 50,000 ppmv. Incineration efficiency is greater than 99 percent for vapor concentrations exceeding 200 ppmv and about 95 percent for vapor concentrations in the 50- to 200-ppmv range.

- Packed bed thermal processors - In these processors, which are similar to catalyst oxidation, the vapor stream passes through ceramic beads electrically heated to a fairly uniform temperature, 980° to 1,800°C. Vapor concentrations of greater than 2,000 ppmv will sustain the operating temperature at operational flow rates in the 100- to 500-scfm range.

- Internal combustion engines - These units are essentially modified automotive engines. At idling speeds, they can accommodate flow rates of approximately 100 scfm per 300 cubic inches. Internal combustion engines require labor-intensive equipment monitoring and have relatively high operational noise levels.

- Vapor-phase bioreactors - Because these bioreactors are relatively new and therefore have limited site experience, their capabilities are not well defined. Their low cost suggests that they may have a significant application in the future, once their capabilities are known.

4.1.3 Regulatory Considerations

Regulatory considerations fall into the broad categories of timetables and constraints. In the view of the regulatory community, remediation schedules may be driven by pressure from adjoining property owners, the need to protect drinking water resources, or the workload of the regulatory staff. Time required for an SVE to reach target cleanup goals can be minimized in certain cases through installation of many closely spaced extraction wells operating under high airflow rates. Physical constraints resulting from the mass transfer of volatile hydrocarbons, however, may require additional time for the remediation of certain sites. In addition, SVE at certain sites may cause a significant decrease in contaminant concentrations, but may not necessarily achieve remediation goals.

Regulatory constraints are far more common and may not be as open to negotiation. In some jurisdictions, these constraints may result in the ruling out of technical solutions that would otherwise be the most suitable for a given site. The following regulatory constraints are typical:

- Emissions/Discharge control requirements are imposed on vapor emissions to the air and liquid releases to sanitary systems or surface water bodies. Air emission controls are most common for SVE-based technologies and are normally expressed in terms of an allowable mass per unit time. Multiple standards are often in place, such as one limitation on total hydrocarbons and another for a compound of special interest or concern. Meeting these restrictions may require upgrading vapor treatment capabilities or downgrading operational flow rates. Either alternative is not likely to optimize system economy.

- Underground injection control requirements are generally intended to control the injection of liquids into the subsurface. In some jurisdictions, these regulations may be phrased or interpreted in such a way that they may not allow the use of SVE-based system options such as air sparging, subsurface heating through the reinjection of treated effluent vapors, or the reinjection of untreated effluent vapors in uncontaminated areas to stimulate microbial activity.

- Noise level requirements are common in many light-commercial or residential areas. These requirements can often be met by enclosing vacuum pumps or regenerative blowers in structures. Some vapor treatment options, such as internal combustion engines, may not be able to conform to local requirements.

4.2 Processes and Parameters

The basic soil venting process involves inducing a vacuum at a well, which produces vapor flow through the subsurface, which in turn enhances the natural rate of volatilization and removes soil contaminants. Higher vapor pressure components are removed first, with the less-volatile compounds taking more time for removal. Basically, the vapor flow rate, composition of the residual contamination, and location of the contamination relative to the vapor flow path are the key processes and parameters that determine the effectiveness of soil venting at a particular site. These can be grouped into three governing phenomena (Johnson et al., 1990a): (1) vapor flow, (2) chemical partitioning, and (3) contaminant/soil distribution.

4.2.1 Vapor Flow

There are three governing equations for vapor flow porous media (Johnson, et al., 1990b): Equation 4-1 is the "continuity equation," Equation 4-2 is "Darcy's Law" for flow

through a porous media, and Equation 4-3 is the equation of "Ideal-Gas" assumption relating air density differences to air pressure differences.

$$\frac{\partial}{\partial t}(\varepsilon\ \rho) = -\nabla \cdot (\rho\ \underline{u}) \tag{4-1}$$

$$\underline{u} = -\frac{k}{\mu}\nabla(P + \rho\ g) \tag{4-2}$$

$$\rho = \rho_{atm}\left(\frac{P}{P_{atm}}\right) \tag{4-3}$$

where:

ρ	=	vapor density (g/cm^3)
g	=	gravity vector (cm/s^2)
ϵ	=	vapor-filled void fraction of soil (-)
$\underline{u}$	=	Darcian vapor velocity (cm/sec)
k	=	soil permeability (cm^2)
μ	=	vapor viscosity (g/cm-s)
P	=	vapor phase pressure (g/cm-s^2) or (atm)
∇	=	gradient operator (1/cm)
t	=	time (s)
ρ_{atm}	=	air density at atmospheric pressure (g/cm^3)
P_{atm}	=	atmospheric pressure (1.013 x 10^6 g/cm-s^2).

The relationships established in Equations 4-2 and 4-3 can be substituted into Equation 4-1 to produce the governing equation for vapor flow:

$$\left(\frac{2\varepsilon\mu}{k}\right)\frac{\partial P}{\partial t} = \nabla^2 P^2 \tag{4-4}$$

Given an estimate of soil permeability to vapor, and the air-filled soil porosity, the solution procedure involves solving for P, using P in Darcy's Law (Equation 4-2) to obtain $\underline{u}$ and integrating $\underline{u}$ at extraction/injection points. Equation 4-4 can be applied to specific vapor flow problems by using either numerical or analytical solutions.

4.2.1.1 Analytical Solutions

Equation 4-4 can be solved for the general case of radial horizontal flow to a soil venting well (Johnson et al., 1990b). To do this the pressure, P, in Equation 4-4 is expressed in terms of the ambient air pressure P_{atm} and a deviation P* from this pressure. P* is equivalent to the vacuum that would be measured in the soil at any given radius from the vacuum extraction well. The substitution of P_{atm} and P* into Equation 4-4, and assuming ε, *k*, and μ are constant and that the product P^2 is negligible compared to the product P^*P_{atm}, provides the resulting equation for radial flow as shown in Equation 4-5.

$$\left(\frac{\epsilon\mu}{kP_{atm}}\right)\frac{\partial P^*}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P^*}{\partial r}\right) \tag{4-5}$$

The resulting time-dependent solution for pressure on vacuum response P* is shown as Equation 4-6 (Bear 1979). Equation 4-5 shows that the vacuum P* in the soil at a given radial distance from the vacuum extraction well will increase as a function of the natural log of time.

$$P^* = \frac{Q}{4\ \pi\ H\ (k/\mu)}\ [-0.5772\ -\ ln(\frac{r^2\ \varepsilon\ \mu}{4\ k\ P_{atm}})\ +\ ln(t)] \tag{4-6}$$

where:

Q = airflow rate (L^3/T)
H = thickness of venting zone (L).

The boundary conditions for the steady-state Equation 4-4 ($\nabla^2 P = 0$) are:

$$P = P_w \text{ for } r = R_w$$

$$P = P_{atm} \text{ for } r = R_I$$

where:

P_w = vapor or pressure at the vacuum extraction well with radius R_w

R_I = radial distance from vacuum extraction well at which the vapor or air pressure in the soil equals ambient air pressure P_{atm} (i.e., vacuum pressure P* = 0)

R_w = radius of vacuum extraction well.

The steady-state solution to Equation 4-4 yields a solution for P(r) (Equation 4-7) and for Q (Equation 4-8).

$$P\ (r) = \left[P_w^2 + (P_{atm}^2 - P_w^2)\ \frac{\ln\ (r/R_w)}{\ln\ (R_I/R_w}\right]^{1/2} \tag{4-7}$$

$$Q = H\ \pi\ (\frac{k}{\mu})\ P_w\ \frac{[1 - (P_{atm}/P_w)^2]}{\ln\ (R_w/R_I)} \tag{4-8}$$

Equation 4-7 shows the relationship between the pressure distribution and radius of influence. The radius of influence, R_I, is an empirical parameter that is primarily dependent on soil permeability and stratigraphy. R_I also depends on boundary effects and the degree of horizontal flow. Thus, Equation 4-7 appears to be independent of soil type; however, the R_I parameter incorporates soil properties. Figure 4-3 illustrates the changes in vacuum, P*, as a function of radial distance for three different assumed R_I values.

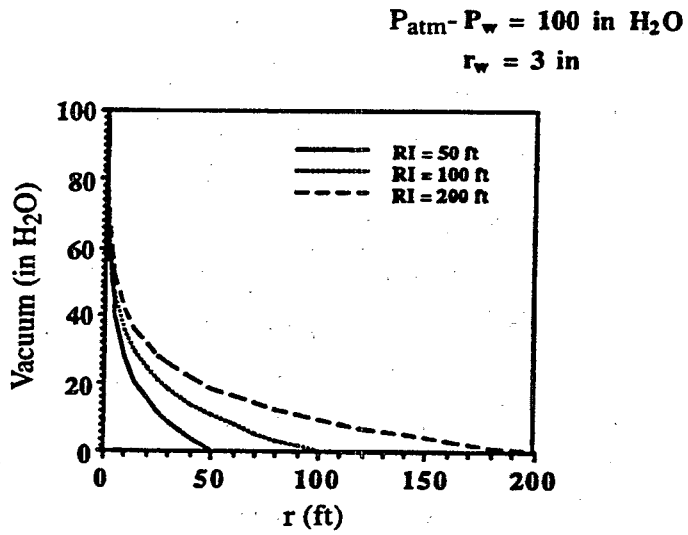
Equation 4-8 establishes the relationship between vapor flow rate, Q, well head vacuum, P_w, soil permeability, k, and air viscosity, μ. The flow rate, Q, is also somewhat sensitive to the value of R_I as shown in Figure 4-4. At R_I values above 50 ft, there is little effect on flow rate. The flow rate is directly dependent on soil permeability and vacuum at the extraction well (ΔP or P_{atm} - P_w), as shown in Figure 4-5.

4.2.1.2 Numerical Solutions

Several vapor flow, compositional flow, and transport models currently available use numerical solutions to analyze site-specific soil venting problems. The vapor-flow models include MODFLOW or AIR3D, AIRFLOW/SVE, and CSUGAS. Numerical solutions provide a way to simulate 2-D and 3-D effects such as site heterogeneity, vertical flow, and conduits. Vapor flow models allow an analysis of multiple well systems with both extraction and injection flows, simulations of layered systems, and an evaluation of complex airflow pathways. Airflow codes alone, however, are not sufficient for design and performance evaluation primarily because they do not allow the determination of mass removal from a multicomponent contaminant. Compositional flow and transport models such as VENT2D can also be used to simulate similar vapor flow problems, composition changes over time, mass removal, and possibly multiple phases. These models and others are discussed in Section 4.5.

4.2.2 Chemical Partitioning

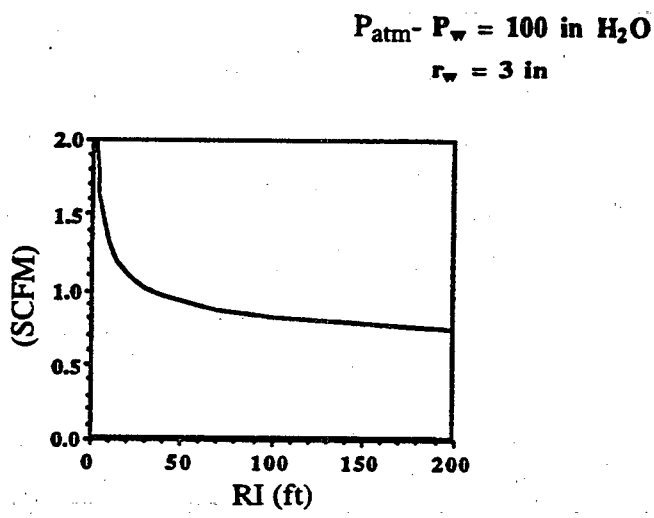
Hydrocarbon contaminants released from leaking USTs into a soil matrix may partition into four phases. These phases are: (1) nonaqueous phase liquids (NAPL) or the



Steady-state radial flow solution

Figure 4-3. Vacuum vs. radial distance for three values of R_i.

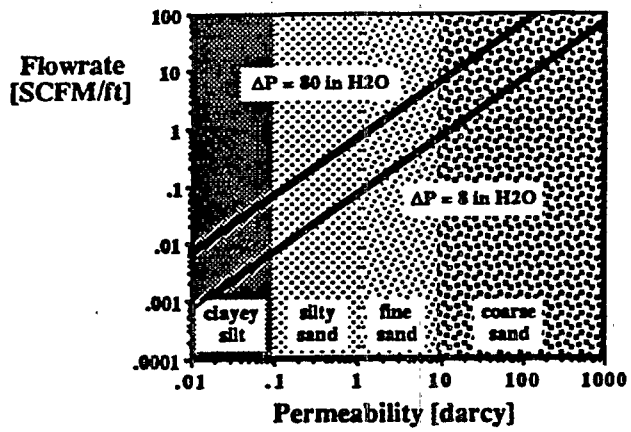
Source: after USEPA, 1993a.



Steady-state radial flow solution

Figure 4-4. Flow rate (scfm) vs. radius of influence.

Source: after USEPA, 1993a.



Steady-state radial flow solution

Figure 4-5. Flow rates (scfm) vs. Permeability for two values (ΔP) of wellhead vacuum.

Source: after USEPA, 1993a.

"immiscible phase," (2) the soil moisture or "dissolved phase" in interstitial water, (3) the "adsorbed phase" or sorbed to soil particles and colloidal material, and (4) "vapor phase" (Figure 4-5). The partitioning of contaminants into the different phases is dependent on the chemical and physical characteristics of the hydrocarbon, the degree of weathering that has occurred, and the soil characteristics. These phases will be present in and transient between one or more of 13 locations, referred to as physico-chemical-phase locations or loci (EPA, 1990a). Of these 13 loci, 4 have a high storage capacity for hydrocarbons. In theory, hydrocarbon partitioning proceeds until equilibrium conditions between the four phases are established. The partitioning of petroleum hydrocarbons in the subsurface can be defined by the relationships described below.

As stated above, components in the residual contaminant partition between vapor, adsorbed, soluble (dissolved in soil moisture), and free-liquid (or solid) residual phases. Much of the following discussion of chemical partitioning is from Johnson et al., 1990c. The mass balance can be described for any component:

$$\frac{M_i}{M_{soil}} = y_i \left[\frac{\alpha_i P_i^v \epsilon_A}{RT\rho_{soil}} + \alpha_i \frac{M^{HC}}{M_{soil}} + \frac{M^{H_2O}}{M_{soil}} + \frac{k_i}{M_{w,\,H_2O}}\right] \qquad (4\text{-}9)$$

where:

M_i = total moles of component I in soil matrix
y_i = mole fraction of I in soil moisture phase
α_i = activity coefficient for I in water
k_i = sorption coefficient for I [(mass-I/mass-soil)/(mass-I/mass-H_2O)]
P_i^v = pure component vapor pressure of I (g/cm-s^2 or atm)
ϵ_A = vapor-filled void fraction in soil matrix
ρ_{soil} = soil matrix density (g/cm^3)
R = gas constant (82.1 cm^3-atm/mole-°K)
T = absolute temperature (°K)
M^{HC} = total moles of free-liquid residual contaminant
M^{H_2O} = total moles in soil moisture phase
M_{soil} = mass of soil matrix (g)
M_{w,H_2O} = molecular weight of water (18 g/mole).

The first term on the right-hand side of Equation 4-9 represents the number of moles of I in the vapor phase, the second represents the number of moles of I in the free-liquid residual phase, the third term is the number of moles of I dissolved in the soil moisture, and the last term is the number of moles of I sorbed to the soil particles.

Most of the hydrocarbon contaminant mass is often partitioned into the sorbed phase for low concentrations. Most of the contaminant mass is in the immiscible phase at high concentrations, and the mass of the vapor phase is often negligible. The relationships that approximate equilibrium partitioning among the vapor, sorbed, dissolved, and free-liquid phases are discussed below.

Raoult's Law is an approximation that is used to relate the partial pressures of a constituent at equilibrium to its respective liquid phase mole fraction and the vapor pressure of the pure constituent. Raoult's Law is applicable only for mixtures that approximate ideal solution behavior.

It is expressed as:

$$P_i = x_i P_i^o \tag{4-10}$$

where:

P_i = partial pressure of constituent I, above mixture containing mole fraction x_i
x_i = mole fraction of constituent I
P_i^o = vapor pressure of the pure constituent I as a function of temperature.

The concentration in the vapor phase in contact with a free-liquid phase can be approximated by Equation 4-10.

$$C_i^v = \frac{X_i \, P_i^v \, M_{w,i}}{RT} \tag{4-11}$$

where:

C_i^v = concentration in the vapor phase (mg/L or ppmv)

X_i = mole fraction of constituent I

P_i^v = vapor pressure of constituent I

$M_{w,i}$ = molecular weight of constituent.

Henry's Law is an approximation for evaluating the partitioning of hydrocarbons between "dissolved" and "vapor" phases and can be described as:

$$C_i^v = H_i C_i^L \tag{4-12}$$

where:

C_i^v = concentration in the vapor phase (mg/L or ppmv)

C_i^L = concentration of I in the liquid phase (mg/L)

H_i = Henry's Law constant for constituent I as a function of temperature [cm^3 - liquid/cm^3 - vapor].

The contaminant concentration dissolved in soil water can be approximated by:

$$C_i^w = X_i \, S_i \tag{4-13}$$

where:

C_i^w = concentration of constituent in water phase (mg/L)
X_i = mole fraction of constituent in contaminant
S_i = solubility of constituent in rinse water (mg/L).

Each constituent common to gasoline blends has a unique solubility in water in its pure form, and the solubilities of these constituents are different when present in a mixture. As a result, the concentration of dissolved hydrocarbons in water at any given site will be dependent on the composition of the blend of gasoline involved. Constituents present in petroleum products have widely varying solubilities. As shown in Table 4-1, pure constituents such as phenols and simple aromatic hydrocarbons (benzene and toluene) are highly soluble compared with alkane constituents.

The capacity of various soil media to sorb different hydrocarbon constituents present in the liquid phase, vapor, and dissolved phases is described by various adsorption isotherms that approximate partitioning between dissolved and sorbed phases. The Linear and Freundlich isotherms are most commonly used.

Linear isotherms are:

- Appropriate for sorption relationships in which the energetics of sorption are uniform with increasing concentration.
- Appropriate when sorbent loading is low.
- Most commonly used at very low solute concentrations.
- Used for solids exhibiting low sorption potential.
- Are often the result of the association of neutral, relatively nonpolar organic molecules with soils.

The advantage of using this isotherm is that it reduces the complexity of mathematical modeling and is applicable for soils with low organic content. The linear isotherm is expressed as:

$$S = K_d C \tag{4-14}$$

where:

S = solute sorbed per unit of sorbing phase (M/M)
K_d = distribution coefficient or partition coefficient (L^3/M)
C = equilibrium concentration (M/L^3).

The Freundlich isotherm is used in describing nonlinear relationships between solutes and the adsorbing media. It may be expressed as:

$$S = K_d C^n \tag{4-15}$$

Table 4-1. Chemical Properties of Hydrocarbon Constituents

Chemical Class	Representative Chemical	Liquid Density (g/m^3) at 20°C	Henry's Law Constant (cm^3-liquid/ cm^3-vapor)	Water Solubility (mg/L) at 20°C	Pure Vapor Pressure (mm Hg) at 20°C	Vapor Density (g/m^3) at 20°C	Octanol-Water Coefficient (K_{oc}) (L/kg) at 25°C
n-Alkanes							
C4	n-Butane	0.579	25.22	61.1	1560	4960	250
C5	n-Pentane	0.626	29.77	41.2	424	1670	320
C6	n-Hexane	0.659	36.61	12.5	121	570	600
C7	n-Heptane	0.684	44.60	2.68	35.6	195	1300
C8	n-Octane	0.703	52.00	0.66	10.5	65.6	2600
C9	n-Nonane	0.718	NA	0.122	3.2	22.4	5800
C10	n-Decane	0.730	NA	0.022	0.95	7.4	13000
Mono-a-romatics	Benzene	0.885	0.11	1780	75.2	321	38
C6	Toluene	0.867	0.13	515	21.8	110	90
C7	m-Xylene	0.864	0.12	162	6.16	35.8	220
C8	Ethylbenzene	0.867	0.14	167	7.08	41.1	210
C9	1,3,5-Trimethylbenzene	0.865	0.09	72.6	1.73	11.4	390
C10	1,4-Diethylbenzene	0.862	0.19	15	0.697	5.12	1100
Phenols							
Phenol	Phenol	1.058	0.038	82000	0.529	2.72	110
C1-phenols	m-Cresol	1.027	0.044	23500	0.15	0.89	8.4
C2-phenols	2,4-Dimethylphenol	0.965	0.048	1600	0.058	0.39	NA
C3-phenols	2,4,6-Trimethylphenol	NA	NA	NA	0.012	0.09	NA
C4-phenols	m-Ethylphenol	1.037	NA	NA	0.08	0.53	NA
Indanol	Indanol	NA	NA	NA	0.014	0.1	NA
Di-aromatics	Naphthalene	1.025	NA	30	0.053	0.37	690

where:

S	=	solute sorbed per unit of sorbing phase (M/M)
K_d	=	distribution coefficient/partition coefficient (L^3/M)
C	=	equilibrium concentration (M/L^3)
n	=	measure of the degree of nonlinearity.

Vapor molecules tend to sorb more strongly when the soil moisture content is less than that required to provide complete monolayer coverage of water molecules on the soil particle surfaces (Valsacaj and Thibodeaux, 1988). This corresponds roughly to the "wilting point" of a soil, and for sandy soils is in the 0.02 to 0.05 g-H_2O/g-soil moisture content range. More often than not, the moisture content of soils greater than one foot below ground surface will be greater than the wilting point (Johnson et. al., 1990c).

4.2.2.1 Maximum Vapor Concentration

After Equation 4-8 is solved, the vapor concentration in equilibrium with the contaminant/soil matrix, $C^{eq}_{i,v}$, [mass-I/volume-vapor] can be obtained from (Johnson, et al., 1990c):

$$C^{eq}_{i,v} = \frac{\alpha_i \, y_i \, M_{w,i} \, P^v_i}{RT} \tag{4-16}$$

where $M_{w,i}$ = the molecular weight of component I.

In the limits of low and high residual contaminant soil concentrations, Equation 4-8 reduces to forms that do not require iterative solutions. In the low concentration limit (i.e., no free-liquid or solid precipitate phase present), Equation 4-16 becomes:

$$C^{eq}_{i,v} = \frac{H \, C_{i,soil}}{[(H\epsilon_A/\rho_{soil}) + \theta_M + k_i]} \tag{4-17}$$

where:

H	=	Henry's law constant (= $\alpha_I \, P_I^V \, M_{w,H_2O}/RT$)
$C_{i,soil}$	=	residual contamination level of I [mass-I/mass-soil]
Θ_M	=	soil moisture content [mass-H_2O/mass-soil].

In the high residual contaminant concentration limit, the maximum vapor concentration of any compound that can be achieved in the vapor-filled pore space I is its equilibrium or "saturated" vapor concentration. Equation 4-16 becomes:

$$C_i^v = \frac{x_i \, P_i^v \, M_{w,i}}{R \, T} \tag{4-18}$$

where:

C_i^v	=	vapor concentration (mg/L, or ppmv*)
$M_{w,i}$	=	molecular weight of constituent, I
P_i^v	=	pure component vapor pressure of constituent I
R	=	gas constant (0.0821 l-atm/mole-°K)
T	=	absolute temperature of residual constituent.

For mixtures composed of constituents with similar molecular weights, x_i is roughly equal to the mass fraction of constituent I.

*Converting mg/m^3 to ppmv:

$$ppmv = (mg/m^3)\ (24.45)\ \left(\frac{760}{P}\right)\ \left(\frac{T + 273}{298}\right) \tag{4-19}$$

where:

P	=	standard pressure (mm Hg)
T	=	temperature of vapor (°C).

The conversion factor 24.45 is the number of liters per mole at standard temperature and pressure.

Table 4-2 shows the expected vapor concentrations of select organic compounds based on Equation 4-17. (Note that the gasoline vapor concentration is obtained by summing the contributions of all individual mixture components.)

Equations 4-16 and 4-17 are the two most commonly incorporated in vapor transport models. Equation 4-16 predicts vapor concentrations that are proportional to the residual soil concentrations of each constituent and are independent of the relative concentrations of each constituent in the contaminant mixture, while the vapor concentrations predicted by Equation 4-17 are independent of residual soil concentration levels and depend only on the relative concentrations of constituents. It is important to recognize that these transport models are only valid for specific limiting conditions, and generalization to other concentration ranges can produce very misleading results. For example, Equation 4-16 predicts that vapor concentrations always increase with increasing residual contaminant levels, but realistically the equilibrium vapor concentration of any compounds cannot exceed its saturated vapor concentration, $P_i^v M_{w,i}/RT$.

Table 4-2. Composition of a Regular Gasoline

Compound Name	Mw (g)	Weight Fraction	Mole Fraction	P_i^v (20°C) (atm)
Propane	44.1	0.0005	0.0001	8.50
Isobutane	58.1	0.0085	0.0137	2.93
N-butane	58.1	0.0259	0.0415	2.11
trans-2-Butene	56.1	0.0019	0.0032	1.97
cis-2-Butene	56.1	0.0018	0.0030	1.79
3-Methyl-1-butene	70.1	0.0010	0.0013	0.96
Isopentane	72.2	0.0916	0.1181	0.78
1-Pentene	70.1	0.0032	0.0042	0.70
2-Methyl-1-butene	70.1	0.0068	0.0090	0.67
2-Methyl-1,3-butadiene	68.1	0.0068	0.0092	0.65
n-Pentane	72.2	0.0628	0.0810	0.57
trans-2-Pentene	70.1	0.0138	0.0184	0.53
2-Methyl-2-butene	70.1	0.0129	0.0171	0.51
3-Methyl-1,2-butadiene	68.1	0.0003	0.0004	0.46
Cyclopentane	70.1	0.0185	0.0245	0.35
2,3-Dimethylbutane	86.2	0.0111	0.0120	0.26
2-Methylpentane	86.2	0.0515	0.0556	0.21
3-Methylpentane	86.2	0.0314	0.0340	0.20
n-Hexane	86.2	0.0411	0.0444	0.16
Methylcyclopentane	84.2	0.0214	0.0237	0.15
2,2-Methylpentane	100.2	0.0077	0.0071	0.11
Benzene	78.1	0.0172	0.0250	0.10
Cyclohexane	84.2	0.0059	0.0065	0.10
2,3-Dimethylpentane	100.2	0.0063	0.0058	0.072
3-Methylhexane	100.2	0.0099	0.0092	0.064
3-Ethylpentane	100.2	0.0168	0.0156	0.060
n-Heptane	100.2	0.0356	0.0331	0.046
Methylcyclohexane	98.2	0.0055	0.0052	0.048

(continued)

Table 4-2. (continued)

Compound Name	Mw (g)	Weight Fraction	Mole Fraction	Pi^v (20°C) (atm)
2,2-Dimethylhexane	114.2	0.0046	0.0038	0.035
Toluene	92.1	0.0899	0.0908	0.029
2-Methylheptane	114.2	0.0028	0.0023	0.021
3-Methylheptane	114.2	0.0062	0.0051	0.020
n-Octane	114.2	0.0647	0.0528	0.014
2,4,4-Trimethylhexane	128.3	0.0015	0.0011	0.013
2,2-Dimethylheptane	128.3	0.0003	0.0002	0.011
Ethylbenzene	106.2	0.0205	0.0180	0.0092
p-Xylene	106.2	0.0153	0.0134	0.0086
o-Xylene	106.2	0.0221	0.0194	0.0066
n-nonane	128.3	0.0155	0.0112	0.0042
3,3,5-Trimethylheptane	142.3	0.0033	0.0022	0.0037
n-Propylbenzene	120.2	0.0346	0.0268	0.0033
1,3,5-Trimethylbenzene	120.2	0.0201	0.0156	0.0024
1,2,4-Trimethylbenzene	120.2	0.0061	0.0047	0.0019
n-Decane	142.3	0.0343	0.0224	0.0036
Methylpropylbenzene	134.2	0.0210	0.0146	0.0010
Dimethylethylbenzene	134.2	0.0173	0.0120	0.00070
n-Undecane	156.3	0.0078	0.0046	0.00060
1,2,4,5-tetramethylbenzene	134.2	0.0511	0.0354	0.00046
1,2,3,4-tetramethylbenzene	134.2	0.0053	0.0037	0.00033
1,2,4-trimethyl-5-ethyl-benzene	148.2	0.0191	0.0120	0.00029
n-dodecane	170.3	0.0050	0.0027	0.00040
naphthalene	128.2	0.0041	0.0030	0.00014
methylnaphthalene	142.2	0.0061	0.0040	0.00005
Total		0.996	0.999	

Figure 4-6 compares vapor concentrations predicted by Equations 4-8, 4-15, and 4-16 for the regular gasoline defined by Table 4-1. The required chemical parameters (vapor pressures, octanol-water partition coefficients, water solubility values) can be found in Johnson et al., 1988. As an example, model parameters for a sandy soil are organic carbon fraction (f_{oc}) = 0.002, soil moisture content (e_M) = 5%, total void fraction (ϵ_T) = 0.35, and soil bulk density (ρ_{soil}) = 1.60 g/cm^3.

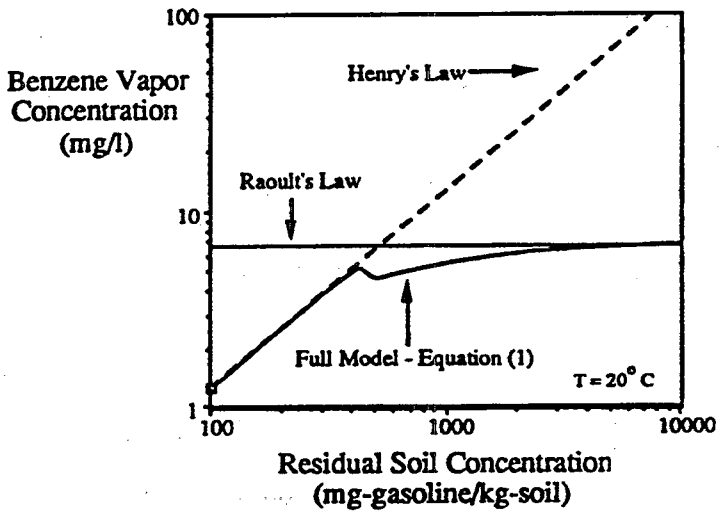


Figure 4-6. Comparison of vapor concentration models.

Source: after USEPA, 1993a.

For these values, Figure 4-6 indicates that Equation 4-16 is applicable below a residual soil contamination level of about 500 mg of gasoline/kg of soil. Above this residual concentration level, however, Equation 4-16 predicts increasing vapor concentrations with increasing residual levels, while the complete model predicts that vapor concentrations become independent of the residual concentration level. This limiting behavior is predicted by Equation 4-17. Care must be taken when using transport models based on a "three-phase model," such as Equation 4-16, because they will overpredict vapor concentrations and emission rates for many situations. Usually there are no internal checking procedures in these models to ensure that unrealistic vapor concentrations are not being predicted.

Equation 4-17 can be used to approximate maximum equilibrium vapor concentrations because it is most applicable for the residual concentration levels encountered at typical UST release sites.

4.2.3 Contaminant Distribution in Soil

The distribution of contaminants in different soil types is affected by any one of a number of processes that limit the subsurface vapor flow from becoming saturated (i.e., reaching the equilibrium concentration) with hydrocarbon vapors. These processes are referred to as "mass transfer limitations."

Mass transfer limitations are most often the result of diffusional "resistances," which may occur on the micro- (pore size) or macro (larger) scale. With respect to vapor extraction processes, mass transfer limitations most often arise from subtle permeability variations that cause air to flow past, but not through, zones of contamination as shown in Figure 4-7. This is easy to picture if one considers drawing air through a formation consisting of alternating sand and clay layers. In this case, significant airflow can be expected to occur only through the permeable sand zones, and remediation of clay layers can occur only if the vapors somehow travel to the sand zones. This most likely occurs as a result of "diffusion," or the movement of molecules from one location to another as a result of concentration changes with distance.

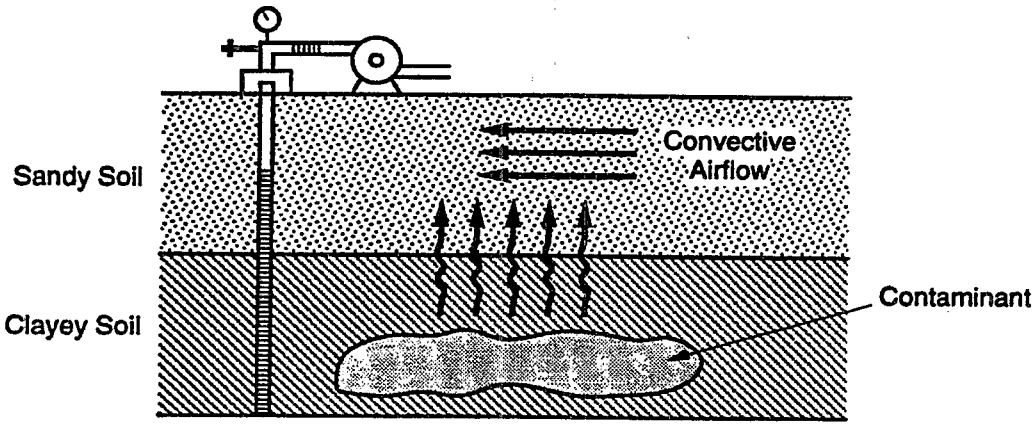


Figure 4-7. Diffusion-limited mass transfer.

Source: after USEPA, 1993a.

The rate of transport by diffusion is most often described by Fick's Law of diffusion:

$$F = D^{eff} \frac{dC}{dx} \tag{4-20}$$

where

D^{eff} = effective diffusion coefficient (cm^2/s)

$\frac{dC}{dx}$ = concentration gradient.

D^{eff} is estimated by the Millington-Quirk (Millington and Quirk, 1961) expression:

$$D_v^{eff} = D_v^{\circ} \frac{\epsilon_A^{3.33}}{\epsilon_T^2} \tag{4-21}$$

$$D_L^{eff} = D_L^{\circ} \frac{\epsilon_L^{3.33}}{\epsilon_T^2} \tag{4-22}$$

where:

D_L° = diffusion coefficient in water [cm^2/s]
D_v° = diffusion coefficient in air [cm^2/s]
ϵ_A = vapor-filled porosity
ϵ_L = liquid-filled porosity
ϵ_T = total porosity.

The effective diffusion coefficient is described in Lyman, et al., 1982. As an example, for the significant difference between D_L^{eff} and D_v^{eff}, for benzene at 20°C, $D_v^{\circ} = 0.087$ cm^2/s and $D_L^{\circ} = 1.0 \times 10^{-5}$ cm^2/s. With $E_A = 0.26$, $E_L = 0.12$, and $\epsilon_T = 0.38$, the calculated $D_v^{eff} = 7 \times 10^{-3}$ cm^2/s and $D_L^{eff} = 6 \times 10^{-8}$ cm^2/s (Johnson and Ettinger, 1991).

Two cases for determining removal rates where mass transfer is limited are discussed below.

4.2.3.1 Diffusion-Limited Transport

Figure 4-7 illustrates a situation in which vapors flow primarily past, rather than through, the contaminated soil zone. As described previously, the air flows past the contaminated zone, such as in the case of a contaminated clay lens surrounded by sandy soils. Vapor-phase diffusion through the clay limits the removal rate, with maximum removal occurring when airflow is fast enough to maintain a low vapor concentration at the permeable/impermeable soil interface. At any time, t, a contaminant-free or "dried-out" zone of low permeability will exist with a thickness δ. The removal rate is estimated by the equation (Johnson, et al. 1990a):

$$R_{est} = \pi \, (R_2^2 - R_1^2) \, C_{i,v}^{eq} \, D/\delta(t) \tag{4-23}$$

For a single component thickness, the dry-zone thickness change with time can be calculated as:

$$\delta(t) = \sqrt{\frac{2\ C_{i,v}^{eq}\ D\ t}{\rho_b\ C_s}} \qquad (4\text{-}24)$$

For Equations 4-23 and 4-24, the following terms are defined:

$C_{i,v}^{eq}$	=	vapor concentration in equilibrium with the contaminant/soil matrix (Equations 4-14, 4-15)
C_s	=	residual level of contamination in the low-permeability zone (g-contaminated/g-soil)
R_{est}	=	estimated removal rate (kg/d)
R_1	=	extraction well radius (cm)
R_2	=	radial area of contamination (cm)
D	=	effective soil vapor diffusion coefficient (cm^2/s)
ρ	=	soil bulk density (g/cm^3)
t	=	time (s).

It should be noted that Equation 4-24 assumes a single-component system. Mixture removal rates for this and the next situation are difficult to estimate because of continual system changes in composition and liquid-phase diffusion. Although no simple analytical solutions exist for these more complex situations, the removal rates would be estimated to be lower than the rates predicted for pure components.

4.2.3.2 Removal From Free-Product Layers

In this case, air flows parallel to, but not through the zone of contamination, and vapor phase diffusion is the limiting factor. An example case is a layer of liquid hydrocarbon resting on top of an impermeable stratum or the water table (Figure 4-8). For a single component, the removal rate can be estimated by use of the following equation (Johnson et. al., 1990a):

$$R_{est} = \eta Q\ C_{est}$$

$$\eta = \frac{1}{3H}\ (6\ D\mu/k)^{1/2}\ [\ln\ (R_1/R_w)\ /\ (P_{atm} - P_w)]^{1/2}\ \sqrt{R_2^2 - R_1^2} \qquad (4\text{-}25)$$

where:

η	= efficiency relative to maximum removal rate
D	= effective soil-vapor diffusion coefficient [cm^2/s]
μ	= viscosity of air = 1.8×10^{-4} g/cm-s
k	= soil permeability to vapor flow [cm^2]
H	= thickness of screened interval [cm]
R_I	= radius of influence of venting well [cm]
R_w	= venting well radius [cm]
P_{atm}	= absolute ambient pressure = 1.016×10^6 g/cm-s^2
P_w	= absolute pressure at the venting well [g/cm-s^2]
$R_I<r<R_2$	= defines region in which contamination is present.

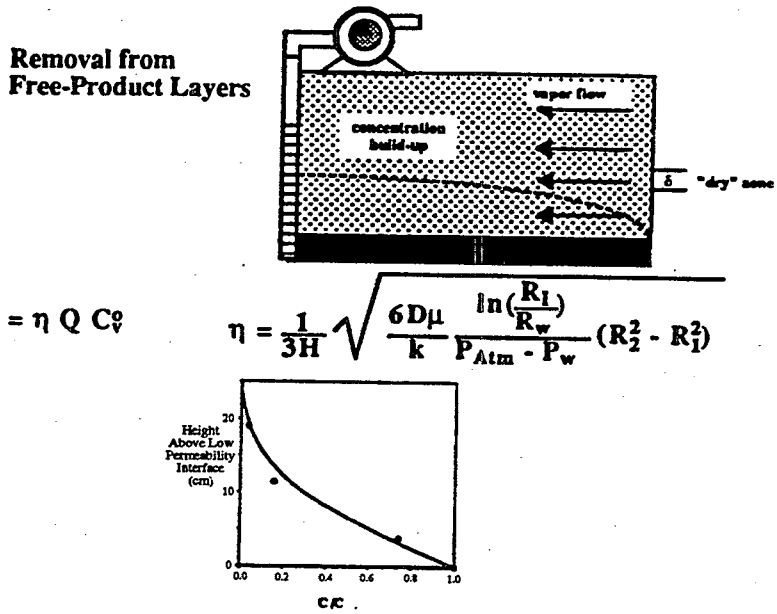


Figure 4-8. Removal of contaminants from free-product layer.

Source: after USEPA, 1993a.

The efficiency η is inversely proportional to the screened interval thickness H because a larger interval will pull in unsaturated air passing above the liquid-phase contamination. D is calculated by the Millington-Quirk expression as defined in Equations 4-21 and 4-22. As an example, consider a layer of free-phase hydrocarbon overlain by sandy soil (k = 1 darcy). A vapor extraction well with 2-inch radius and 10 feet of screen is operating at P_w = 0.9 atm. Contamination extends 30 feet from the well. Assuming appropriate values for other input parameters, a venting efficiency of about 9 percent is calculated. This efficiency is much less than the maximum removal rate not limited by vapor-phase diffusion.

4.3 Feasibility Screening

4.3.1 Is Venting Appropriate?

The primary factors governing the behavior of an in-situ soil venting system (previously discussed) are airflow rate, contaminant vapor concentration, and airflow path relative to contaminant distribution in the subsurface. In order to determine if in-situ soil venting is appropriate at a given site, the following questions should be answered:

- What range of airflow rates can be realistically achieved?
- What is the likely maximum contaminant vapor concentration?
- Under ideal airflow paths, is this concentration adequate to yield acceptable removal rates?
- What vapor composition and concentration changes will occur with time? What residual, if any, will be left in the soil? How do these values relate to the regulatory requirements?
- Are there likely to be any negative effects of soil venting?

If site conditions do not produce acceptable removal rates, in-situ soil venting should be ruled out as a practical treatment method. A detailed discussion of the approach and steps for addressing these questions is presented in Johnson, et al. (1990a).

4.3.1.1 Airflow Rate

The first step in feasibility screening is to estimate a realistic airflow rate range for the given site conditions, according to the equation (Johnson, et al., 1990a):

$$Q = H\ \pi \left(\frac{k}{\mu}\right) P_w \frac{[1 - (P_{atm}/P_w)^2]}{\ln\ (R_w/R_I)} \qquad (4\text{-}26)$$

where:

k	=	soil permeability to airflow [cm^2 or Darcy]
μ	=	viscosity of air = 1.8×10^{-4} g/cm-s or 0.018 cp
P_w	=	absolute pressure at extraction well [g/cm-s^2 or atm]
P_{atm}	=	absolute ambient pressure ≈ 1.01×10^6 g/cm-s^2 or 1 atm
R_w	=	radius of vapor extraction well [cm]

R_I = radius of influence of vapor extraction well [cm]

$\frac{Q}{H}$ = flow rate per unit thickness of well screen [cm^3/s].

The airflow for this equation is assumed to be horizontal. The calculated flow rate should be considered as a rough initial estimate of flow. If k can be measured or estimated, based on soil grain-size characteristics, then the radius of influence R_I is the only unknown parameter. Because Equation 4-26 is not sensitive to changes in R_I, it is suggested that an average value of R_I = 12 meters or 40 feet, based on ranges reported in the literature, be used for estimation purposes. Typical vacuum well pressures can range from 0.50 to 0.90 atm. Flow rates are usually measured in standard volumetric units (Johnson, et al., 1990a):

$$\frac{Q*}{H} = \frac{Q}{H}\left(\frac{P_w}{P_{atm}}\right) \quad [scfm/ft] \tag{4-27}$$

In this equation, H is the thickness of the screened interval, which is often chosen to be equal to the thickness of the zone of soil contamination (this minimizes removing any excess "clean" air). The largest uncertainty in flow-rate calculations is the air permeability, k, which can vary several orders of magnitude at a site.

4.3.1.2 Vapor Concentrations

The likely maximum contaminant vapor concentrations are estimated based on results of either soil-vapor surveys, analyses of headspace vapors above contaminated soil samples, or equilibrium vapor models. In the absence of soil-vapor survey data, an estimate of the maximum or "saturated" vapor concentration can be obtained from:

$$C_{est} = \sum_i x_i \frac{P_i^v(T)\, M_{w,i}}{RT} \tag{4-28}$$

where:

C_{est} = estimate of contaminant vapor concentration [mg/L]

x_i = mole fraction of component I in liquid-phase residual (x_i = 1 for single compound)

$P_i^v(T)$ = pure component vapor pressure of constituent I as a function of temperature [mg/mole]

$M_{w,i}$ = molecular weight of component I [mg/mole]

R = gas constant = 0.0821 1-atm/mole-°K

T = absolute temperature of residual [°K].

More-sophisticated equations are available for predicting vapor concentrations in soil systems based on equilibrium partitioning arguments, but input generally includes data such as organic carbon content or soil moisture, which are not normally available. If a site requires remediation, total residual hydrocarbons are usually greater than 500 mg/kg, with most hydrocarbons present as a separate phase. If so, vapor concentrations are independent of residual concentration and Equation 4-28 is applicable. It should be noted that all of the above applies to the start of venting, when removal rates are the greatest. Contaminant concentrations in the extracted vapors decline with time because of changes in composition, residual levels, or increased diffusional resistance.

4.3.2 Airflow Conditions and Removal Rates

The concentration estimate C_{est} is multiplied by a range of reasonable flow rates Q to yield R_{est}, an estimated removal rate:

$$R_{est} = C_{est}\, Q \tag{4-29}$$

Typical sites report airflow rates in the range of 10 to 100 scfm, although sandy soils or large numbers of extraction wells can yield flow rates up to 1,000 scfm.

Pore volume calculations are used along with extraction flow rate to determine the pore volume exchange rate. The exchange rate is calculated by dividing the pore space within the treatment zone by the design vapor extraction rate. The pore space within the treatment zone is calculated by multiplying the soil porosity by the volume of soil to be treated. Some literature suggests that one pore volume of soil vapor should be extracted at least daily for effective remedial progress. The time required to exchange one pore volume of soil vapor can be estimated by the following equations:

$$E = \frac{nV}{Q} \tag{4-30}$$

$$E = \frac{(m^3\ vapor/m^3\ soil)\ x\ (m^3\ soil)}{(m^3\ vapor/h)} = h \tag{4-31}$$

where: E = pore volume exchange time (h)
n = soil porosity (m^3 vapor/m^3 soil)

V = volume of soil to be treated (m^3 soil)
Q = total vapor extraction flow rate (m^3 vapor/h).

At this point, it is necessary to consider decreasing vapor concentrations during venting because of compositional changes and mass transfer resistance. Removal rates can be calculated as a function of vapor concentrations for a range of flow rates.

Acceptable removal rates R_{acc} can be calculated by dividing the estimated spill mass M_{spill} by the maximum acceptable cleanup time t:

$$R_{acc} = M_{spill}/t \tag{4-32}$$

Maximum removal rates are achieved when the induced vapor flow travels only through the zone of soil contamination and when no mass-transfer limitations are encountered. That is, all vapor flows become saturated with contaminant vapors and the estimated removal rate is described by Equation 4-32. Figure 4-9 illustrates the ideal model predictions, in which the percent residual removed is inversely proportional to the initial vapor concentration decrease.

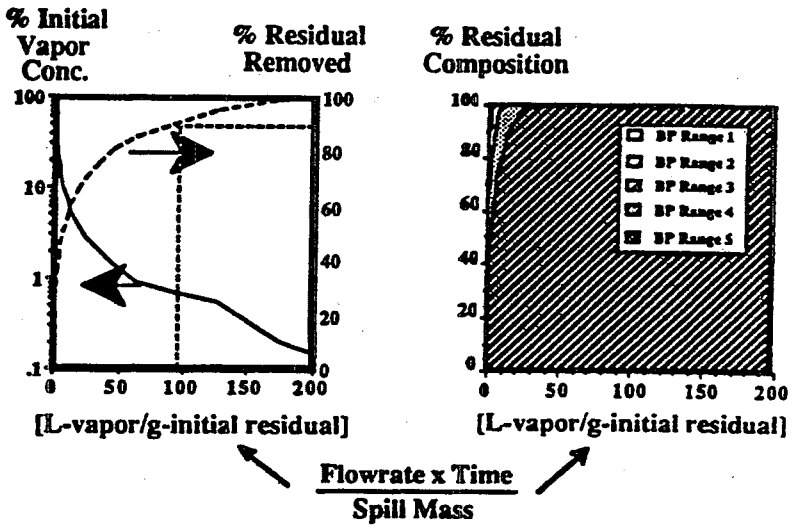


Figure 4-9. Ideal model predictions and composition changes.

Source: after USEPA, 1993a.

4.3.2.1 Residuals and Air Volume Calculations

As contaminants are removed, residual soil contamination decreases and mixtures become richer in less-volatile compounds, with consequent decreases in removal rates

over time. As venting continues and residuals decrease, it becomes more difficult to remove the residual contamination.

The maximum efficiency of a venting system is limited by the equilibrium partitioning of contaminants between the soil matrix and vapor phases. This efficiency changes with time as a function of the initial residual composition, vapor extraction well flow rate, and initial soil contamination level.

In addition, there is a practical limit to the amount of residual contamination that can be removed by venting. In the case of gasoline, for example, after 90 percent of the initial residual has been removed, the remainder consists of relatively insoluble and nonvolatile compounds. A much larger airflow volume will be required to remove each remaining gram in the final 10 percent than in the first 90 percent. This inherent limitation indicates that soil venting alone may be inadequate to meet a mandated regulatory cleanup concentration, which often will require enhanced biodegradation or other applied technologies to achieve lower concentrations than achievable by venting alone.

Soil venting systems have the following potentially negative effects:

- Off-site contaminant vapors may induce migration toward extraction wells, especially in more industrialized areas such as an intersection with multiple gasoline stations. In such cases, a vapor barrier should be established at the perimeter of the contaminated zone by allowing vapor flow into perimeter groundwater monitoring wells, which will act as passive air-supply wells. Trenches may also be installed in lieu of wells.

- The water table may rise below the vapor extraction wells as a result of the vacuum induced by the extraction well pumping system. A dewatering system may be necessary to ensure that contaminated soils remain exposed to vapor flow.

4.3.3 Site Screening, Levels I and II

To summarize, before installation of an in situ soil venting system, it is important to evaluate the appropriateness of venting for site remediation. Following the measurement or estimate of the parameters relevant to vapor flow conditions, the first step is to calculate the maximum potential removal rate (maximum removal rate = flow rate x maximum vapor concentrations) and to compare that rate with the desired removal rate (desired removal rate = residual mass/desired cleanup time). If the value for the de-sired removal rate is less than the range of maximum removal rates, then the site is a candidate for SVE remediation according to the first screening approximation.

If the desired removal rate is achievable, then the minimum number of extraction wells needed can be calculated as a function of the vapor flow rate per well, residual

contaminant mass, and minimum vapor volume requirement. If that number of extraction wells is realistic within constraints of site geometry and access limitations and budget re-straints, then installation and operation of a soil venting system is realistic.

In the remedial design process, the values of air permeability used in calculations to determine the appropriateness of SVE were estimates derived from the site investigation hydrogeologic data collected to define the nature and extent of contamination. During a pilot test program, air permeability values are measured in the field and the site-specific values are used to revise the calculated values of soil permeability to air. Based on the revised calculations, the number of vapor extraction wells necessary for remediation is revised for the system design.

4.4 SVE System Design

4.4.1 Determining Remedial Goals For Technology Selection

The goals of a given site remediation that drive the selection of the remedial technology are based on the following:

- Composition and distribution of contaminants in the subsurface
- Effectiveness (limitations of available technologies)
- Cost
- Regulatory requirements.

A brief discussion will be presented of each of these factors and their influence on the selection of appropriate and effective corrective action technologies for achieving the desired remediation goal.

4.4.1.1 Contaminant Composition

The majority of petroleum products released from UST systems include motor fuels (such as gasoline and diesel fuel), jet fuel (such as JP-4), heating oil, and lubricating oil. These products are often referred to as single bulk fluids; however, each product consists of a complex mixture of organic constituents. Gasolines, for example, typically consist of C_4-C_{12} constituents, whereas diesel fuel consists of C_{12}-C_{25} constituents. For aliphatic compounds, low-carbon-number constituents are more volatile and have a higher water solubility, while higher-carbon-number constituents are less volatile and more immiscible. Aromatic compounds such as benzene, toluene, ethylbenzene, and xylene (BTEX) are more soluble in water than aliphatic compounds of the same carbon number. Figure 4-10 matches the representative range of hydrocarbon constituents in different petroleum products with the most commonly considered soil treatment technologies.

Approaches to cleaning up petroleum-contaminated soil do not generally address the entire mixture of compounds in a bulk blend, but are designed to address specific constituents or classes of constituents. For example, soil vapor extraction may be

effective only for volatile constituents (< C_{12}). In addition, no single *in situ* technology is effective in addressing constituents in all phases or subsurface locations. Traditional pump-and-treat technologies only address light nonaqueous phase liquids (LNAPLs) on the groundwater table and some of the contaminants dissolved in groundwater; whereas contaminants present in other phases or locations are not addressed. Consequently, corrective action technologies are being misapplied in many cases, or the effectiveness of single or multiple technologies is not being optimized.

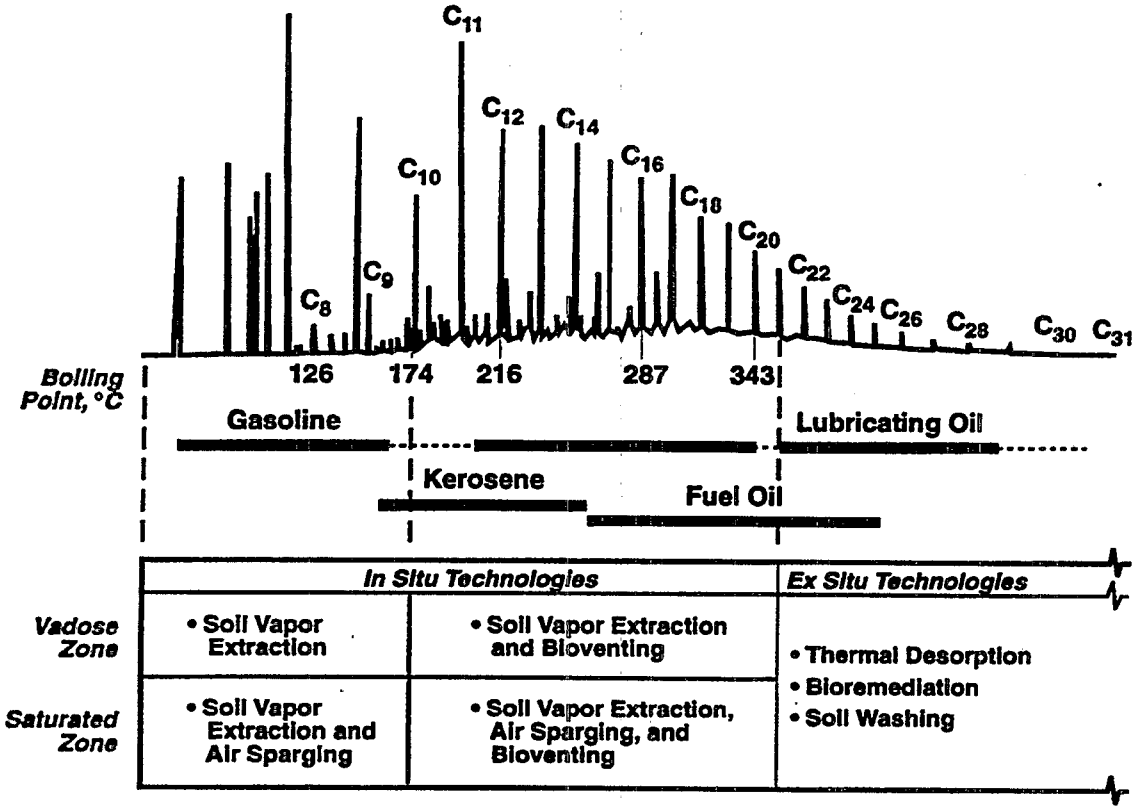


Figure 4-10. Range of hydrocarbon constituents in different petroleum products associated with the most commonly considered cleanup technologies.

Source: after USEPA, 1993a.

4.4.1.2 Cost Considerations

The level of capital investment for a site is limited based on the level of contamination present at a site and the solvency of the responsible party (RP) or Trust Fund. These remedial costs are often tied to an imposed time frame to complete the cleanup. Remediation by an SVE-based technology commonly requires 3 years or more. This

time frame may exceed the O&M commitment of an RP or Trust Fund, or it may not be rapid enough because of external issues.

4.4.1.3 Regulatory Requirements

The selection of SVE-based technologies may be constrained by remediation targets. The problem could be a function of the numerical concentration target (risk-based approach to corrective action, ASTM ES-38) or the analytical parameter or method that is required. The rate and degree of soil remediation achievable through SVE technology is a function of the physical characteristics of the affected soils (primarily permeability) and the overall carbon number range of the hydrocarbon contaminant. The low-carbon-number volatile fuels such as gasoline will evaporate readily, and the rate and degree of achievable remediation is a function of airflow rates through the affected soils. Higher-carbon-number fuels such as diesel are much less volatile and may be more slowly consumed through biodegradation. The rate-limiting controls for biodegradation are primarily oxygen availability, as well as temperature, nutrients, and moisture. Low-permeability soils cannot be readily remediated through either evaporation or biodegradation because low airflow rates are achievable through SVE. In either SVE or bioventing applications, a small fraction of the affected soils is likely to require long treatment periods to achieve cleanup goals even though the majority of contaminated soils have been adequately remediated. Existing regulatory requirements may prolong treatment periods for such sites beyond practical limits.

If the hydrocarbon contaminant mass contains heavy fraction compounds, SVE could remove all the volatile constituents present in the subsurface, but still not achieve a remediation goal on the basis of TPH analyses. Available evidence indicates that SVE is very effective for removing those fractions of contamination located in the vapor and free-liquid phases or adsorbed to the external surfaces of the soil matrix. Both theoretical considerations and field studies, however, indicate that SVE will not be effective for removing contamination trapped in the interior of the soil matrix. Because the quantity of contaminants trapped in the interior of the soil matrix may exceed surface contamination by 1 to 2 orders of magnitude, SVE cannot be relied upon to return long-contaminated soils to their original condition (Travis and MacInnis, 1992).

4.4.2 Range of Common SVE Design Approaches

In practice, the approaches employed in designing an SVE-based remediation system are as varied as the sites themselves. The basic design approaches fall into the following five broad categories: (1) intuition or empirical, (2) matching existing equipment, (3) radius of influence analyses, (4) screening model analysis, and (5) detailed modeling analyses. A summary of these five approaches is provided in Table 4-3 (Johnson et al. 1992).

Table 4-3. Soil Vapor Extraction Process Design Approaches (Johnson, et al. 1992b)

Approach	Required Information[a]	Advantages	Disadvantages
"Intuition," or empirical approach based on past experience	1, 2	Quick, easy, low skill level required	Unknown system performance, technology may not even be applicable
System design matched to existing equipment	1, 2, inventory of existing equipment	Quick, easy, minimizes new capital expenditure, maximizes use of existing equipment	Unknown system performance, technology may not even be applicable
Radius-of-influence-based approach	1, 2, 4, 5[b], 6	Insures containment of hydrocarbon vapors	Unknown system performance, does not insure remediation in reasonable time frame
Based on screening level model results	1, 2, 3[b], 4, 5, 6, economic data	Little effort required, design based on desired performance; cost of analyses not prohibitive	Requires higher level of expertise and ability to interpret data
Detailed modeling, numerical optimization	1 through 10 economic data	Design can be optimized and based on desired performance	Requires highest level of expertise and ability to interpret data; cost may be prohibitive

[a] Refers to activities defined in Table 4-4.
[b] Optional, not always used in this approach.

4.4.2.1 Intuition or Empirical

The intuition or empirical approach is usually applied at small sites with a limited vadose zone contamination problem. These could be sites where tank replacement operations have revealed a limited area of soil contamination or where a site assessment has identified an area of limited soil contamination around one or two wells or borings. Using an intuitive approach, many contractors simply put a soil vent system in the tank excavation or hook up to the existing monitor works. A standard 1½- to 3-hp soil vent blower system is typically installed. The systems are permitted as necessary and operated until vapor concentrations are consistently below detection limits. The systems are then shut down, and the vadose zone is assumed to have been remediated. For many small soil contamination sites, this can be a quick, easy, and cost-effective approach. The limitation of this approach is that in several cases the performance of the System is unknown and the extent of residual soil contamination is not addressed. In addition, the SVE systems being employed may be either too large or too small for the site. In some cases, SVE may not even be applicable for site conditions.

4.4.2.2 Matching Existing Equipment

The approach of matching the SVE system to existing site wells and other equipment is similar to the intuitive or empirical approach. The main difference is that in most cases the matching approach typically will involve more analyses up-front as to the extent and characteristics of the soil contamination, analysis of the well head vacuum, total vapor flow rates, expected maximum discharge concentrations, and selection of appropriate SVE equipment. The emphasis of this approach is to both utilize existing equipment and to try and achieve site remediation goals. For many small service station sites with ample existing monitoring wells and a relatively simple vadose zone, this can be a practical and cost-effective approach because it minimizes new capital expenditure and maximizes use of existing equipment. If an up-front analysis is not conducted, however, the performance of the SVE system is not necessarily known and (as in the sampling approach) may not even be applicable.

4.4.2.3 Radius of Influence

The radius of influence approach is perhaps the most common approach currently being used for SVE design and implementation. In this approach, the site assessment has been completed and the extent of soil and groundwater contamination has been delineated. An SVE system is then designed and/or specified that will have the required "radius of influence" to encompass the area of soil contamination. The radius of influence all too often is "assumed" based on previous experience with the equipment used and the soil types from similar sites in which the SVE wells are screened. This type of approach is very similar to the intuitive/empirical approach and has the same limitations and disadvantages.

At many sites, a pilot test is usually run to provide a better estimate of the radius of influence (see Pilot Tests for SVE-Based Systems). The vacuum readings at different distances are plotted as a function of the distance from the pilot vapor extraction well. The radius of influence is then interpreted as the distance at which the vadose zone vacuum is approximately 0.1 inch of H_2O or as a region contributing 90 percent of total airflow to a vapor extraction well that roughly corresponds to that area where the measured soil vacuum is $\geq$ 1 percent of the applied vacuum at the vapor extraction well. Figure 4-11 presents an example of the plots used to determine radius of influence. In this example, the radius of influence is different depending on whether it is based on vacuum or airflow measurements. The SVE system is then designed based on this radius and the use of enough wells to overlap and encompass the area of soil contamination. The blower is then sized to pull vapors from the SVE well system. This approach assumes that a measurable vacuum reading is an indication of vapor flow and does not ensure that remediation occurs in a reasonable time frame. Problems with this approach include the following:

- Measurable pressure/vacuum readings are no guarantee of <u>significant</u> vapor flow or remediation.

- The current approach is not related to any remedial objective (i.e., cleanup time, removal, cost minimization, etc.).

- The current approach is based on a containment philosophy.

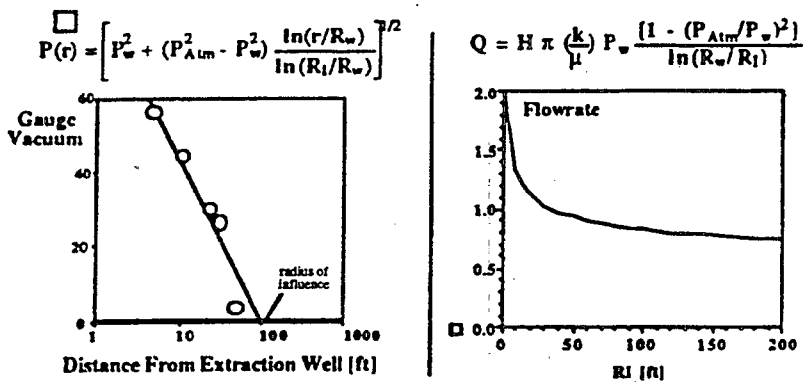


Figure 4-11. Field measurements and plots for determining radius of influence.

Source: after USEPA, 1993a.

The "radius of influence" defines a zone of "containment" and not a region of remediation. The time for remediation is proportional to the ratio of containment mass/airflow through the region. The approach for evaluating and designing the SVE system should consider the following:

- The zone of treatment will be a function of geometry, soil characteristics, and total flow rate.

- Measurable vacuum/pressure readings are not sufficient evidence of significant vapor flow in a given region.

- The most accurate estimates of flow behavior can only be obtained by combining modeling with field observations.

- Flow strength can be inferred by pressure gradients ($\Delta P/\Delta X$) and soil permeability.

- In the absence of numerical simulations, guess estimates can be based on extrapolations from results of modeling similar situations where the radius of influence is equal to the depth to screened interval (no cover), or the radius of influence is equal to cover width (perfect surface seal).

- Soil gas monitoring points (concentration and composition) are used to monitor remediation effectiveness.

The use of screening models and detailed modeling with field measurements are briefly discussed below (also see Screening and Modeling Tools).

4.4.2.4 Screening Model Analysis

In this approach, the concentrations and characteristics of the petroleum contaminant and the site conditions are evaluated by using screening models to (1) determine if SVE is inappropriate at a given site, and (2) to identify, estimate, and evaluate required site-specific data. If economic data is available, the feasibility of SVE can be evaluated. Screening models use analytical solutions for airflow and contaminant-removal calculations and typically require estimates of the radius of influence, contaminant distribution/mass, and desired remediation time as input. An overview of these models is presented in Section 4.4.4, Screening and Detailed Modeling Tools. This approach requires minimal effort in terms of data requirements and use. For relatively homogenous sites, this approach can be used to initially evaluate design criteria based on the desired performance (e.g., achieving site cleanup goals in a reasonable time frame). Although this approach is relatively inexpensive, it requires a higher level of expertise and ability on the part of the practitioner than does the previous design approaches discussed.

4.4.2.5 Detailed Modeling Analysis

The detailed modeling approach is generally used on larger more complex sites. Detailed modeling simulates vapor behavior in the vadose zone as an aid in designing and optimizing SVE-based systems. This approach can be used to (1) select design parameters, (2) determine if SVE is appropriate, if economic data is available, and if SVE is feasible at a given site, (3) determine the optimum number and location of extraction wells, (4) size aboveground treatment systems, if required, (5) evaluate modifications to existing systems, and (6) provide a basis for more realistic cost estimates.

Two types of models are used in this approach: airflow models and compositional flow and transport models. Airflow models simulate 2-D or 3-D airflow paths and account for differences in vertical and horizontal permeability in the subsurface and in boundary conditions that affect airflow to the extraction wells. Airflow models can only predict potential airflow and do not estimate the mass removal or effectiveness of SVE systems. Compositional flow and transport models simulate similar airflow problems, but they also model the mass transport of multicomponent mixtures and compositional changes of the residual contaminant over time in addition to their possible application to multiple phases.

The readily available screening and detailed models for evaluating SVE systems are identified in Section 4.4.4, Screening and Detailed Modeling Tools. Use of these

models in conjunction with site characterization and pilot test data provide a means to quantify important SVE operating processes. Site-specific data that is used in these modeling approaches for evaluating and designing SVE systems is obtained as part of both the site characterization and from pilot tests. The types of site characterization and pilot test activities that are conducted as part of the different design approaches are described below.

4.4.3 Pilot Tests for SVE-Based Systems

4.4.3.1 Purpose of Pilot Tests

A pilot test is a small-scale, short-duration (typically less than 8 hours) test of a basic SVE system in order to obtain the data required to design an effective large-scale SVE-based remediation system. For the data to be useful, the test must be conduced long enough to ensure one "pore volume" of air has been moved through the contaminated soils to the vapor extraction wells. To be successful, a pilot test must provide accurate and reliable data to (1) identify sustainable airflow rates, (2) anticipate contaminant composition and removal rates, (3) determine airflow patterns in the subsurface, and (4) estimate the number and location of vapor extraction wells that will be required to capture volatile constituents from the target areas of contamination.

SVE pilot testing is an integral step in the process leading to proper SVE system design. Table 4-4 presents a comprehensive list of activities that should be considered during the planning and performance of a pilot test. The preliminary site characterization activities consist of an assessment of (1) the vertical and horizontal distribution of the hydrocarbon phases and type of hydrocarbon present and (2) the local geology/hydrogeology (see Chapter 2). The geologic/hydrogeologic assessment for evaluating the application of SVE systems should identify the different soil strata in the unsaturated zone, assess the permeability of the soils that are contaminated (by core tests, sieve analysis, etc.), determine the static groundwater table and seasonal fluctuations, and identify and delineate any subsurface conduits, piping, tanks, etc., that may influence airflow.

When modeling is used in combination with field measurements, laboratory column studies are sometimes used in evaluating the feasibility of SVE systems. These tests move large pore volumes of air through a soil column in order to evaluate the effectiveness of the SVE system to remove contaminants in the soil, to determine the residual contaminants that are not readily removed by the SVE system, and to estimate vapor concentrations., Column studies cannot simulate nonideal conditions. The results of these studies can be generally similar to ideal model predictions and are most effectively used if there is some question of model applicability or the exact nature of the final leachate from the study.

The activities that can be conducted in a field-scale pilot study are listed in Table 4-4 (Johnson et al., 1992) and include: (1) applied vacuum/pressure and flow rate

Table 4-4. Site Characterization and Pilot-Test Activities (Johnson et al., 1992b)

Activity No.	Description
	Preliminary Characterization Activities
1	Hydrocarbon Assessment • vertical/horizontal • hydrocarbon characterization (type, boiling point distribution, regulated component identification)
2	Geologic/Hydrogeologic Assessment • identification of soil strata • permeability assessment (core tests, sieve analysis, etc.) • static water table determination (and seasonal fluctuations) • subsurface conduits, piping, tanks, obstructions, etc.
	Laboratory Characterization Activities
3	Laboratory Soil Column Feasibility Studies (optional)
	Field Pilot-Scale Activities
4	Airflow -vs- Applied Pressure/Vacuum Test • vacuum test for vapor extraction wells • pressure test for air injection wells
5	Effluent Vapor Characterization -vs- Time • total hydrocarbon concentrations • regulated compound speciation • hydrocarbon characterization (i.e., boiling point distribution) • O_2/CO_2 speciation
6	Subsurface Pressure Distribution • as function of depth and distance • steady-state and transient measurements
7	Subsurface Vapor Concentration Distribution • as function of depth and distance • hydrocarbon concentrations and composition • O_2/CO_2 speciation
8	Groundwater Elevation Changes Resulting from Air Extraction/Injection
9	Groundwater Monitoring • hydrocarbon levels • dissolved oxygen
10	Tracer Gas Tests

measurements that include vacuum and flow rate measurements for vapor extraction wells, and pressure and flow rate measurements for air injection wells (for air sparging pilot tests), (2) the off-gas characterization over time where the total hydrocarbons are measured, the boiling point distribution is determined for the type of hydrocarbons present, and the speciation of regulated compounds is determined for off-gas treatment requirements, (3) subsurface pressure distribution as a function of depth and distance under steady-state and transient conditions, (4) subsurface vapor concentrations, composition, and distribution to monitor SVE effectiveness, (5) groundwater elevation changes from air extraction (for SVE systems) or air injection (for air sparging systems), and (6) monitoring of groundwater quality primarily for changes in concentrations of contaminant indicator compounds and dissolved oxygen (for air sparging systems). Tracer tests using helium or sulfur hexafluoride are beginning to be used to better define flow paths, flow strengths, and areas of treatment and efficiency for air sparging and SVE systems. Typically, not all of these measurements and tests are conducted as part of a field-scale pilot test for SVE. In fact, appropriate procedures and methods are still being developed for both SVE and air sparging pilot tests. The following discussion will focus on common practices that are currently used in conducting field-scale SVE pilot tests (CRTC, 1991).

4.4.3.2 Common Practices, Errors, and Limitations

A pilot test typically involves applying a vacuum to an extraction well and then collecting vacuum and airflow data at the extraction well, collecting vacuum data at two or more vacuum monitoring points, and collecting effluent vapor concentrations and compositions. During the test, the steady-state pressure distribution is measured prior to the application of pressure/vacuum and measurement of the flow rate versus applied vacuum. Incremental steady-state pressure data are plotted versus the logarithm of distance from the extraction well to graphically determine the radius of influence R_I. Well locations are selected to ensure that the calculated radii of influence overlap the zone to be remediated.

When a pilot test is conducted to collect site data for SVE system design, the following should be considered:

- Selection of existing wells, or location of newly installed wells, for vapor extraction
  - location and completion interval relative to delineated petroleum hydrocarbons and soil strata
  - location relative to potential observation wells
  - location relative to man-made airflow pathways/barriers
  - well construction (surface seal, filter pack and screen size, screened interval)

- Selection of vacuum observation points
  - existing wells, temporary vacuum monitoring points, or both

- Data collection procedures
  - vacuum measurement
  - airflow measurement
  - effluent vapor concentrations and composition
  - monitoring frequency

- Equipment
  - vacuum pump/blower
  - effluent treatment

- Estimated length of pilot test

- Data interpretation
  - determination of radius of vacuum influence.

The following sections will discuss the selection of vapor extraction wells, vacuum monitoring points, pilot-test measurements, and collection of data for evaluating system design.

4.4.3.3 Extraction Wells

The extraction wells used in the pilot test are to be located at or near the center of the area of highest contaminant concentrations. The screen slot size of the well and filter pack should be consistent with proper hydraulic design protocols to promote compatibility with the surrounding formation and to prevent soil from entering the well casing. The well should be completed with an adequate grout seal extending from above the filter pack to the ground surface in order to prevent or reduce short circuiting of air along the outside of the well casing or bore hole.

An existing groundwater monitoring well can be used as the vapor extraction well during a pilot test, providing:

- The screened interval targets the depth interval where contamination is present.

- The target interval is located sufficiently above the water table, so that vapor extraction from that depth is unaffected by groundwater upwelling.

- The monitoring well is constructed so that short circuiting will not occur through annular materials.

The initial criterion for evaluating a well for purposes of vacuum extraction should be the length of well screen extending above the water table during the maximum pilot-test vacuum. The screened interval and filter pack should be long enough to prevent screen blockage when the water table and capillary fringe rise under the maximum

operating vacuum. The rise in water table elevation within the well casing will be directly proportional to the expected pilot-test operating vacuum as measured in inches of water. An evaluation of the screened interval of a potential vacuum extraction well should include an additional 2 to 3 feet of capillary fringe in vadose zone soils outside the well bore (extra fringe is required in fine-grained soil).

If high vacuums are expected and the well screen extends into or near the water table, groundwater may need to be pumped during the test to counteract the expected rise in water table and capillary fringe. Groundwater should be pumped at sufficient rates to maintain a static water level. If no floating liquid hydrocarbon is present, groundwater pumping rates may be increased to lower the water table adjacent to the extraction well itself, or from an adjacent well.

Pumping of groundwater during pilot testing is advisable where the large-scale SVE system is also likely to require groundwater extraction. When soil contamination is present at or below the water table, or when water levels fluctuate over a large interval, optimal SVE performance will depend on groundwater pumping to control and lower the water table, thereby keeping contaminated soils exposed to airflow.

4.4.3.4 Vacuum Monitoring Points

The vacuum monitoring points for the pilot test are placed at varying distances and depths and in varying directions outward from the extraction well. Ideally, the number of vacuum monitoring points should be sufficient and placed to determine vapor flow patterns that could result from subsurface heterogeneities. The screened intervals of the vacuum monitoring points will coincide with the depth of contamination.

Many groundwater monitoring wells are suitable for vacuum monitoring in vapor extraction pilot tests. The current network of groundwater monitoring wells should be evaluated for this purpose by use of similar criteria as those used for the vacuum extraction well: screen placement, well construction, and quality of surface seal. Wells with a minimal screened interval above the water table and capillary fringe should not be used because of the possibility of submergence during the test. Likewise, a well with a screened interval extending to within 1 or 2 feet of ground surface may record little or no vacuum because of its proximity to the surface. Suitable existing wells may need to be supplemented with additional monitoring wells or temporary soil probes.

The number of groundwater monitoring wells suitable for vacuum monitoring at a particular site may be limited, and the cost associated with installing new wells prohibitive. Temporary vacuum monitoring probes are an alternative to installing additional wells to supplement pilot-test vacuum data. Two types of vacuum probes are commonly used: small-diameter PVC well screen and slotted or perforated steel probes.

4.4.3.5 Lateral and Vertical Placement of Vacuum Monitoring Probes
Radial placement of probes for vacuum measurement is somewhat arbitrary, but generally they should be located at regular intervals outward from the extraction well (e.g., about 5 to 10 feet, 10 to 20 feet, 20 to 40 feet, and greater than 40 feet). If directional differences in pressure response are expected, as in extremely anisotropic or fractured soils, two sets of vacuum monitor points may be oriented radially from the main vent well and at right angles to each other.

The vertical section of vadose zone soils sampled by a given vacuum monitoring device may control the measured vacuum value. For example, a pressure response reading from a temporary probe will be a point value representing vacuum in a limited vertical section of the unsaturated zone, while a pressure reading from a monitoring well screened over a vertical section of several feet will be a composite of the vacuum from the screened interval. Adjacent vacuum measurements from these two types of instruments may vary markedly, especially if the temporary probe is placed in a unit having a different permeability than the average permeability of the section penetrated by the well screen. Since permeability affects the time required for vacuum to stabilize, vacuum monitoring probes placed in low-permeability units may only measure the transient vacuum developed during the period of the pilot test, compared with an adjacent monitoring well that measures stabilized vacuum in more permeable units. This relationship is common in heterogeneous sites where airflow may be largely restricted to beds of high-permeability sediments. As a result, if temporary soil probes are used as the primary measure of vacuum pressure, it is best to install several probes at different depths in close lateral proximity (i.e., "nested" probes).

Monitoring vacuum near the water table is desirable, but care must be taken not to place the probes near or within the capillary fringe. When water table and capillary fringe elevations rise during the pilot test, vacuum probes may fill with water.

4.4.3.6 Pilot-Test Measurements
The measurements required for pilot-test analysis are:

- Extraction well
  - vacuum (inches of water)
  - airflow rates (scfm)
  - effluent vapor concentration and composition (portable field analytical instrument with Tedlar bag samples for laboratory confirmation)

- Monitoring Points
  - vacuum (inches of water)
  - time of measurements.

The vacuum and airflow measurements at the extraction wellhead, the vacuum distribution at the vapor monitoring points, and the effluent vapor concentrations and composition are used to evaluate the design of a full-scale SVE system.

4.4.3.7 Vacuum and Flow Rate Measurements

Vacuum applied to the vapor extraction wellhead should be held constant, with frequent readings taken to ensure this condition. The associated airflow readings are used to determine if a given airflow is sustainable at the vacuum extraction well vacuum used during the test. A procedure for determining airflow versus the applied vacuum and the extraction wellhead is described by Johnson et al., 1992, and involves the following steps:

1) Open the air inlet valve.

2) Close the valve leading to the wellhead.

3) Turn on the blower/vacuum pump so that air is being drawn in only through the air inlet line.

4) Open fully the valve leading to the wellhead.

5) Once the flow rate has stabilized, record the wellhead vacuum and flow rate from the extraction well.

6) In a series of increments, slowly close the air inlet valve until it is fully closed.

7) For each increment, allow the flow rate to stabilize and record the wellhead vacuum and flow rate.

These wellhead measurements can be used with those collected from the vapor monitoring points to evaluate the pressure distribution and airflow in the unsaturated zone.

At regular intervals during the pilot test, vacuum readings are made at the extraction well and all soil vacuum monitoring points. Soil vacuum readings should be made at regular intervals until the vacuum field has stabilized (i.e., vacuum measurements at observation points show little or no change at successive sampling intervals). Vacuum readings should be taken frequently early in the pilot test (5- to 10-minute intervals) with the time between readings lengthening over the course of the test. As shown in Figure 4-12, the stabilized soil vacuum will be a percentage of the vacuum applied at the vapor extraction well. This percentage decreases with increased distance from the vapor extraction well.

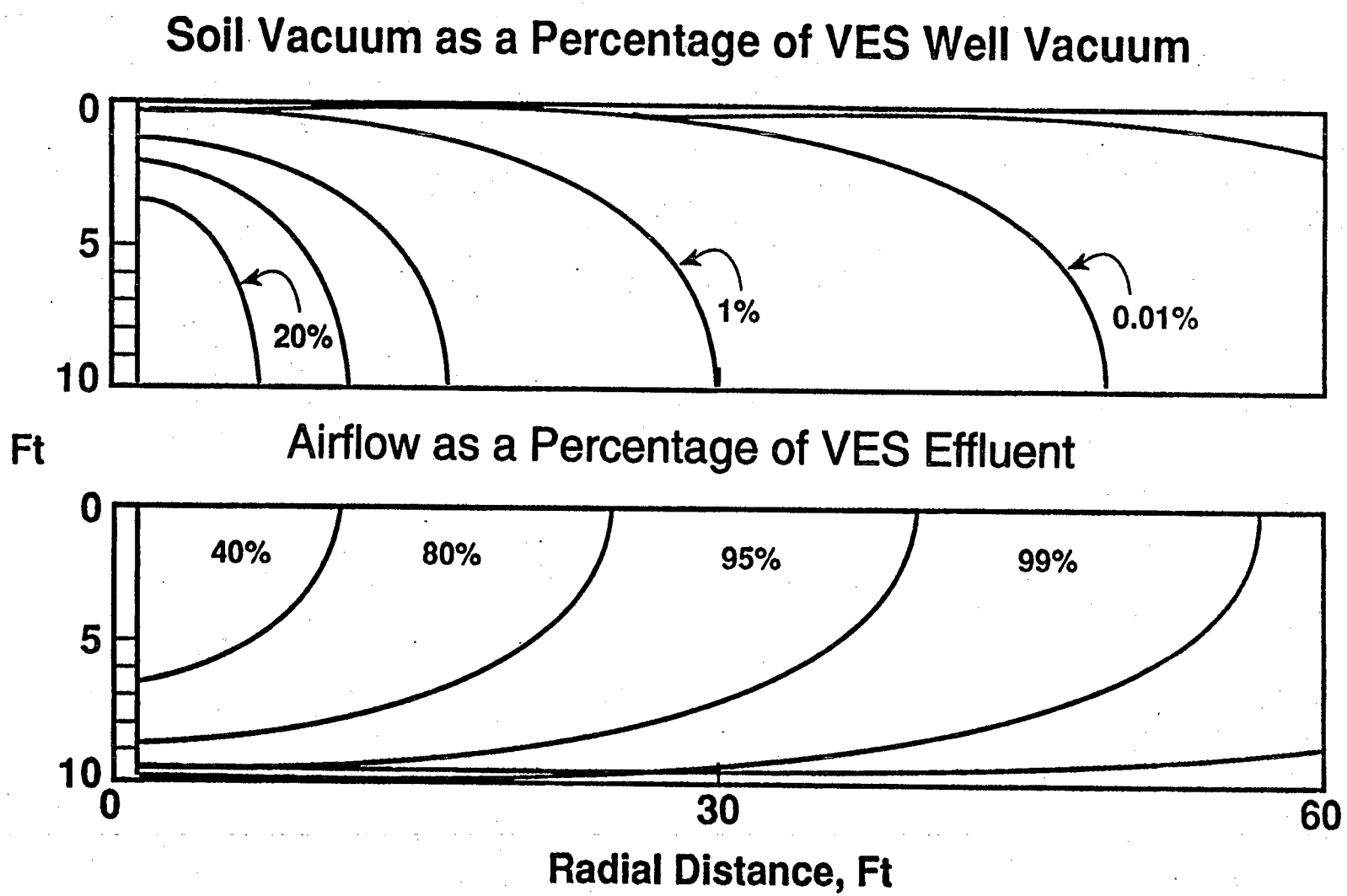


Figure 4-12. Soil vacuum measurements as a function of well vacuum and system effluent.

Source: after USEPA, 1993a.

Two vacuum levels should be utilized in each pilot test (step testing) in order to establish a range of operating parameters. The highest pilot-test vacuum setting should be near the maximum capacity of the blower used on site, and should be within the likely range of the full-scale system. In a homogenous subsurface environment, soil vacuum and airflow will stabilize nearest the extraction well first and will stabilize at progressively greater distances from the well as the pilot test continues. At higher permeability settings, the vacuum field adjacent to the extraction well typically stabilizes rapidly and each vacuum level of the step tests may require 2 hours or less to complete. Longer step tests may be necessary in lower permeability soils.

A source of error in measuring soil vacuum can result from the vertical location of the vacuum monitoring probe screen. Recognizing that variations in depth can impact soil vacuum measurements, many contractors try to place the probe screen as deep as possible. As shown in Figure 4-13, however, field studies (CRTC, 1991) have indicated that, under isotropic subsurface conditions, contours representing equal values for the soil vacuum as a percentage of the applied vapor extraction well vacuum are nearly parallel to the well screen (orthogonal to the water table) at depths equal to 50 to 75 percent of the depth to groundwater. This zone should then be a suitable interval for the placement of vacuum monitoring probes. When the pilot test starts, groundwater will respond to the vacuum applied to the vapor extraction well by upwelling. Any probes too near the water table could then be plugged by the groundwater upwelling. Vacuum monitoring probes that are plugged during a test must be disregarded, thereby reducing the number of available data points for evaluating pilot test results. Vacuum monitoring probes that are not plugged will result in an inaccurate estimation of the radius of influence.

4.4.3.8 Effluent Vapor Concentrations and Composition

Effluent and subsurface vapors are sampled for total hydrocarbon concentrations by use of a portable FID (refer to SVE system monitoring). Effluent vapor concentration readings should be measured with a portable FID with the same approximate frequency as the time interval for soil vacuum readings. Perhaps one in ten FID readings should be followed by the collection of samples in Tedlar bags for confirmational analyses at a laboratory. Of the samples collected in Tedlar bags, the initial, final, and one intermediate sample should also be subjected to analyses that would identify the concentrations of the individual constituents in the vapor stream. The concentration data collected during the pilot test can be used to determine the need for effluent vapor stream treatment during site remediation. The vapor composition analyses will provide supporting information on the nature of the contaminant in the subsurface and can be used in conjunction with some analytical design tools.

In conjunction with project operational system flow rates, the time-series analytical data will allow calculation of expected hydrocarbon removal rates following start-up, and determination of the size and nature of any effluent vapor treatment that may be necessary.

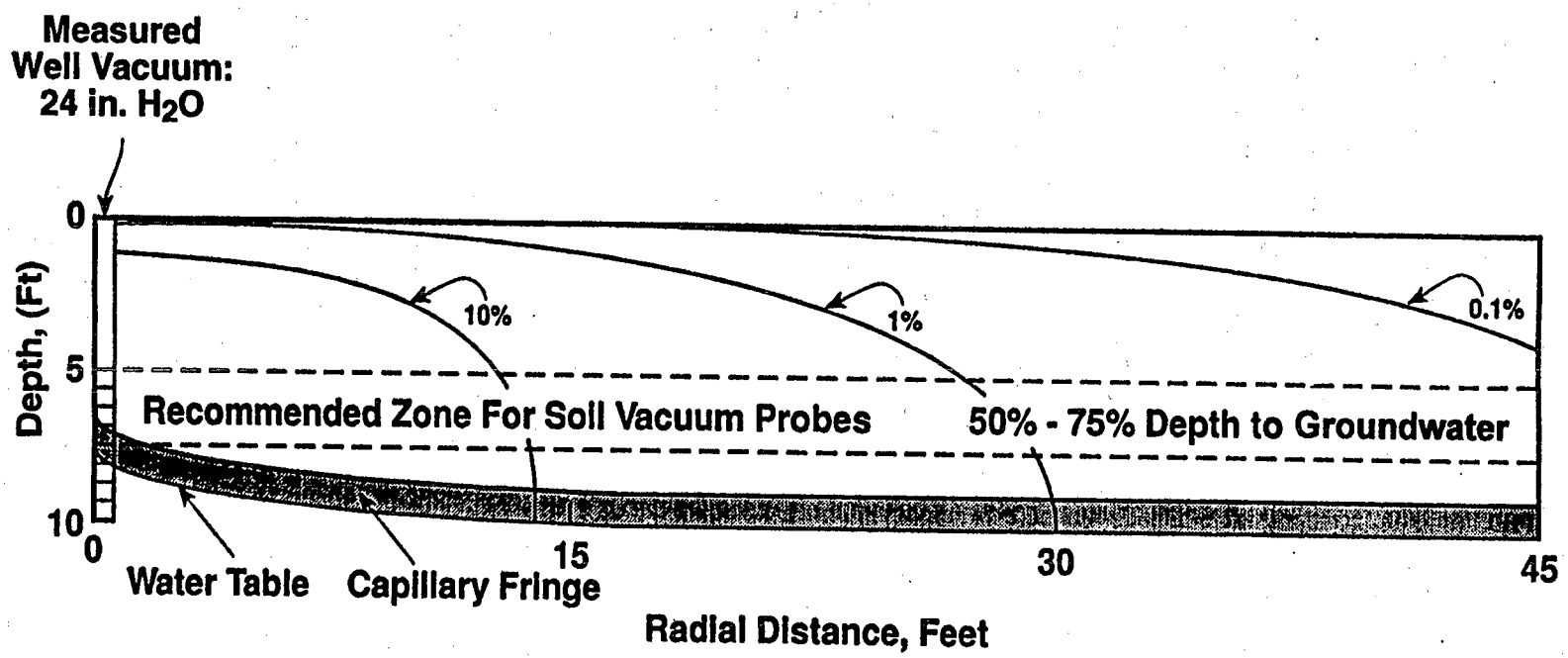


Figure 4-13. Depth of vacuum monitoring during pilot test.

Source: after USEPA, 1993a.

A PID may be used to determine the concentration of volatile aromatics in the system effluent, but should not be used as a substitute for the FID to measure total hydrocarbon removal rates. Baseline BTEX concentrations should be collected during the pilot test and early in the life of the SVE system operation. Periodic measurement of the BTEX fraction of total effluent serves to confirm system efficiency in contacting the majority of contaminated subsurface soils.

4.4.3.9 Vacuum Radius of Influence, Airflow, and Hydrocarbon Removal Rates
Pilot tests typically simulate the pressure and airflow regime developed around a single SVE well during a relatively short operating period. Airflow rates and hydrocarbon vapor concentration/composition data can be used to calculate an initial hydrocarbon removal rate per well. The subsurface distribution of pressure developed during the pilot test is typically used to determine well spacing for the full-scale SVE system. It is important, however, to understand the relationship between pressure, airflow, and hydrocarbon removal rates in order to properly design the SVE system. Figure 4-12 illustrates the stabilized vacuum distribution and airflow lines for a hypothetical SVE well installed in a 10-foot-thick vadose zone. The illustration is derived from the output of a proprietary airflow model developed by Chevron Research and Technology Company. The model uses the finite element technique to solve the Laplace equation for pressure, and a related equation to solve for the discrete airflow line function. Important boundary conditions of the model are that atmospheric pressure exists at the surface and at an infinite horizontal distance from the well screen, and that there is circular flow symmetry around the SVE well. The illustration depicts a two-dimensional view of vacuum distribution and airflow for uniform soils in which horizontal permeability is twice that of vertical permeability ($K_h/K_v = 2$).

The upper portion of Figure 4-12 shows the highest vacuum developed immediately adjacent to the well screen, with vacuum decreasing exponentially with increasing radial distance from the well and proximity to the surface. Airflow lines are orthogonal to vacuum isobars, with the greatest percentage of airflow occurring adjacent to the extraction well. Based on the boundary conditions of the model, radial vacuum never reaches zero, but would decline to some low asymptotic value close enough to zero to be unmeasurable in the field.

The vacuum radius of influence is defined as the radial distance from a vacuum extraction well at which soil pore pressure is equal to ambient atmospheric pressure. By measuring soil vacuum at vacuum monitoring points during a pilot test, an approximate vacuum radius of influence can be determined as the radial distance from the extraction well at which induced vacuum is too small to be measured. It is important to note, however, that the vacuum radius of influence does not correlate with the radial distance within which sufficient airflow is induced to adequately remediate soils within an acceptable time frame. The lower schematic in Figure 4-12 shows that even though measurable soil vacuum may extend beyond 60 feet, 80 percent of the airflow originates in an area within 27 feet of the SVE well and 95 percent is obtained from

within 35 feet. Thus, radial distances of 27 to 35 feet more accurately reflect an "effective or design" radius of influence for soil remediation based on airflow rates.

By means of example, consider the hypothetical situation depicted in Figure 4-14. In this case, the subsurface soil is uniformly contaminated by gasoline at a concentration of 1,000 ppm. During the pilot test, a vacuum of 40 inches H_2O was applied at the vapor extraction well. The measurable radius of influence, based on soil vacuum measurements of 0.01 inch H_2O, was 60 feet. Figure 4-15 represents the anticipated results of operating a vapor extraction system for two years as a function of the percentage contribution to total vapor extraction well airflow. As shown in this diagram, more than 90 percent of the initial contaminant mass has been removed from the soils within ≈30 feet of the vapor extraction well where 95 percent of the airflow originated. In that portion of the subsurface responsible for only 4 percent of the airflow to the vapor extraction well, hydrocarbon concentrations in the soils had decreased only 40 percent to 600 ppm. Similarly, that region contributing <1 percent of the total airflow realizes removal of only 5 percent of the initial contamination. Finally, soil contamination levels outside this last zone will be unaffected by the vapor extraction system.

Figure 4-16 is a plot of the hydrocarbon mass removal rate (as a function of time) at a hypothetical site. As depicted, hydrocarbon mass removal began to approach asymptotic conditions after approximately six months of operation. This would normally be a reasonable indicator that site remediation was approaching closure. Figure 4-15, however, clearly showed that significant residual contamination was present within the vacuum radius of influence of the vapor extraction well, as defined on the basis of soil vacuum readings during the pilot test. This contamination results from the failure of effective airflow to contact all soil within the vacuum radius of influence. If confirmatory borings are not used as a precursor to closure, remediation at this site would cease with appreciable contamination still present in the soils. The design flaw in this instance was the assumption that the soil vacuum radius of influence matched the "effective" or design radius of influence for effective subsurface airflow.

4.4.3.10 SVE Pilot Test Interpretation

The empirical "radius of influence" design approach relies on the results of a pilot test to determine the vacuum radius of influence developed during the duration of the test, and uses this data to estimate an "effective" airflow radius of influence to determine extraction well spacing. It needs to be reemphasized that the vacuum radius of influence observed during the pilot test rarely corresponds to the effective radius of influence in terms of airflow contribution. Instead, the soil vacuum readings are used to determine a conservative approximation of the airflow radius of influence.

The interpretation of the pilot-test vacuum data involves calculating a series of normalized vacuum values using the following technique:

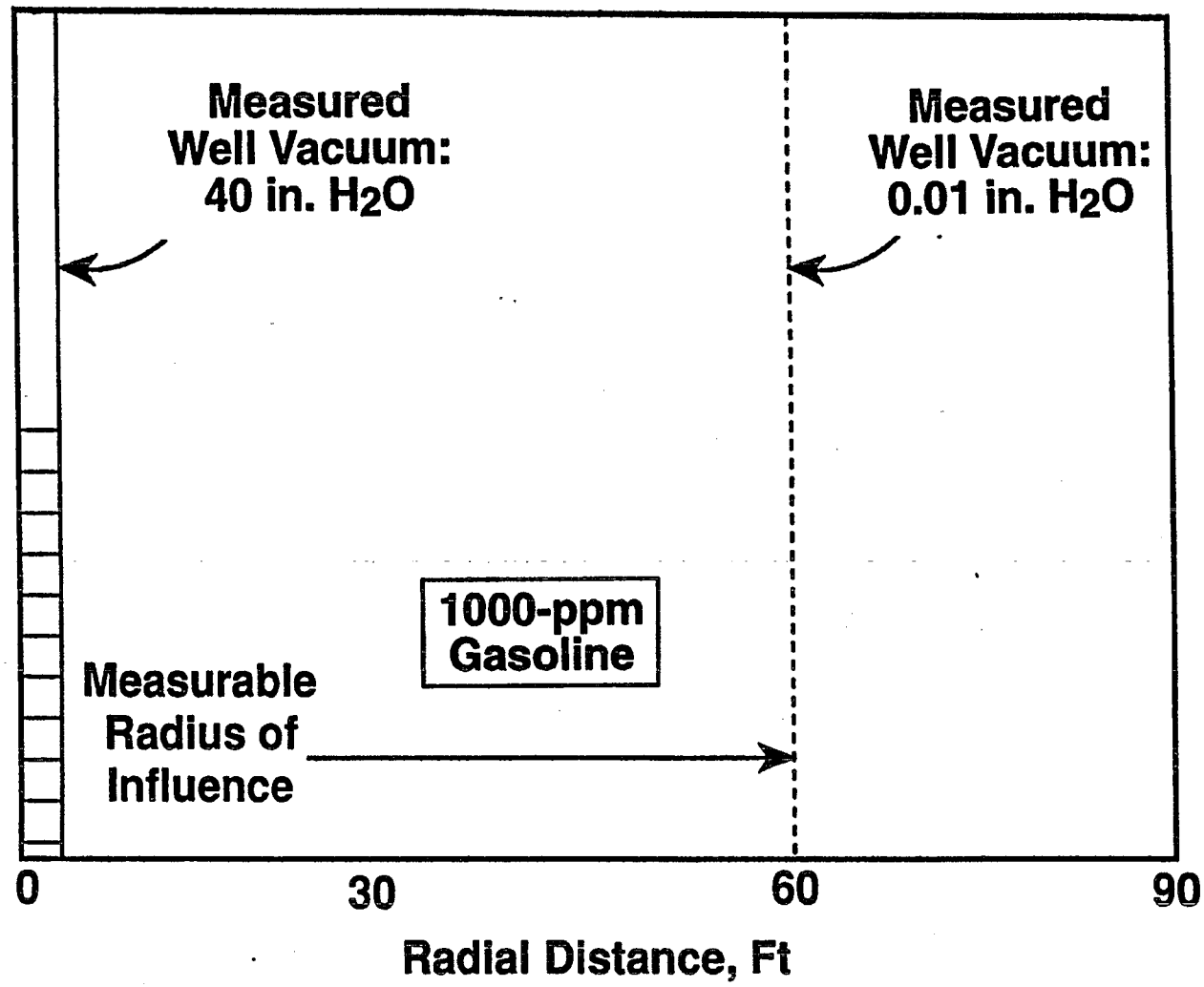


Figure 4-14. Results from an SVE system pilot test.

Source: after USEPA, 1993a.

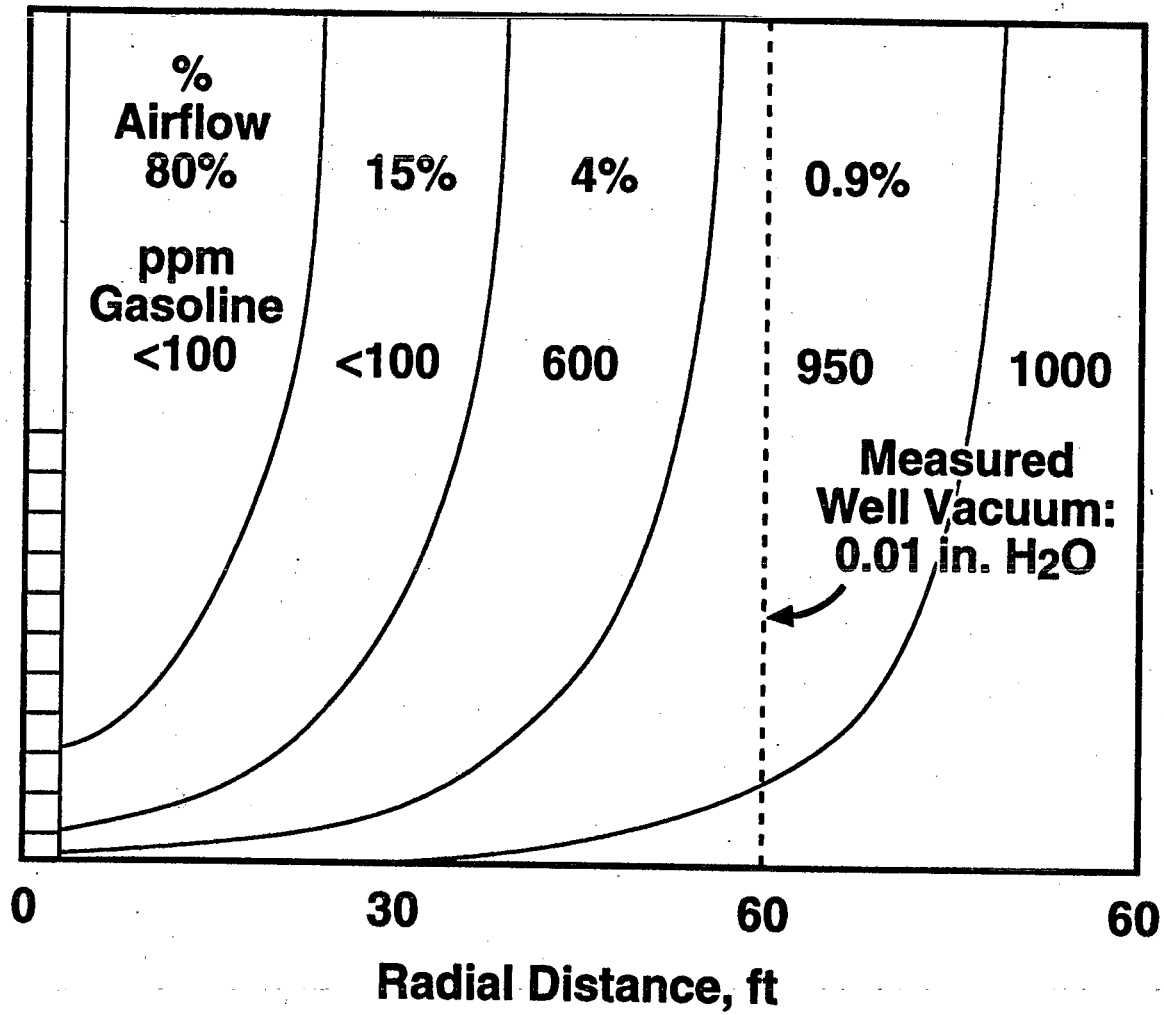


Figure 4-15. Expected performance of an SVE system after two years of operation.

Source: after USEPA, 1993a.

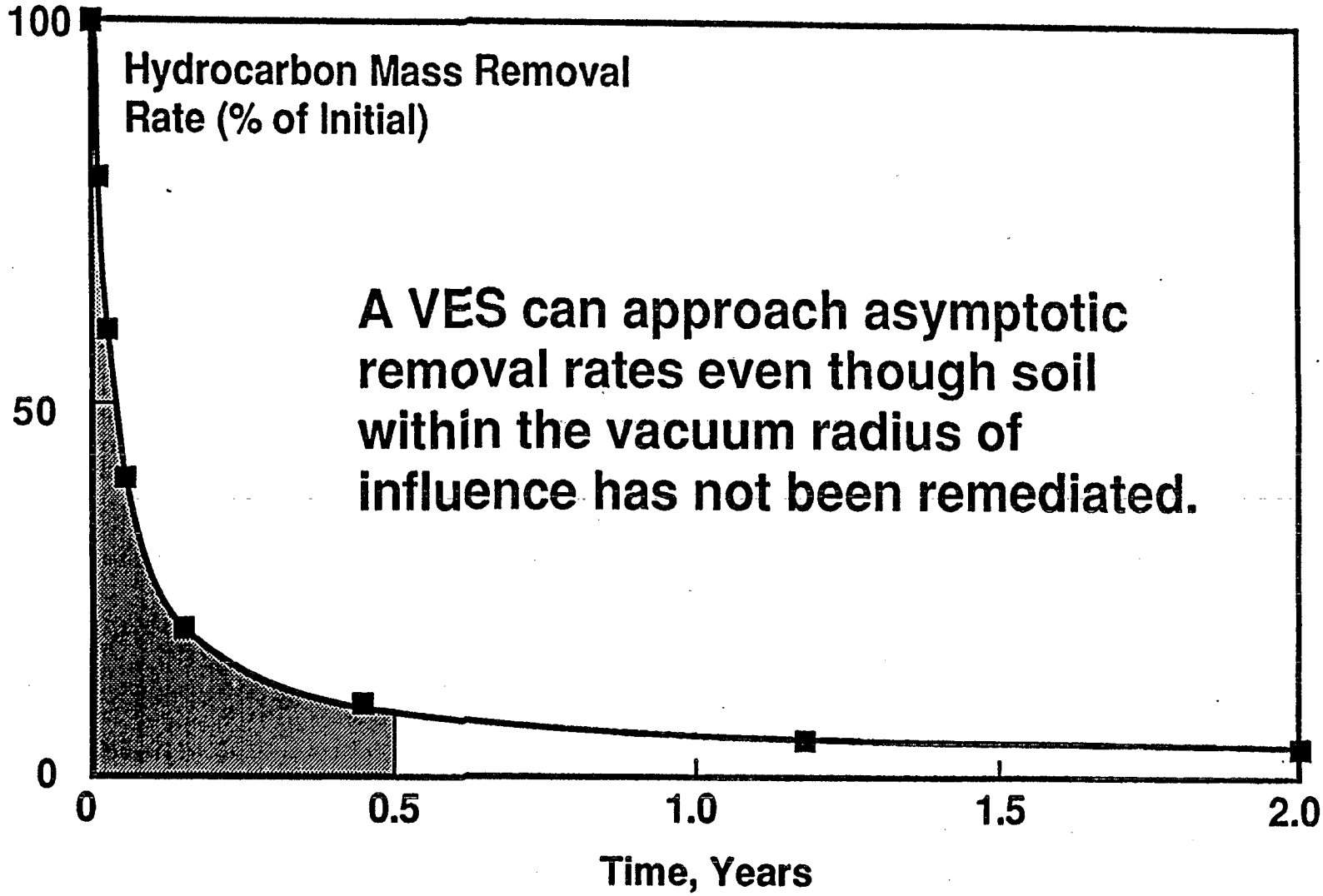


Figure 4-16. Hydrocarbon mass removal rates for SVE.

Source: after USEPA, 1993a.

- Plot normalized vacuum data on semi-log graph.
- Fitting a straight line to data, determine site-specific vacuum/distance function.
- Extrapolate radial distance corresponding to 1 percent operating vacuum.

These normalized vacuums are the ratio of the monitoring point vacuum to the vapor extraction well vacuum.

The normalized vacuum is plotted on semi-logarithmic paper versus radial distance from the vapor extraction well to the vacuum monitoring point (Figure 4-17). A straight line is fit to the plotted data representing the radial vacuum distribution for the site, with the slope of the line representing the horizontal-to-vertical permeability ratio (K_h/K_v). The linearity of this data has been demonstrated through field trials for monitoring points greater than approximately 5 to 10 feet from the extraction well.

Based on airflow modeling performed by Chevron Research and Technology Company, an empirical relationship has been determined between the region that contributes approximately 90 percent of total airflow to the vapor extraction well and the radial distance at which the measured soil vacuum is approximately 1 percent of the applied vacuum at the extraction well. This relationship can be seen by comparing the 90 percent airflow radial distance ($K_h/K_v = 2$) and the 1 percent vacuum radial distance for the $K_h/K_v = 2.5$ vacuum distribution line in Figure 4-17. The empirical "radius of influence approach" design method may be a useful "rule of thumb" approach for establishing SVE well spacing for sites matching the boundary conditions of the model (uniform, moderate to highly permeable soils). This method yields a more-conservative estimate of an "effective" or design vacuum radius of influence for SVE design purposes by empirically relating vacuum to airflow.

At sites where soils are fairly uniform and permeabilities are great enough for vacuum to stabilize in all monitoring points, the radial vacuum distribution plot should be fairly linear. Sites with heterogenous soils, or with uniform but lower permeability soils, may exhibit varying degrees of scatter in the data. For heterogenous sites, normalized vacuum points that plot below an obviously linear radial vacuum distribution line represent points installed in lower permeability units where vacuum pressure was unable to stabilize during the pilot tests.

Heterogenous sites containing significant quantities of lower permeability soils will be subject to greater mass transfer limitations for hydrocarbon removal. Diffusion-limited sites will require longer time frames to reach remedial goals than will advection-limited settings. The Radial Vacuum Distribution Line plotted through the higher permeability sediments is used to determine well spacing distances in order to optimize the cleanup of sediments within the primary airflow pathways. This design approach does not emphasize special well completion intervals, higher operating vacuums, or closer well spacing to specifically address low-permeability sediments.

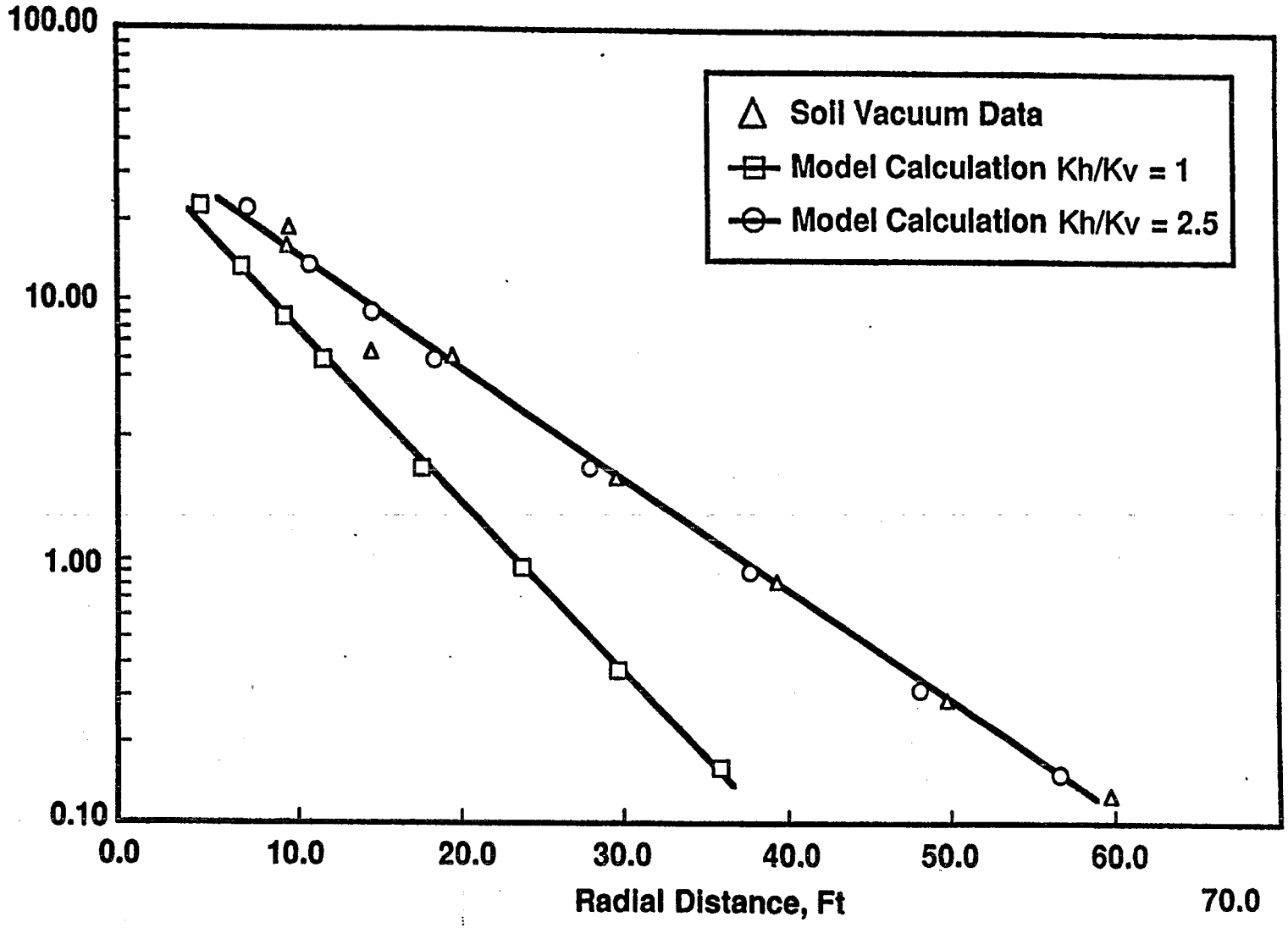


Figure 4-17. SVE pilot test vacuum versus distance.

Source: after USEPA, 1993a.

4.4.4 Screening and Detailed Modeling Tools

Commercial models are available to assist remediation contractors and regulatory officials in determining the appropriateness and potential effectiveness of SVE as the remediation technology option for a given site. SVE models are used in providing a structured approach for understanding remedial processes and limiting factors that are not readily understood by direct observation. Models are particularly valuable in evaluating the performance of an SVE system prior to construction, thereby minimizing the cost associated with trial-and-error system design and operation. Modeling leads to a better examination of process feasibility, a more accurate evaluation of potential performance, and the development of system engineering design criteria prior to SVE implementation. Two general types of SVE models are used: screening models and detailed models. The detailed models include airflow models and compositional flow and transport models. This section presents a short summary of the types of models available for evaluating SVE systems. A thorough examination of the types of problems addressed by SVE models, the need for and selection of appropriate models, and the data needs and a review of available SVE models are presented by EPA (1994). Table 4-5 presents a summary of the general types of models.

4.4.4.1 Screening Models

SVE screening models are primarily used to evaluate the feasibility of SVE at a specific site based on limited input data. These models are not intended for evaluating detailed SVE, although preliminary conceptual design plans can be examined with model results. Johnson et al. (1990a,b) presented a useful screening approach for determining the feasibility of SVE at a particular site. This practical approach makes use of analytical equations that estimate VOC removal rates and pressure distributions for various SVE design parameters. The two models that were developed based on this approach are HyperVentilate and VENTING.

HyperVentilate, which was developed independently from VENTING, is designed to be used as an instructional tool to identify required site data, decide if SVE is appropriate at a site, evaluate air permeability tests, and estimate the minimum number of wells needed. It is especially useful for a quick feasibility evaluation based only on soil permeability and the thickness of the screened interval. Soil permeability can be calculated from air-pumping tests or estimated from the types of soils present. The flow rate is then calculated from the input of the soil permeability, desired radius of influence of the extraction well, screened interval for the well, and extraction well diameter or radius. Calculated estimates of extraction flow rates and vapor concentrations can be used to estimate maximum mass removal rates. The analytical mass removal rates assume the presence of residual free product in the vadose zone. Two boundary-layer screening calculations are included for estimating removal rates above a liquid layer of free-phase NAPL and above low-permeable soil with residual contamination.

HyperVentilate contains "help cards" that define the equations used and also provide supplementary information. Chemical files for weathered and unweathered gasoline

Table 4-5. Summary of the Screening, Airflow, and Compositional Flow and Transport SVE Models (EPA, 1994)

Hyperventilate, v2.0 (IBM PC), v1.01 (Apple Macintosh)
Type - Screening
Functionality - Simplistic steady-state, radial-symmetric airflow and transient one-dimensional multicomponent contaminant transport
Solution Methodology - Analytical solution; finite-difference solution of a one-dimensional mass balance equation
Assumptions - Two-dimensional, radial, confined airflow to a vapor extraction well; one-dimensional, mass-balance approach, volatilization based on Raoult's law
Capabilities - Calculates air permeability, well flow rates, mass removal rate; residual leaks removal rates in 2 ideal mass transfer limited scenarios; calculates contaminant concentrations over time for multiple constituents
Advantages - Provides rapid estimates for determination of the potential feasibility of SVE; provides rapid estimates of contaminant concentrations in extracted gas, allows comparison of removal rates of different constituents
Limitations - Analytical airflow solution; mass removal rates based on advection from free-phase NAPL, diffusion-limited models for two scenarios are given; should not be used to design SVE systems
Hardware/Software Requirements - IBM PC or Compatible 80386/80387 coprocessor or 80486, 4 MB, RAM, DOS 3.1 or higher, Microsoft Windows 3.x and runtime version of Object PLUS; Apple Macintosh (Plus, SE, SE230, II, IIX, or portable): 1 MB RAM, Apple HyperCard Software (v2.0 or greater)
Availability - Available from EPA as EPA/600/R-93/028 (EPA ORD Publications, 513/569-7562), Price: FREE. Available to Public from NTIS, Price: $22 IBM PC, $17 Macintosh. Object PLUS available from Object PLUS Corp., 125 Cambridge Park Dr., Cambridge, MA 02140, Price: $100 (run time version)
Venting, v3.1
Type - Screening
Functionality - Transient, one-dimensional multicomponent contaminant transport.
Assumptions - Calculations based on user-defined flow rate, assumes equilibrium partitioning between phases in a one-dimensional volume of soil.
Limitations - User supplies flow rate to extraction well; simplistic one-dimensional representation of mass transport; should not be used to design SVE systems
Hardware/Software Requirements - IBM PC/AT or Compatible, DOS, 512 KB RAM, math coprocessor
Availability - Environmental Systems and Technologies, Inc., 2608 Sheffield Drive, Blacksburg, VA 24060, 703/552-0685, Price: $400.00

AIRFLOW™, v3.01 Airflow
Type - Airflow
Functionality - Steady-state, radial-symmetric (two-dimensional cross-section) airflow
Solution Methodology - Finite-element solution of the airflow equation
Assumptions - Based on Darcian flow of an ideal compressible gas in a porous medium
Capabilities - Calculates pressure distribution in a radial domain, calculates airflow pathlines and velocities
Advantages - Easy-to-use CAD-type graphical user interface which simplifies model input and setup; rapid setup for simple problems, aids in hypothesis testing; many sample problems included with the code
Limitations - Only allows for one extraction well; no mass removal
Hardware/Software Requirements - IBM PC or compatible, 80386/80486, 4 MB RAM, DOS 2.0 or higher, mouse and math coprocessor for 80386-based machines recommended
Availability - Waterloo Hydrogeologic Software, 19 McCauley Drive (RR#2), Bolton, Ontario, Canada, L7E SR8, 905/880-2886, Price: $650.00
CSUGAS
Type - Airflow
Funtionality - Transient, two- or three-dimensional airflow
Solution Methodology - Finite-difference solution of the airflow equation
Assumptions - Based on Darcian flow of an ideal compressible gas in a porous medium
Capabilities - Calculates vacuum distribution in the subsurface, in inches of water
Advantages - Allows full, three-dimensional analysis of heterogeneous, multiwell airflow problems; text-based input/output is flexible and up to the user
Limitations - Lack of easy-to-use input/output interface may intimidate beginners; no steady-state solution, option; no mass removal
Hardware/Software Requirements - IBM PC AT/XT or compatible, 640 KB RAM, DOS 2.0 or higher
Availability - Dr. James W. Warner, Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523, 303/491-5048, Price: $125
AIR3D
Type - Airflow
Functionality - Three-dimensional airflow

Solution Methodology - Finite-difference solution of the airflow equation posed in terms of the groundwater flow equation and solved by the MODFLOW code
Assumptions - Based on Darcian flow of an ideal compressible gas in a porous medium
Capabilities - Calculates pressure distribution in the subsurface
Advantages - Easy-to-use CAD-type graphical user interface which simplifies model setup and input; allows three-dimensional analysis of complex problems
Limitations - Users need to have an awareness of the operation and limitations of the MODFLOW code; no mass removal
Hardware/Software Requirements - IBM PC or compatible, DOS 3.3 or higher, 4 MB RAM, FGA card and color monitor, mouse is highly recommended
Availability - American Petroleum Inst., 1220 L Street Northwest, Washington, DC 20005, Price: $500.00
VENT2D, v1.3
Type - Airflow and multicomponent contaminant transport
Functionality - Steady-state, two-dimensional airflow and transient contaminant transport
Solution Methodology - Finite-difference solution of the airflow equation, finite-difference solution of the transport equation
Assumptions - Transport equation is simplified by ignoring mechanical dispersion (includes diffusion)
Capabilities - Calculates pressure distribution in the subsurface, multicomponent contaminant constituent concentrations over time in the subsurface
Advantages - Only readily available compositional flow and transport code; source code is available; text-based input/output is flexible and up to the user
Limitations - Grid size limited to 25 x 25 cells (can be increased with a different version available from the author)
Hardware/Software Requirements - IBM PC or compatible, 80x86 with math coprocessor, DOS 3.0 or higher, 525 KB RAM
Availability - David A. Benson, 425 Claremont Street, Reno, NV 98502, 702/322-2104, Price: $495.00

are provided, and a customized file can be created for other compound mixtures. HyperVentilate has a friendly graphic-user interface of useful calculation cards for estimating airflow rates, soil permeability, and mass removal rates.

Both HyperVentilate and VENTING are based on assumptions of uniform properties and subsurface geometries and use an analytical steady-state, horizontal radial flow solution to produce flow to a vertical extraction well (Johnson, et. al. 1990a,b). Advantages of these models include minimal data requirements and quick setup and execution. These models can provide initial estimates for determining whether SVE is appropriate for a given site.

Although relatively simplistic, the analytical solution approach used in these models can provide reasonable results for sites where airflow is essentially confined and the airflow patterns are primarily horizontal. Such sites include those with surface seals such as pavement cover with no short-circuiting in the subgrade, or sites where the zone of contamination is confined by low-permeability layers. The basic model principles and computer software structure are discussed further in this section.

VENTING can be used to estimate the rate of VOC removal from the vadose zone based on user-defined extraction well flow rate from single or multiple wells. This model assumes a steady-state airflow, equilibrium or diffusion-controlled phase partitioning, and complete mixing within the contaminated zone to complete the extracted mass of each contaminant constituent during the extraction time. The mass balance considers partitioning among the free-product aqueous, adsorbed, and vapor phases and assumes that all the contaminant mass is homogeneously distributed at all times in a defined volume of soil. It also assumes that the aqueous and adsorbed phases make negligible contributions to the vapor phase. The mass removal rates of the more-volatile constituents in a multicomponent mixture are iteratively calculated. The volumetric airflow rate is the key parameter that determines the VENTING modeling results. The flow rate may either be input directly based on field measurements or may be estimated based on the permeability of the contaminated soil and the vent pressure. VENTING also provides a method of estimating permeability by use of permeability test data. Hydrocarbon composition files can be created to produce common hydrocarbon blends. Composition files for fresh and weathered gasoline are also provided. The model can also generate mass-removal-versus-time plots for each constituent in a multicomponent mixture.

4.4.5 Detailed Models

4.4.5.1 Airflow Models

Subsurface airflow models are used with the two- or three-dimensional flow of air through a porous medium as a result of the pressure gradient created by an extraction well. These models do not consider contaminant concentrations in soil vapor, mass removal, and overall SVE system effectiveness.

Airflow models can be used to develop a detailed design for SVE systems involving well placement/location for multiple extraction wells. Depending on the type of airflow model used, heterogeneities such as low-permeability zones and layered soils can be simulated in either two or three dimensions. In general, these numerical models can provide a more detailed analysis of the airflow field because they have fewer restrictive assumptions. Airflow models can account for nonideal conditions such as a leaky ground surface boundary condition or the presence of low-permeability layers. The potential pressure distributions, airflow, and different radius or zone of influence for a well system can be simulated to determine optimum well placement to visualize the differences in permeability and preferential flow paths in determining the zones that will be most affected by the SVE system. An overview of the airflow models CSUGAS, AIRFLOW, and AIR3D is provided below (see Table 4-5).

CSUGAS is a three-dimensional finite difference model (Sabadell, 1988) that numerically simulates the flow field of a compressible gas in a porous medium as a result of the influence of an SVE system. The finite differences method is used to numerically approximate a solution to the system of equations. This method also allows for use of a heterogeneous and isotropic porous medium with airflow under steady-state or transient conditions. Model applications include selecting design parameters, determining feasibility of SVE at a particular site, and evaluating proposed modifications to existing SVE systems.

AIRFLOW is a two-dimensional finite element radial-symmetric model (Waterloo Hydrogeologic Software, 1993) that simulates the flow of vapors in the unsaturated zone. It calculates steady-state pressure distribution, airflow, and pathlines in cross section to the extraction well for an ideal, compressible gas. It can be an effective tool for analyzing the effects of layering, surface seals, and low-permeability zones on the flow of air to an SVE well. Different vapor characteristics can be simulated by using different vapor pressure, molecular mass, viscosities, and temperatures. The model can simulate heterogeneous and isotropic permeability zones. A variety of boundary conditions can also be imposed.

AIR3D is a finite difference model that calculates steady-state or transient air pressure distribution and airflow in the vadose zone resulting from inducing vacuum at SVE wells. AIR3D uses the MODFLOW groundwater code (McDonald and Harbaugh, 1984) to solve the equation of airflow in the vadose zone (Joss and Baehr, 1994). AIR3D transforms the input variables in terms of pressures required for MODFLOW. The model can simulate anisotropic subsurface conditions where the user defines the zones of different permeability that can be defined independently of the layers.

AIR3D also includes an optimization module as an aid in selecting optimal well locations and extraction rates. This module is used to select the number of potential well locations, range of extraction rates, and a set of pressure gradient constraints; the optimization module then identifies the best configuration.

4.4.5.2 Compositional Flow and Transport Models

Compositional flow and transport models are used to evaluate both the airflow field and the transport or removal of contaminant constituents. Some of these models simulate transport of multiple constituents in mixture when multiple phases are present. These models can be used as an aid to determine residual concentrations of less-volatile constituents in the mixture. Most available compositional flow and transport models consider only a single set of vapor properties, thereby requiring a simulation to be run for each constituent. Compositional flow and transport can be used in evaluating SVE design and operation from well placement to contaminant extraction rates.

VENT2D incorporates steady-state airflow and transient multiple-constituent transport. Unlike other models, it simulates advective and diffusive transport for a number of chemical constituents simultaneously in two dimensions. The model also solves for equilibrium distribution of each constituent among four phases (vapor, adsorbed, dissolved, and nonaqueous phase liquid). Nonideal conditions considered in this model include nonhomogeneous soil permeability, leakage of atmospheric air into the subsurface, and irregular contaminant distribution of each contaminant constituent. Contaminant saturation relative to airflow regimes is considered to reflect the depletion of pore fluids over time.

This model can be used by a large number of practitioners to simulate multiconstituent vapor flow in multiple dimensions through unsaturated soils with variable permeability and contaminant distributions among a number of phases. This simulation is especially useful in evaluating irregular SVE well-field geometries. Dispersion is considered only on the macro-scale in order to simplify the execution time and to minimize the data needed.

4.4.5.3 Detailed Model Applications

The detailed models presented do not represent an all-inclusive list, but are examples of the types of models currently available. The selection of one of these or similar models should, in general, be based on the complexity of the site and the questions that need to be answered concerning SVE system design. The AIRFLOW model is perhaps the easiest to use of these detailed design models, but it can only provide a steady-state solution to a radial flow problem in cross-section. CSUGAS and AIR3D can provide analysis at different time steps and, therefore, they can provide information on the expected change in pressures and flow velocities in soils with varying permeabilities. This function is particularly important in evaluating field observations in low-permeability soils where steady-state conditions might take months or years to achieve. CSUGAS and AIR3D can also stimulate the airflow for complex SVE system designs such as horizontal wells or piping structures. These models, however, do not calculate chemical partitioning and transport. Although these models are more flexible for the evaluation of airflow regimes, they may be more time-intensive to set up and execute, may require greater hardware capabilities for complex problems, and may require more data than is practical.

VENT2D is the only combined compositional and steady-state flow model presented here. As previously discussed, this model can stimulate the chemical and physical processes affecting the movement of multi-constituent vapor-phase chemical mixtures (such as gasoline). The principal application of this model is to more accurately evaluate the rate at which the various chemical constituents will be extracted from the vadose zone. This model would be appropriate for estimating mass removal rates from a flow-field in order to determine SVE system performance. Other models with combined compositional and transient airflow solutions have been developed for internal use or are currently under development. As these models become available, they should provide additional tools for evaluating sites with complex physical and chemical conditions.

Recent SVE system designs for removing volatile organic compounds (VOCs) have mostly been empirically based because of the simplicity of the process and the lack of an understanding of the use of SVE models in aiding system design. Compositional flow and transport models have practical applications in actual field situations that can be used to evaluate the effectiveness of SVE in removing organic vapors. Sensitivity analyses can be used to determine the role of soil moisture, temperature, soil heterogeneity, and other factors in controlling the migration of volatile constituents through the unsaturated zone. The process of contaminant desorption from soil particles involves three consecutive mass transport steps during the operation of the SVE system. This process can be examined when final cleanup efficiency is determined. It also can result in significant differences in removal rates for the various types of soils and volatile organic components.

All of the airflow and compositional flow and transport models are useful tools for estimating well placement; however, they must be used with an understanding of the model assumptions and limitations. For example, some models are based on the number of soil pore volumes. Estimates for contaminant removal are then used to determine appropriate airflow rates. The models should evaluate three-dimensional airflow (Shan et al., 1992) to account for differences in vertical and horizontal air permeability and the boundary conditions of air that enters the well through the ground surface. Other models are based on horizontal airflow only and do not take into account vertical air recharge from the ground surface. The models are useful for screening and rough estimates, but are not designed to determine an exact distance for well placement.

4.5 SVE System Monitoring

4.5.1 Common Monitoring Practices

SVE system monitoring is performed to determine the amount and movements of contaminants in the subsurface before, during, and after remediation. The overall objectives of a monitoring program are to: 1) assess site conditions to determine

remediation approach, 2) evaluate the progress of in situ treatment, and 3) determine site conditions following treatment.

In practice, SVE monitoring is typically performed to meet regulatory (compliance) requirements for site closure and off-gas treatment, and, for a limited number of sites, to assess or optimize system performance.

SVE performance monitoring of airflow rates and vapor-phase concentrations and composition in extracted vapors directly measures the rate of volatile hydrocarbon removal by the system. All too often, SVE effluent concentration and flow rate data are collected as a secondary consideration to equipment maintenance, and are not specifically included in a monitoring program to evaluate system performance. The parameters typically measured during the monitoring of SVE systems include the following.

- Vapor flow rates at each extraction well and injection well. Measurements can be made by a variety of flow meters, pitot tubes, and orifice plates.

- Vacuum/pressure at each extraction and injection well and at monitoring points. These readings can be measured with manometers and magnehelic gauges. Vacuum/pressure should also be monitored at each soil gas probe location.

- Vapor concentrations and composition from each extraction well. Vapor concentrations can be measured by an on-line total hydrocarbon analyzer calibrated to a specific hydrocarbon. This information can be combined with vapor flow rate data to calculate removal rates (mass/time) and the cumulative amount of contaminant removed. Soil gas measurements should be made periodically at different radial distances by using soil gas probes to monitor the reduction in contaminant vapor concentration.

- Temperature of the soil and ambient air. By monitoring soil temperatures, Conner (1988) predicted that biodegradation was occurring in the zone of contamination. At locations with large seasonal differences between air and soil temperatures, extraction air temperature is also a qualitative measure of air residence time in the soil.

- Water table elevation. For soils with a relatively shallow water table, water level measurements can be made with electronic sensors located in airtight monitoring wells.

- Meteorological data. These data also include barometric pressure, precipitation, and similar data.

In addition to these parameters, product thickness on the groundwater should be measured if more than one-eighth inch exists on the water table. Table 4-6 provides a comprehensive list of data interpretation options for SVE-based systems and the corresponding data needed for interpretation and analysis.

4.5.2 Performance Data Quality

The Environmental Group of the Chevron Research and Technology Company conducted a nationwide study to examine and evaluate SVE performance monitoring data from 143 SVE systems operated by Chevron, USA, Inc. (Buscheck and Peargin, 1991). The majority of the SVE systems were installed to remediate gasoline releases. Of the 143 SVE systems in operation, 15 newly installed systems were excluded because of a lack of available information. Figure 4-18 shows the number of SVE systems and their period of operation that were used as screening criteria for this study. The remaining SVE systems were further screened to limit the number of systems evaluated based on the following criteria:

- In operation less than six months.
- Review of site assessment reports, SVE monitoring reports, and other information.
- Overriding imprints of operational or hydrologic overprints on SVE performance data (e.g., periodic opening of effluent dilution valve, fluctuating water table submerging contaminated soils). Only 26 percent of the data generated from SVE system monitoring were adequate for evaluating SVE system performance; 34 percent of the SVE systems had been in operation for less than 6 months; and 40 percent of the monitoring data was inadequate. This subsection presents the results from the evaluation of the SVE system performance data that were determined to be adequate.

4.5.3 Monitoring Frequency

SVE performance should be monitored frequently enough to accurately represent both the variability in the data set and the overall decline of hydrocarbon removal rates over time. Collection of monitoring data on too frequent a basis can generate unneeded quantities of data and can add to the cost of system operation. Selection of an appropriate monitoring frequency is a compromise between data quantity and project costs, and may be influenced by site-specific factors (e.g., location). The majority of SVE systems are monitored either weekly or monthly. This monitoring interval can result from the common practice of weekly (sometimes daily) monitoring of SVE during the period following system start-up, followed by monthly monitoring after several weeks have passed.

Table 4-6. Process Monitoring Options and Data Interpretation (Johnson, et al., 1992b)

Data Interpretation/Analysis Requirement	Data Collection[a]
• Concentration vs. time • Composition vs. time • Flow rate vs. time • Applied pressure/vacuum vs. time • Mass removal rate [mass/time] vs. time • Cumulative removed by volatilization [mass] • Identify mass transfer limitations	1
• Aerobic biodegradation contribution to removal rate [mass/time] vs. time • Aerobic biodegradation contribution to cumulative amount removed [mass]	1, 2, 6°
• Total remediation costs [$] vs. time • Cost per mass of hydrocarbon removed [$/kg removed] vs. time	1, 2[b], 3
• Effect of environmental factors [qualitative]	1, 2[b], 4
• In situ assessment of treatment with time [qualitative areal impact]	1, 2[b], 4°, 5, 6[b], 8°, 9[s]
• Defined zone of vapor containment [qualitative areal impact]	1, 5°, 7, 11°
• Closure monitoring report	1, 2[b], 3°, 4°, 5, 7, 8, 9, 10, 11°
• Areal impact of air sparging	1, 2, 4°, 5°, 6°, 7, 8°, 9, 10, 11°
• Effect of water table elevation changes	1, 2, 4, 5, 6, 7, 9, 10
• Injection/extraction flow rate optimization • Flow field definition	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11

[a]Key: b = Applicable for bioventing applications; o = Optional, or as required; s = Relevant to air sparging.

Data Collection Key:
1 = Process monitoring data; extraction/injection flow rate(s) and vacuum(s)/pressure(s), extraction vapor concentration and composition.
2 = Respiratory gas (O_2, CO_2) monitoring of extracted vapor stream.
3 = Cost monitoring; capital, operation and maintenance, and utilities costs.
4 = Environmental monitoring; temperature, barometric pressure, precipitation.
5 = In situ soil gas monitoring; vapor concentration and composition.
6 = In situ soil gas monitoring; respiratory gases (CO_2 and O_2).
7 = Subsurface pressure distribution monitoring.
8 = Soil samples.
9 = Groundwater monitoring.
10 = Groundwater elevation monitoring.
11 = Tracer gas monitoring.

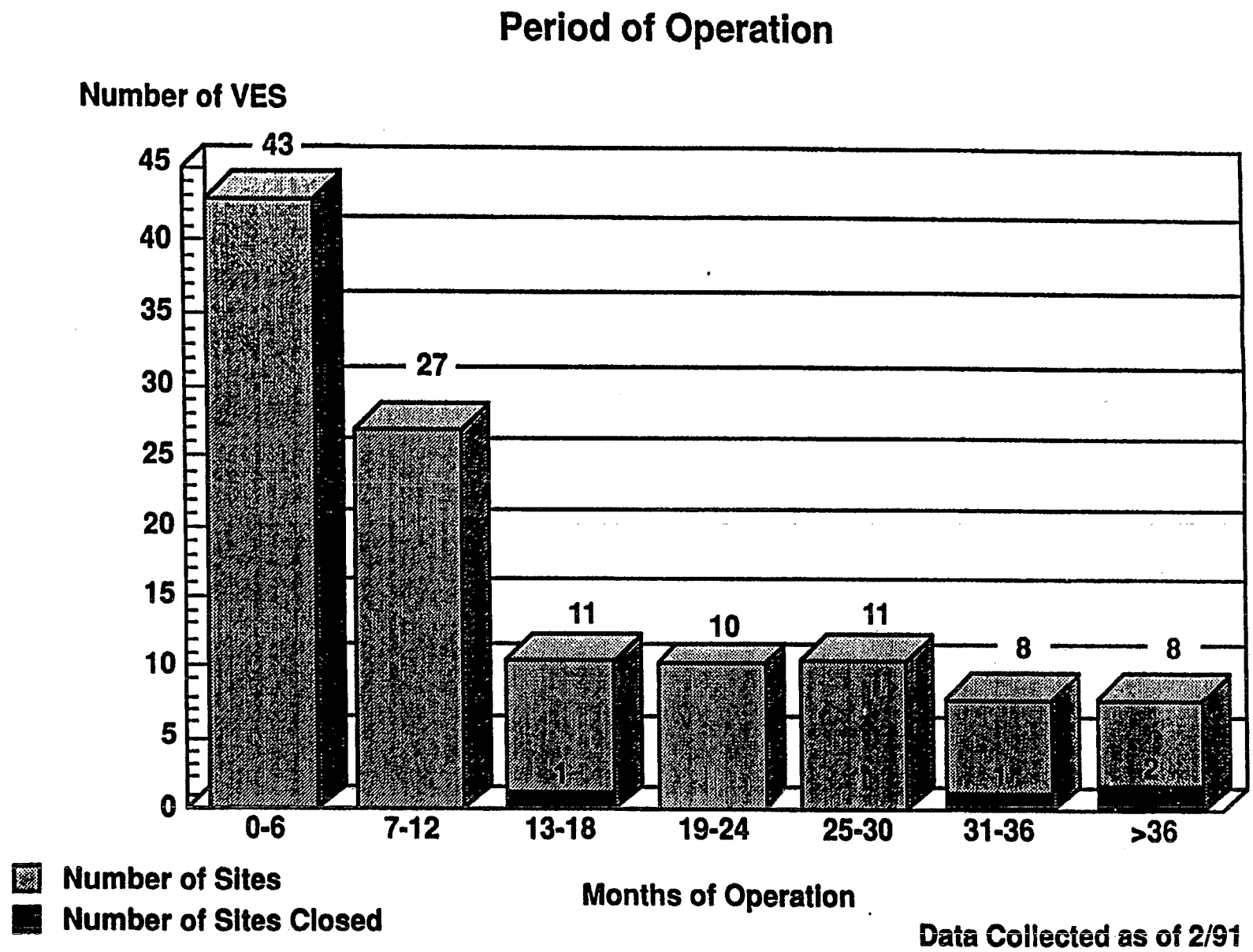


Figure 4-18. Operational periods of SVE systems surveyed by Chevron.

Source: after USEPA, 1993a

To illustrate the effects of sampling frequency on performance data interpretation, Figure 4-19 has been set up to show a complete SVE performance data set from a site in San Diego, California. These graphs show monitoring results for hydrocarbon mass removal rates for all raw data as well as results of biweekly and monthly sampling. These plots show relatively good agreement in data trends between the full (raw) data set, and data sets comprised of biweekly and monthly sampling frequency data. Monthly SVE monitoring appears to be sufficient. More frequent sampling (weekly or biweekly) will generate more data, which increases the confidence level of data analyses, but may not be cost-effective in all cases.

4.5.4 Airflow Rates

Results from the evaluation of SVE performance monitoring have led to the following conclusions:

- Hydrocarbon mass removal rates (lb/day) are sensitive to changes in airflow.
- Airflow should be measured directly and not be estimated from blower performance curves.
- Performance should be measured directly with a dedicated device.
- Use of an orifice plate and averaging pitot tube are cost-effective and they have low maintenance requirements.

SVE flow rates expressed as volume of air removed/day are extrapolated from measurements of airflow in standard cubic feet/minute. Therefore, calculated daily hydrocarbon mass removal rates are sensitive to relatively small changes in measured airflow rate. At some sites, airflow rates are estimated from an initial system vacuum measurement taken shortly after installation, or from the theoretical maximum capacity of the blower. Inaccurate (or nonexistent) airflow rate data severely compromises SVE performance data analysis.

Airflow rates all too often are derived from measured total system vacuum applied to blower performance curves. Most manufacturers provide standard performance curves for their equipment based on testing at standard conditions (70°F and atmospheric pressure at sea level). The following operating factors, however, will significantly alter the accuracy of this information:

- Temperature
- Atmospheric pressure
- Inlet vacuum and
- Discharge pressure
- Moisture content.

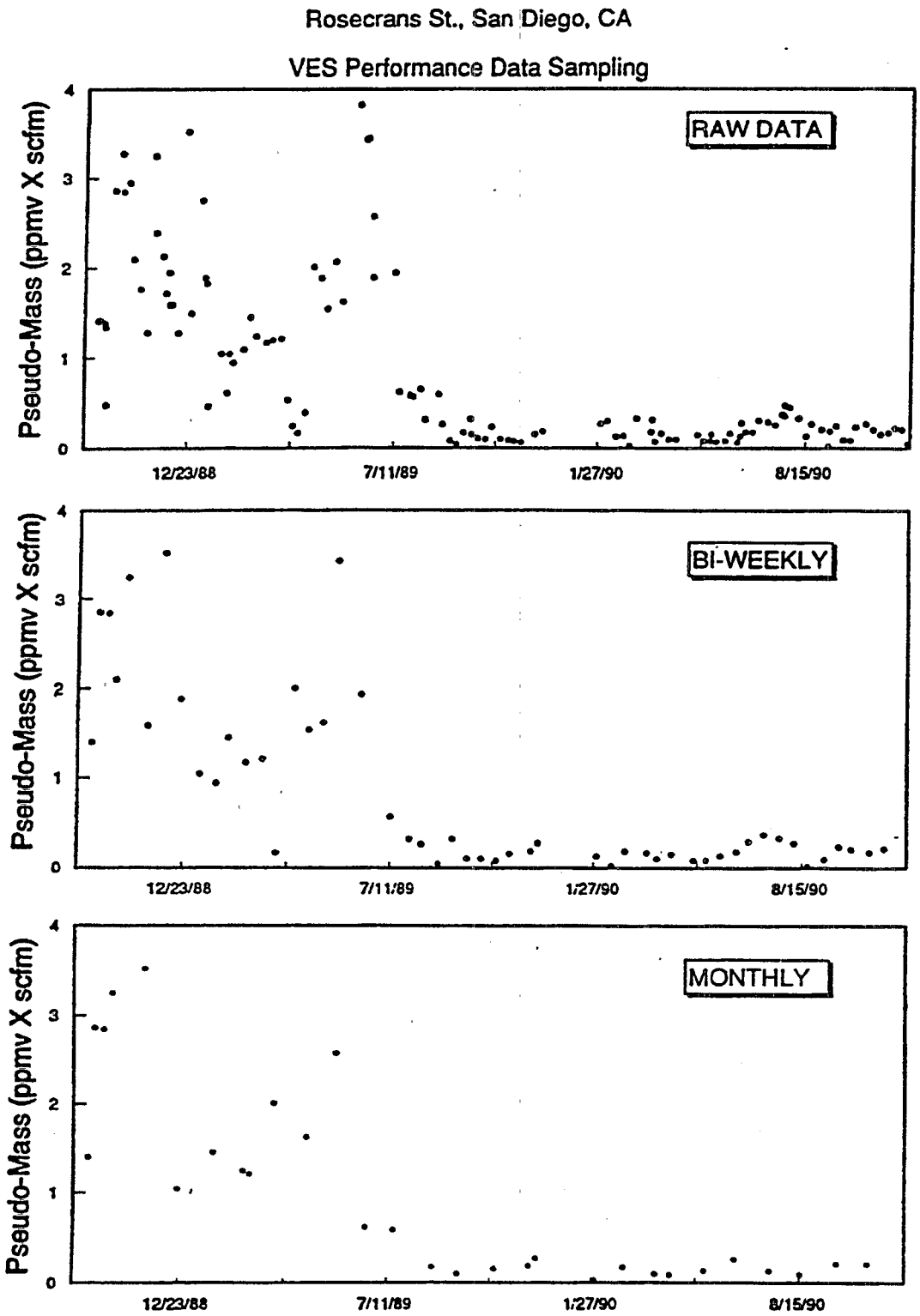


Figure 4-19. SVE monitoring data for a San Diego, CA, site.

Source: after USEPA, 1993a.

Vacuum pump or blower performance curves provided by the manufacturers should not be used as a primary source of flow rate measurement. Performance curves are better employed as checks for the dedicated airflow metering device, rather than as the primary means to measure flow rate.

4.5.4.1 Dedicated Air Flowmeters

Airflow rate measurement should be performed with a dedicated flowmeter that is calibrated to the specific dimensions of the vapor extraction system. The proper selection, calibration, and installation of a flowmeter will provide accurate flow measurement without significantly reducing system performance through excessive flow losses. The relative cost of installing dedicated flowmeters is nominal when compared to the cost of designing and installing a full-scale SVE system.

4.6 Effluent Monitoring

SVE effluent concentrations should be measured with a broad-spectrum hydrocarbon vapor detector with linear response to changes in both hydrocarbon concentration and composition. Ideally, a hydrocarbon vapor detector should generate an electrical output that is proportional to changes in both hydrocarbon vapor concentration (hydrocarbon vapor volume/unit effluent volume) and composition (mass/unit effluent volume). Explosimeters, flame ionization detectors, and photoionization detectors all exhibit linear response with respect to hydrocarbon concentration over given ranges, but vary in their individual response to changes in overall hydrocarbon vapor composition. A detector with linear response to hydrocarbons is necessary to accurately convert measured SVE effluent hydrocarbon concentrations to hydrocarbon mass removal rates.

The LEL (lower explosive limit) meter measures hydrocarbon concentrations in SVE effluent as a function of the heat of combustion of hydrocarbon vapors passing over a catalyst-coated wire. LEL meter response is linear across a broad range of hydrocarbon concentrations (100 to 10,000 ppmv), but is not linear with respect to changes in hydrocarbon vapor composition because changes in average molecular weight of effluent gases are not proportional to the heat released during combustion. This limitation means that expected changes in volatile hydrocarbon composition throughout the life of the SVE system will not be accurately converted to mass removal rate as measured by the LEL meter. This limitation makes the LEL meter an inferior detector for SVE effluent monitoring purposes when compared to other devices such as photoionization and flame ionization detectors.

The gas chromatograph (GC) and PID are sensitive to volatile aromatic constituents but do not detect methane or other alkanes. Volatile aromatic hydrocarbons represent only a limited fraction of the total spectrum of volatile hydrocarbon compounds in SVE effluent, and are not representative of the overall hydrocarbon mass removal efficiency of the system. Volatile aromatic concentration data cannot be extrapolated to represent total volatile hydrocarbon concentrations because the ratio of aromatic to total volatile hydrocarbons decreases throughout the operating life of the SVE system (Johnson, et.

al., 1990a). PID readings, however, can provide limited information on the weathering of the released product and fractionation of volatiles. Aromatic hydrocarbons are approximately three orders of magnitude more detectable than other hydrocarbons. Consequently, BTEX constituents measured by a PID can provide limited use for SVE monitoring.

When calibrated with an appropriate gas (usually hexane), the FID and GC/FID can be used to quantify mass-per-unit-volume concentrations of hydrocarbon vapors in SVE effluent, even though hydrocarbon composition changes with time. FID response is proportional to the number of ionized carbon molecules released by the hydrogen flame, and is reasonably linear with respect to changes in both hydrocarbon composition and concentration (EPA, 1990a). The FID detects all hydrocarbons, including oxygenates, alcohols, and ethers, over a concentration range of approximately 1 to 10,000 ppmv. FIDs are also more sensitive than PIDs to alkanes such as hexane and butane, which make up a higher fraction of gasoline than do the aromatics. The relative differences between hydrocarbon detectors is presented in Table 4-7.

Table 4-7. Comparison of Hydrocarbon Field Analytical Instruments

Detector Type	Cost	Type of Hydrocarbons Detected	Detection Limit (ppm by volume)	Recommended Use
Portable Flame Ionization Detector (FID)	$6-8,000	All	1	Field TPH
LEL Meter	$2,000	All	100	Safety
Portable photoionization detector (PID)	$5-7,000	Aromatics	0.1	Field BTEX

4.6.1 Periodic BTEX Monitoring

Johnson, et. al. (1990a) documented a shift in SVE effluent hydrocarbon composition from highly volatile to progressively less-volatile compounds during system operation. This "chromatographic" shift of hydrocarbon vapor composition is largely a function of higher vapor pressures allowing more rapid mass transfer of highly volatile hydrocarbon compounds to subsurface airflow from the sorbed, free liquid, or dissolve phases. Highly volatile compounds, such as BTEX, should be removed fairly early during system operation, while less-volatile hydrocarbon fractions will take a significantly longer time to be removed.

Periodic monitoring of BTEX as a fraction of total SVE effluent is a useful technique to confirm whether SVE performance for a given site is likely to be advection- or diffusion-limited.

- Advection-controlled sites (i.e., sites where advection is the primary transport mechanism) should exhibit a rapid decline in BTEX fractions, relative to total hydrocarbon mass removal rates, significantly before overall hydrocarbon removal reaches near-zero asymptotic values. This decline occurs for these sites because the majority of hydrocarbon contaminants are being contacted by airflow.

- Diffusion-limited sites should exhibit a rapid decline in BTEX effluent fraction, followed by stabilized low-BTEX levels persisting in SVE effluent even as overall hydrocarbon mass removal rates decline to non-zero asymptotic values. The continuing presence of measurable BTEX at these sites can be attributed to lower permeability soils yielding a broad spectrum of hydrocarbon vapor compositions to SVE effluent.

4.6.2 Hydrocarbon Mass Removal Rates

A review of SVE hydrocarbon removal rate plots from 15 sites suggested the existence of 2 site categories that correlate with hydrogeologic conditions and SVE flow rates. Each of these "categories" is discussed in the following subsections.

4.6.2.1 Category 1 Sites

SVE performance data for Category 1 sites is best described by the exponential regression, with an asymptotic mass removal rate near zero as shown in Figure 4-20.

Table 4-8 provides a summary of the Category 1 sites including the duration of SVE operation, airflow rates, number of venting wells and exponential rate constant, and a hydrogeologic description of each site. In general, these sites are characterized by:

- Typically medium- to coarse-grained sediments with high permeability.

- Per-well airflow rates 25 to 50 scfm or greater.

- Exponential rate constants (k) that fall within the narrow range of 0.0045 to 0.0067 day^{-1}.

With one exception, depth to groundwater varied from 3 to 18 feet at these sites. At Site H, groundwater exceeds 100 feet in depth. Sites B, C, and G are now closed.

Two of these sites (Sites B and E) are underlain by finer-grained sediments. At Site B, groundwater was pumped at three gallons per minute (gpm) in order to lower the water table, concurrent with vapor extraction. During groundwater pumping, sediments that

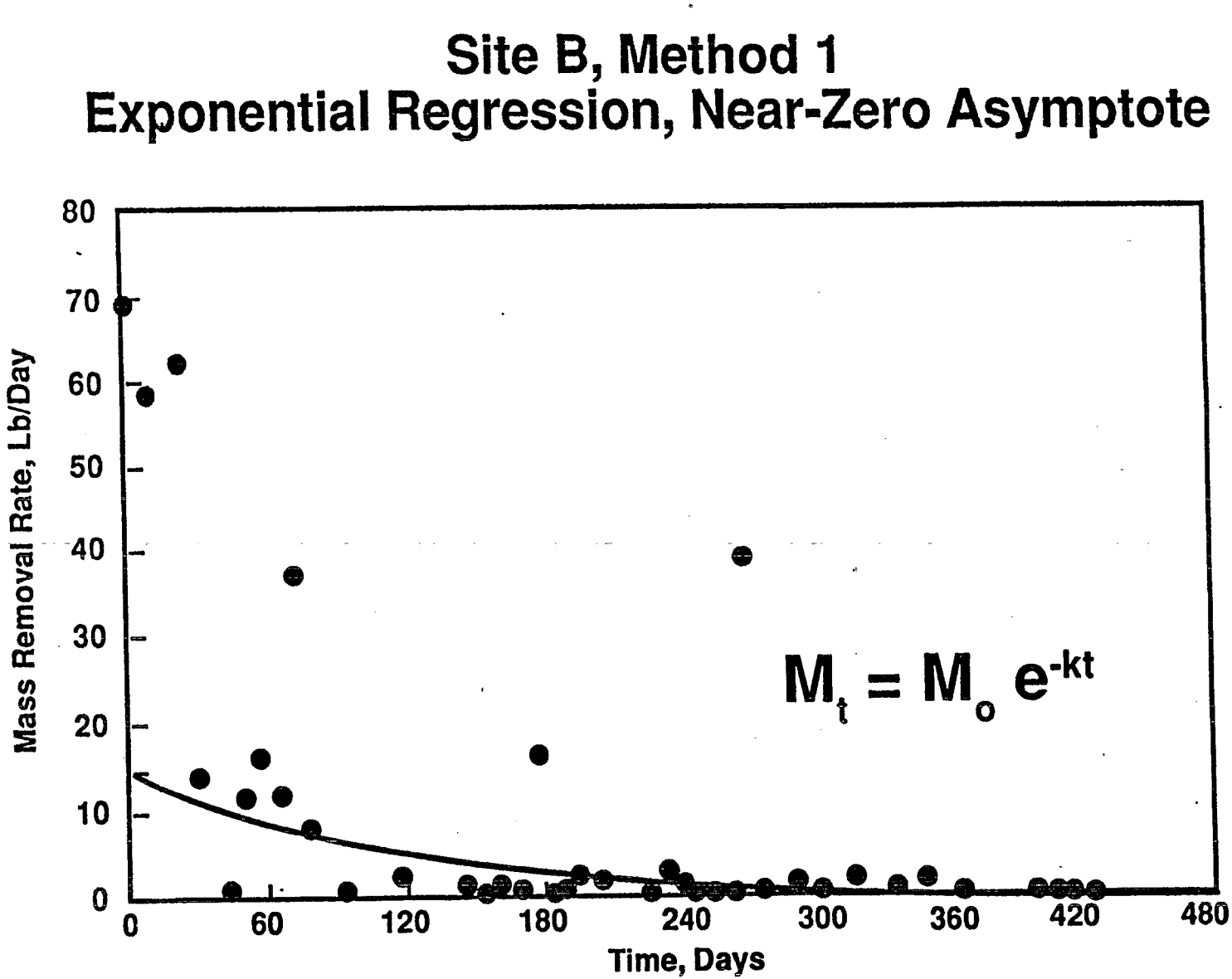


Figure 4-20. Mass removal of hydrocarbons over time for a categgory 1 site (Site D) - exponential regression, near-zero asymptote.

Source: after USEPA, 1993a.

are coarser-grained than the overlying silty clays were exposed to vacuum. The largest exponential rate constant, k, for all the Category 1 sites was calculated for Site B as 0.0091 day^{-1}. This system was operated for the shortest period (506 days), before site closure.

Table 4-8. Summary of SVE System Data for Category 1 Sites

Site	Closed	Duration, Days	Airflow Rate, scfm	No. of Venting Wells	k[a] [day^{-1}]
Site A	No	886	61-116	4	0.0060
Site B	Yes	506	34-59	1	0.0091
Site C	Yes	1131	350-380	36	0.0057
Site D	No	881	52-130	3	0.0049
Site E	No[b]	1202	75-140	3	0.0030
Site F	No	424	33-83	3	0.0067
Site G	Yes	997	70-80	3	0.0053
Site H	No	675	85-115	1	0.0045

[a] Exponential rate constant.

[b] Closure petition submitted to state.

The unsaturated zone at Site E consists of sands and clays overlying natural silt loams (2 to 6 feet deep and 4 feet thick), which in turn overlie igneous bedrock. Unconsolidated sediments at Site E are finer-grained than those found at most of the other Category 1 sites. The smallest exponential rate constant for all the Category sites was calculated for Site E where k = 0.0030 day^{-1}. This site has operated for longer than any of the other sites in this category. The calculated rate constants and operating histories for Sites B and E illustrate that cleanup time is apparently inversely proportional to the exponential rate constant.

The performance of the Category 1 systems is consistent with the expected vadose zone airflow rates derived from Table 4-8. Venting wells operate at 25 to 50 scfm and are completed in relatively permeable, medium- to coarse-grained alluvial materials. If liquid hydrocarbon is present, the early operation of an SVE system is characterized by a "flushing" period, when mass removal rates remain relatively high. As removal rates decline, the system is limited by advection and evaporation (Hinchee, 1990). Mass removal rate plotted versus time generally fits an exponential decline, approaching

asymptotic values near zero. If an early flushing period is observed, the exponential regression should be performed on data following that period.

4.6.2.2 Category 2 Sites

SVE performance data for Category 2 sites decline exponentially but clearly demonstrate a non-zero asymptotic mass removal rate as shown in Figure 4-21. Table 4-9 presents a summary of the Category 2 sites. The exponential rate constant, k, is not included in this table because the constants calculated for these sites showed considerable variability, making it difficult to demonstrate trends. None of these sites has been closed. The period of operation for these systems varies between 205 and 784 days. Although these sites contain multi-well extraction systems, regression analysis for Sites I and O included performance data from only one well (both systems include more than eight wells). With the exception of Site I (70 to 100 scfm), which incorporates groundwater pumping, and Site O (26 to 70 scfm), individual venting wells at Category 2 sites operate below 20 scfm. At Sites J and K, where SVE incorporates 13 to 14 venting wells, total system airflow rates are between 165 and 225 scfm.

Category 2 SVE wells operate at lower flow rates than those of Category 1 systems, which is consistent with the descriptions in Table 4-9. Category 2 sites are characterized by typically fine-grained sediments, low permeability, and per-well airflow rates less than 20 scfm.

As in Category 1, SVE systems at Category 2 sites may also demonstrate an early flushing period. Early in the life of an SVE system, preferential flow paths develop within zones of higher permeability where most of the airflow occurs. Hydrocarbon vapors within the preferential flow paths are removed by advection and evaporation (similar to the Category 1 sites). Mass removal rates generally follow an exponential decline during this period. Ultimately, mass removal rates clearly approach a non-zero asymptote. In this period of asymptotic mass removal rates, hydrocarbon vapors in the pore spaces of low- permeability sediments (silts and clays) must reach the preferential flow paths in order to be removed from the subsurface, and are therefore diffusion-limited.

4.7 Summary

Monitoring the performance of remediation systems and evaluating performance data are key elements in site cleanup. Frequency and quality of effluent monitoring data is critical to system evaluation. Plots of hydrocarbon mass removal rate versus time should be used in performance evaluation. Exponentially declining mass removal rates do not in themselves guarantee site cleanup. If the SVE system is installed and operated in such a way as to adequately access residual hydrocarbon, however, performance plots should be an accurate measure of remediation efficiency.

Advection-controlled and diffusion-limited sites have been defined as two basic SVE performance categories based on geologic controls of hydrocarbon mass removal

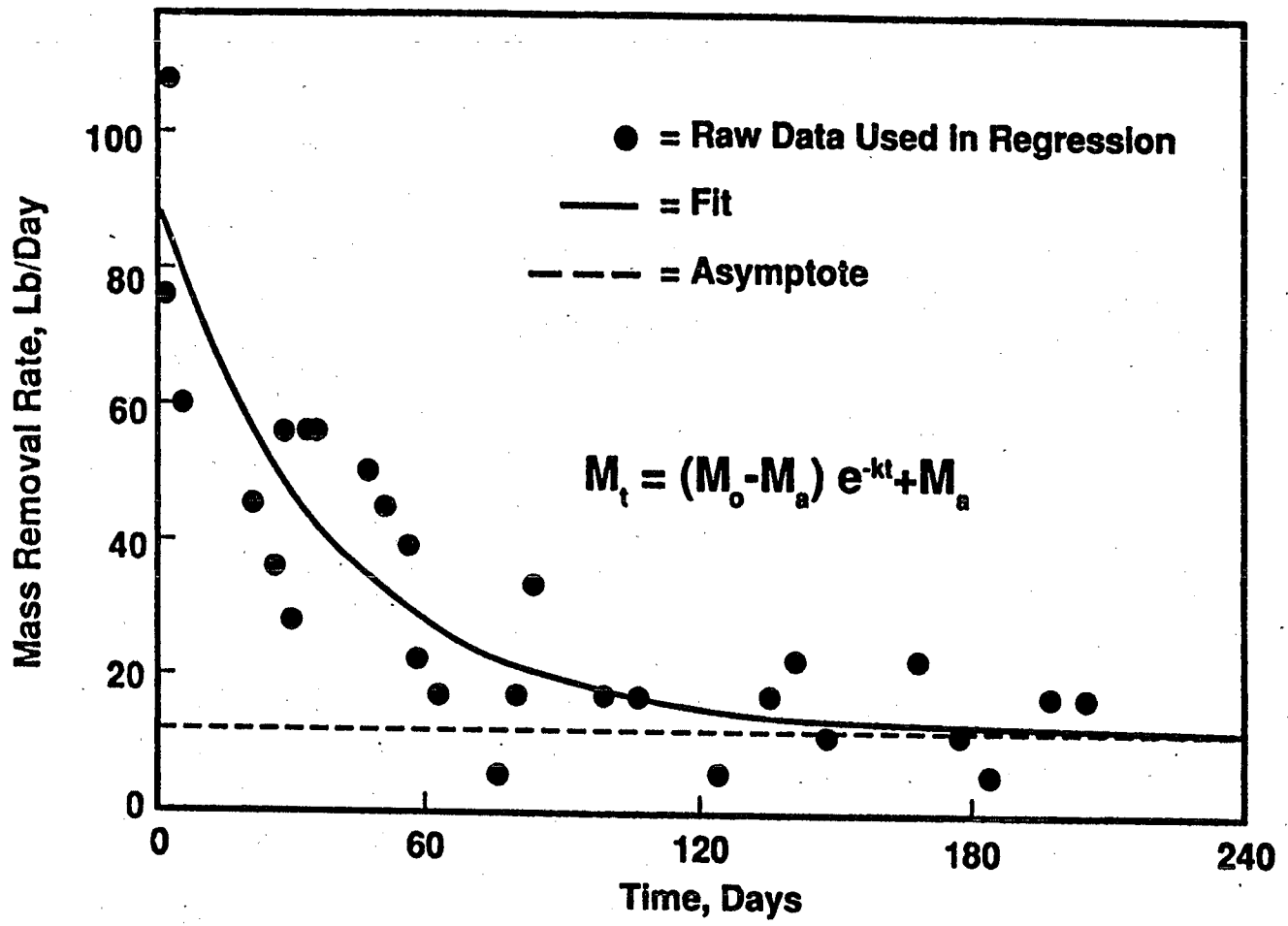


Figure 4-21. Mass removal rate of hydrocarbons over time for a category 2 site (site L) - exponential regression, non-zero asymptote.

Source: after USEPA, 1993a.

Table 4-9. Summary of SVE System Data for Category 2 Sites

Site	Status	Duration, (Days)	Airflow Rate (scfm)	No. of Venting Wells
Site I	Open	613	70-100	1
Site J	Open	237	225 (75)[a]	13 (3)[a]
Site K	Open	408	165 (74)[a]	14 (7)[a]
Site L	Open	205	6-84	4
Site M	Open	700	76-120	6
Site N	Open	784	30	7
Site O	Open	409	26-70	1

[a] Early operation of system.

rates. Advection-limited geologic settings are characterized by relatively permeable soils through which airflow contacts the majority of vadose zone contamination. The rate of hydrocarbon mass removal for advection-limited sites is primarily a function of hydrocarbon volatilization and airflow rates. As a result, hydrocarbon mass removal rates decline toward a near-zero asymptote. Once near-zero asymptotic hydrocarbon mass removal rates have been achieved for advection-controlled sites, they should be ready for confirmatory soil sampling prior to closure.

Diffusion-limited geologic settings are typically sites with heterogeneous soils (sands, silts, clays) through which air flows along preferential pathways in the higher permeability sediments. Soils in the airflow pathways are remediated early in the life of the SVE system, but hydrocarbon mass transfer from the lower permeability sediments is controlled by the rate of diffusion of hydrocarbon vapors into the airflow pathways. Hydro-carbon mass removal rates for these sites decline exponentially to a non-zero, diffu-sion-limited asymptotic value. Diffusion-limited sites may require significantly longer SVE operation times to adequately reduce hydrocarbon concentrations in lower permeability soils. SVE performance for advection- or diffusion-limited sites can be anticipated based on stratigraphy determined during site investigation.

Chapter 5
Bioventing and Intrinsic Bioremediation

5.1 Introduction

Minimum action technologies such as bioventing and intrinsic remediation are gaining popularity as more complex remedial technologies are proving to be very costly while providing marginal results in many cases. Bioventing and intrinsic remediation can be very cost-effective when applied at appropriate sites. Additionally, these two technologies are often complementary when both vadose zone soil and groundwater are contaminated. This chapter describes the application of bioventing systems for the treatment of vadose zone soil, the approaches that can be taken to demonstrate intrinsic remediation in the vadose zone and groundwater, and the benefits of using the two technologies as a total treatment package for soil and groundwater treatment.

5.2 Bioventing Process Overview

In situ treatment of vadose zone soil is very advantageous under a variety of circumstances. Treatment of vadose zone soil without excavation is attractive when space is limited, when soil volume is large, when disposal options are limited, where excavation invokes the need for special permits, or where excavation is impossible such as under buildings and other structures or deep vadose zones.

Soil vapor extraction (SVE) is a widely applied technology for the removal of volatile organic compounds (VOC) from vadose zone soil. There is some debate as to the actual effectiveness of SVE for remediating soil contaminated with volatiles, however, and there is general agreement that SVE is ineffective for the remediation of semi- and nonvolatile compounds (Figure 5-1) (Kent and Graves, 1992). A new technology commonly known as "bioventing" has emerged in the past few years that addresses some limitations of SVE (Hinchee, 1991; Miller, et al., 1990; and Dupont, 1993).

Bioventing is the in situ biological treatment of contaminated vadose zone soil. During bioventing, blowers or vacuum pumps are used to supply oxygen to the subsurface and thus promote remediation (Figure 5-2). Bioventing can effectively treat any compound that is biodegradable, given that bacteria are present in the soil with the metabolic capability to biodegrade the target compounds. In the case of petroleum contamination such as that caused by gasoline, jet fuel, diesel, and heating oils, appropriate bacteria are nearly always present. These bacteria may not be very active, however, because

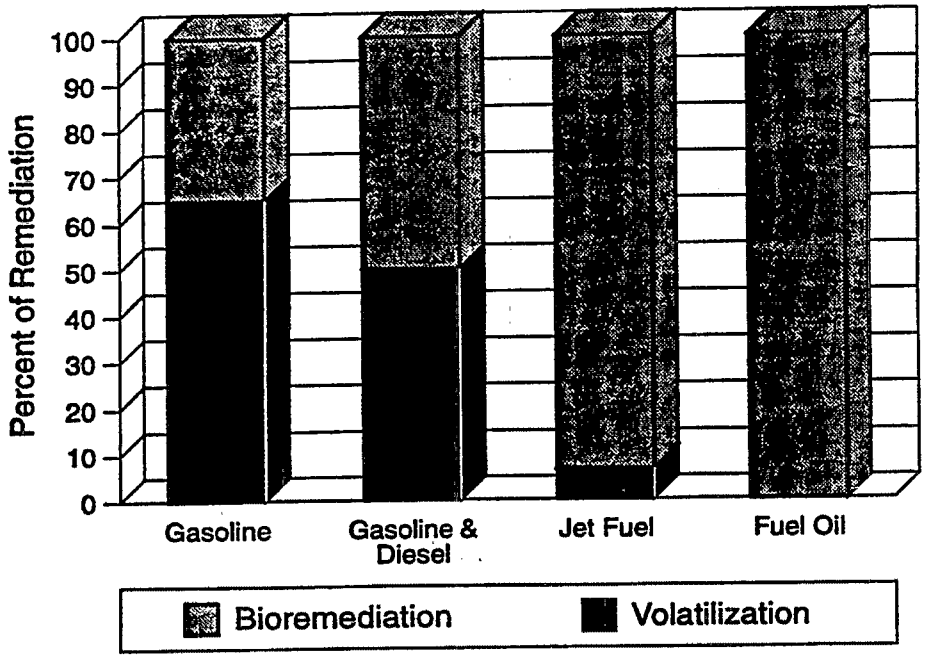


Figure 5-1. Comparisons of volatilization and bioremediation.

of a lack of oxygen, extreme pH, lack of nutrients, lack of moisture, or cold temperature (Sims, et al. 1993).

Bioventing systems use the same equipment as SVE; however, because of the difference in the treatment objectives of biodegradation versus stripping and extraction, some design and operational details are different (Dupont, 1993). As a "rule of thumb" bio-venting systems are designed at one-fifth to one-tenth the capacity of an SVE system designed for the same site (Dupont, 1993). This estimate is based on the evaluation and/or application of bioventing at numerous U.S. Air Force sites. Because of the low recovery of soil vapors, the cost for aboveground treatment systems such as activated carbon units or fume incinerators is reduced. In cases where the principal contaminants are semi- or nonvolatile compounds, vapor treatment may not be necessary.

Another operational avenue to reduce capital and operating cost and complexity is to inject air into the soil to achieve oxygenation (Figure 5-3). This approach should be evaluated cautiously because toxic or flammable fumes can accumulate in poorly ventilated structures such as basements or even trenches or ditches. When vapor

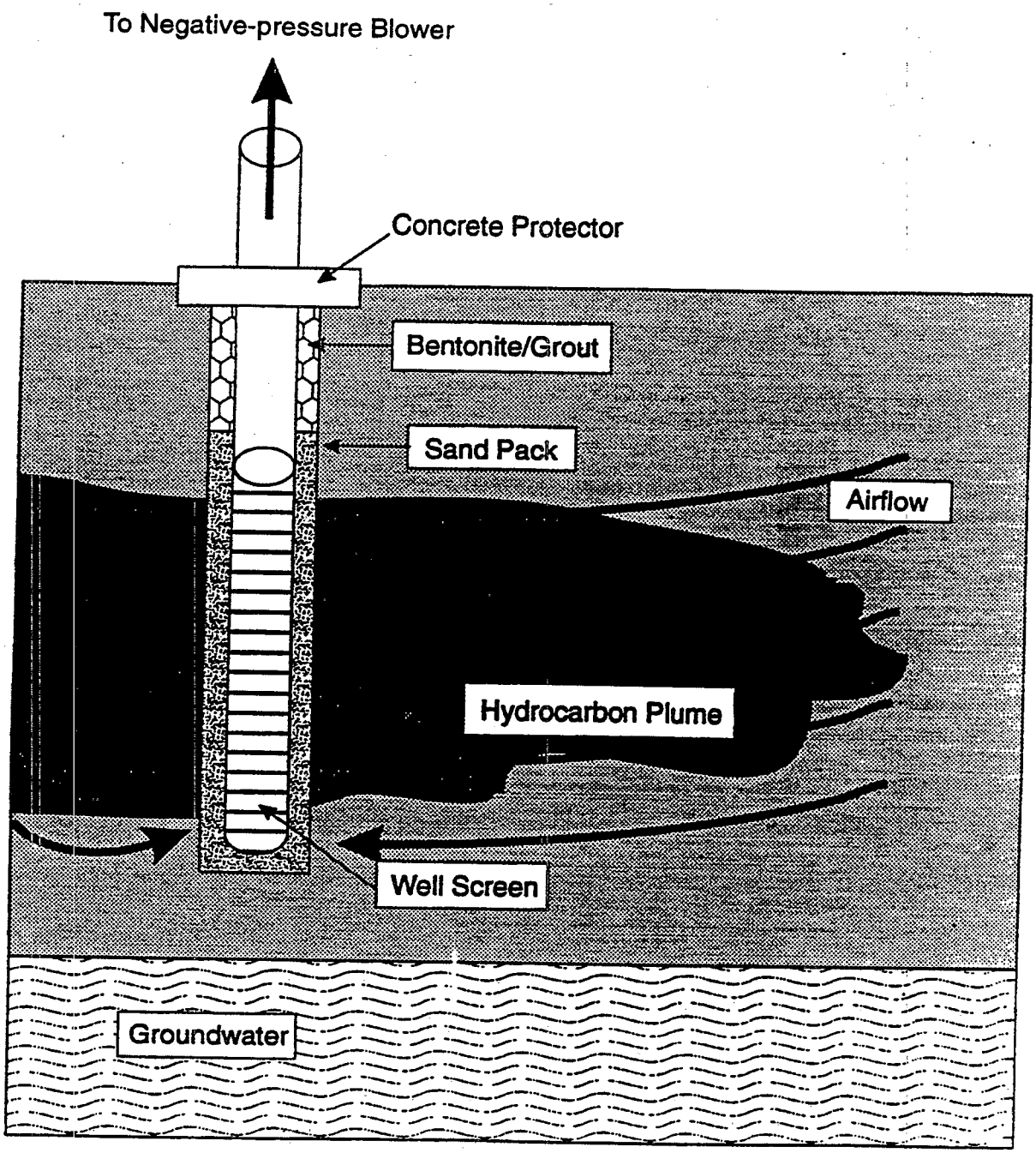


Figure 5-2. Bioventing by air extraction.

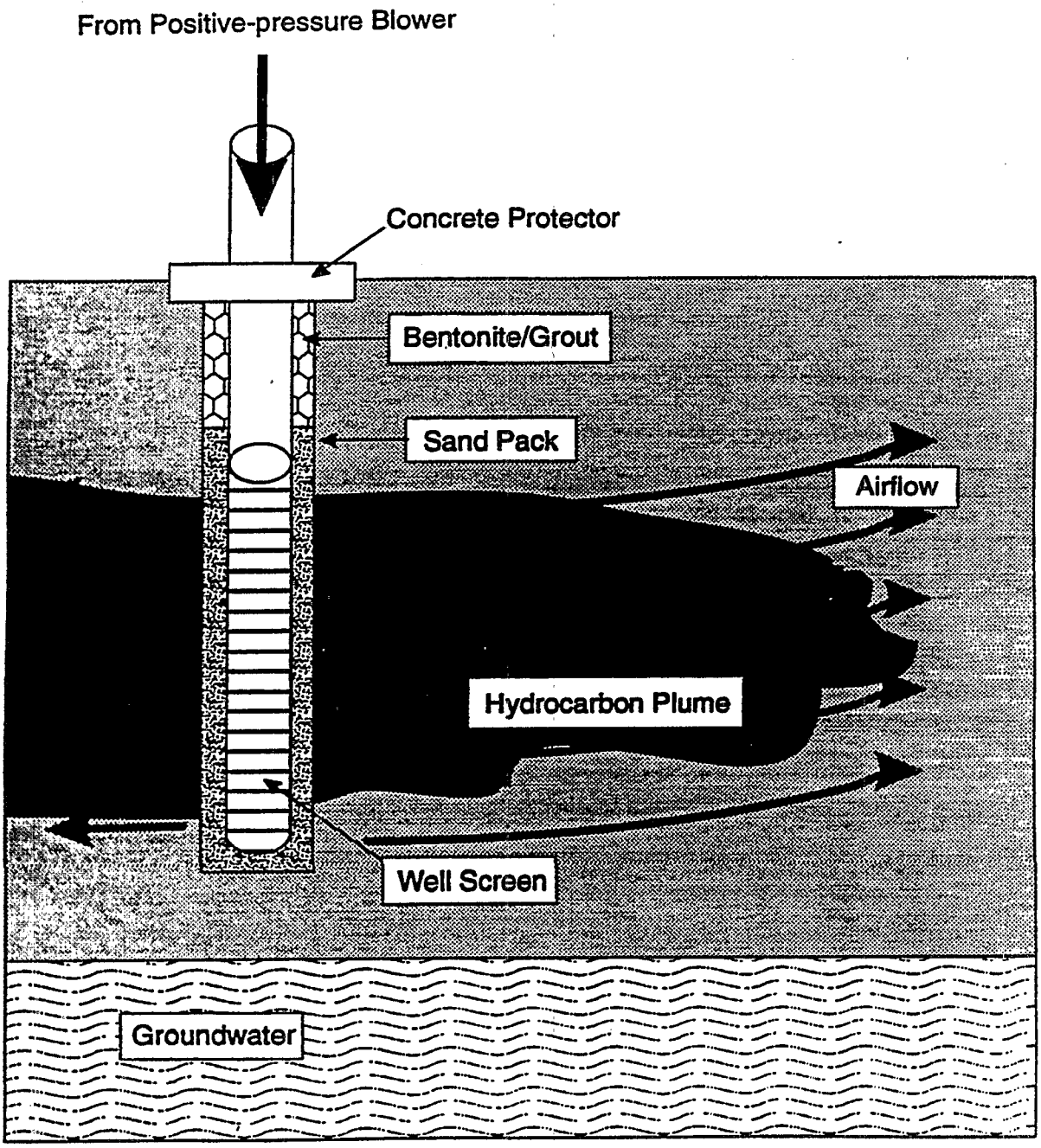


Figure 5-3. Bioventing by air injection.

accumulation is not a concern, the diffuse emission of volatiles from the ground surface is usually undetectable.

Bioventing system design has many similarities to SVE design. Common predesign information that is needed includes the zone of influence about an extraction well, which is determined by measuring vacuum at monitoring points; soil gas composition including VOC, oxygen, carbon dioxide, and methane; the vertical and horizontal location of contamination; type of contamination; and subsurface stratigraphy (EPA, 1993d). Additionally, a few other pertinent site characteristics should be investigated to specifically support the design and operation of a bioventing system.

5.3 Laboratory Testing to Support Bioventing

Bioventing is a form of bioremediation that depends on enhancing biological activity in the subsurface. Therefore, physical, chemical, and microbiological parameters known to impact biological activity in the environment should be evaluated.

5.3.1 Microbial Population Density

The presence of a viable microbial population is critical to the success of bioventing. A very small or nondetectable microbial population may indicate vadose zone conditions that are averse to bioventing. These conditions may be correctable if they are identified. Determining the size and viability of the indigenous microbial population is a simple approach for identifying potential problems.

Some practitioners do not recommend microbial enumerations as part of their bioventing monitoring program. They opt to measure the performance of the system solely by in situ respiration tests. Although this approach is simple and may be adequate in many cases, the status of the microbial population has to be assumed and changes in performance cannot be correlated with changes in microbial population density. Because the remediation process is affected by microorganisms, periodic assessment of the microbial population density can provide useful information, especially at complicated or difficult sites.

The number of bacteria in the impacted soil is determined by using accepted methods for enumerating bacteria. The spread-plate method and the most-probable-number method are the most common techniques for enumerating bacteria; however, microscopic and gene probe techniques are also being successfully used.

Total aerobic heterotrophs and aerobic contaminant-degrading bacteria should be enumerated. The results are reported as the number of bacteria or number of colony forming units (CFU, equivalent to number of culturable bacteria) per gram (g) of dry soil. Typical microbial densities in soil range from 10,000 to 10,000,000 CFU/g of soil. Total microbial density lower than 10,000 CFU/g is not necessarily bad, but it may indicate that some condition in the soil is slowing the growth of the bacteria. Contaminant degraders usually constitute 50 percent or less of the total population.

5.3.2 Microbial Stimulation Testing

A laboratory test evaluating the response of indigenous bacteria to enhanced environmental conditions may be used to test the viability of site bacteria and their potential activity during remediation. These tests are designed to stimulate the growth of bacteria by providing oxygen and nutrients. Although the test can be conducted in several ways, an important criterion for the test is to conduct an independent evaluation of the effect of oxygen on microbial growth as well as an independent evaluation of the effect of oxygen and nutrients on microbial growth. In many cases where the population of bacteria is low, the addition of oxygen alone is adequate to stimulate microbial activity; however, in other cases both oxygen and nutrients may be required to stimulate the growth of bacteria. When oxygen or nutrients limit bacterial activity, the population density may increase several-fold more within a short time after the addition of oxygen or oxygen and nutrients. This result strongly suggests that indigenous bacteria will also respond when site conditions are enhanced by the treatment system. In cases where the bacteria fail to respond during this test, further investigation is warranted to determine why growth did not occur because this may also indicate poor performance of the bioventing system.

Not all practitioners of bioventing advocate the use of microbial stimulation tests to evaluate population viability and responsiveness to treatment conditions. Bioventing systems have been successfully installed without such data; however, the risk of installing an ineffective system is increased. Performance problems can often be anticipated based on the results of a microbial stimulation test.

5.3.3 Residual Nutrients

Oxygen is the principal limiting factor for in situ biodegradation followed by nutrient limitations. Fixed nitrogen is the inorganic nutrient required in the greatest concentration for bacterial activity. Phosphate is also required, but in smaller amounts. Reported ratios of carbon to nitrogen to phosphate required to support bacterial growth range from approximately 100:10:1 to 600:10:1 (Kent and Graves, 1992).

Ammonium, the preferred source of nitrogen for most bacteria, is often found at low to very low concentrations in soil, thus suggesting that microbial activity can be limited by lack of fixed nitrogen. Phosphate, often found in relatively high concentrations in soils, is less likely to limit biological activity in soil. Determining the concentration of these two inorganic nutrients is important for designing a bioventing system that maximizes biological activity. Laboratory tests frequently indicate that nutrients are beneficial and will increase the rate of biodegradation. Field results are mixed, with some published reports suggesting that nutrient addition does not increase biodegradation while others indicate some benefit (Miller et al., 1990; Mark-Brown, 1994; Lakshmiprasad and Dupont, 1993; and Graves and Leavitt, 1993). Nutrient addition may prove to be beneficial in cases where inorganic nutrients are not available.

Although nutrient addition is not recommended *a priori*, it may significantly improve the performance of bioventing systems in nutrient-deficient soils or after several months of operation when residual nutrients have been depleted. Nutrients may be applied in solution or as vapors. Delivery and even distribution of nutrient solutions is challenging, especially in deep vadose zones. Field experience is lacking in vapor-phase nutrient delivery; however, laboratory results show that it is feasible and beneficial (Mark-Brown, 1994; Lakshmprasad and Dupont, 1993; Graves and Leavitt, 1993).

5.3.4 Soil pH

Bacteria generally thrive between a pH of 5.5 and 8.5 (Sims et al., 1993; Dupont, 1993). When the pH deviates from this range, biological activity may be reduced. A pH greater than 9.5 and less than 4.5 virtually stops the metabolic activity of most bacteria. Adjusting the pH of vadose zone soil is such a challenging task that an extreme soil pH may eliminate bioventing as a viable remedial option.

5.3.5 Soil Moisture

An acceptable range of soil moisture that will support bacterial activity in a typical soil is 7 to 20 percent moisture by weight (approximately 25 to 85 percent of the moisture holding capacity [a.k.a. field capacity] of the soil)(Dupont, 1993). Some cases have been reported where a much lower water content was adequate. Higher water content impedes oxygenation and airflow by filling pore spaces; therefore, excessive soil moisture will reduce the effectiveness of the oxygenation process, resulting in reduced activity by aerobic bacteria.

High rates of soil gas extraction can cause excessive soil drying and limit the biodegradation rate. Adding water back to the vadose zone can be difficult; therefore, the best approach is to avoid desiccating the soil. This becomes a serious issue when SVE is used together with bioventing because the operation of an aggressive SVE system before bioventing can dry the soil and inhibit biodegradation.

5.3.6 Conducting Laboratory Tests

A biotechnology laboratory that routinely conducts the indicated tests should be contracted to perform the laboratory tests for the bioventing project. The laboratory should be selected based on bench scale and field experience.

5.4 Field Investigations to Support Bioventing

Bioventing and SVE share several common elements. Therefore, several aspects of field investigations supporting both technologies are similar.

5.4.1 Zone of Influence About a Vacuum Well or Trench

The ability to oxygenate the subsurface is critical to the operation of a successful bioventing program. Therefore, understanding the area that can be oxygenated by a well or trench is critical for designing a system to effect treatment of the entire area. The zone of influence can be determined by connecting a blower to the well or trench

and measuring vacuum in the ground at various distances from the well. For bioventing, an alternative measurement is oxygen content of the soil gas at various distances from the well. The time required to achieve steady-state conditions during zone-of-influence testing varies with soil type and is, therefore, specific to each site (see Chapter 4.0). Based on zone-of-influence measurements, wells are placed to avoid gaps in coverage where oxygen will not be replenished.

Figure 5-4 shows a common layout for measuring the zone of influence about a vacuum well. When a vacuum is applied to the venting well, negative pressure can be detected at the monitoring points. When the vacuum observed at each monitoring point is plotted against the distance from the venting well by using a semi-logarithmic coordinate system, a straight line should result. The point at which the vacuum is reduced by 60 to 90 percent is usually taken as the functional radius of influence for SVE applications.

For bioventing, the defining parameter is the oxygen content of the soil gas. Airflow through the subsurface must only meet the oxygen demand of the contaminated soil. Depending on the permeability of the soil, radial influence frequently ranges from 10 to 100 feet. Achieving a practical zone of influence in shallow soil can be difficult because of air short-circuiting to or from the surface. An impermeable cover can be placed over the treatment area to improve the radius of influence. Plastic sheeting, asphalt, and concrete can be effective barriers to airflow. In cases where extensive surface area is paved, fresh air sources may be unavailable or poorly located to provide thorough aeration. Passive air inlets or injection wells may facilitate aeration of the entire treatment area, thus increasing system effectiveness.

5.4.2 Extent of Contamination

Defining the horizontal and vertical extent of the plume of contamination is critical for the placement of wells and screened intervals. Differences in the air permeability of different soil strata are also an important consideration because air will preferentially flow around less-permeable zones and lenses. This can result in oxygen deficiency in less-permeable strata. Maximum aeration of the plume is ensured when wells are screened within the vertical limits of the contamination.

Additionally, placement of well screens within the contaminated area insures accurate respiration measurements. When wells are screened over a wide vertical area that includes substantial areas of clean soil, the soil gas withdrawn from the impacted area is diluted with soil gas from uncontaminated areas. This dilution causes the soil gas to have a much higher oxygen content and a much lower carbon dioxide and VOC content. This observation can lead to misinterpretation of the actual performance of the bioventing system.

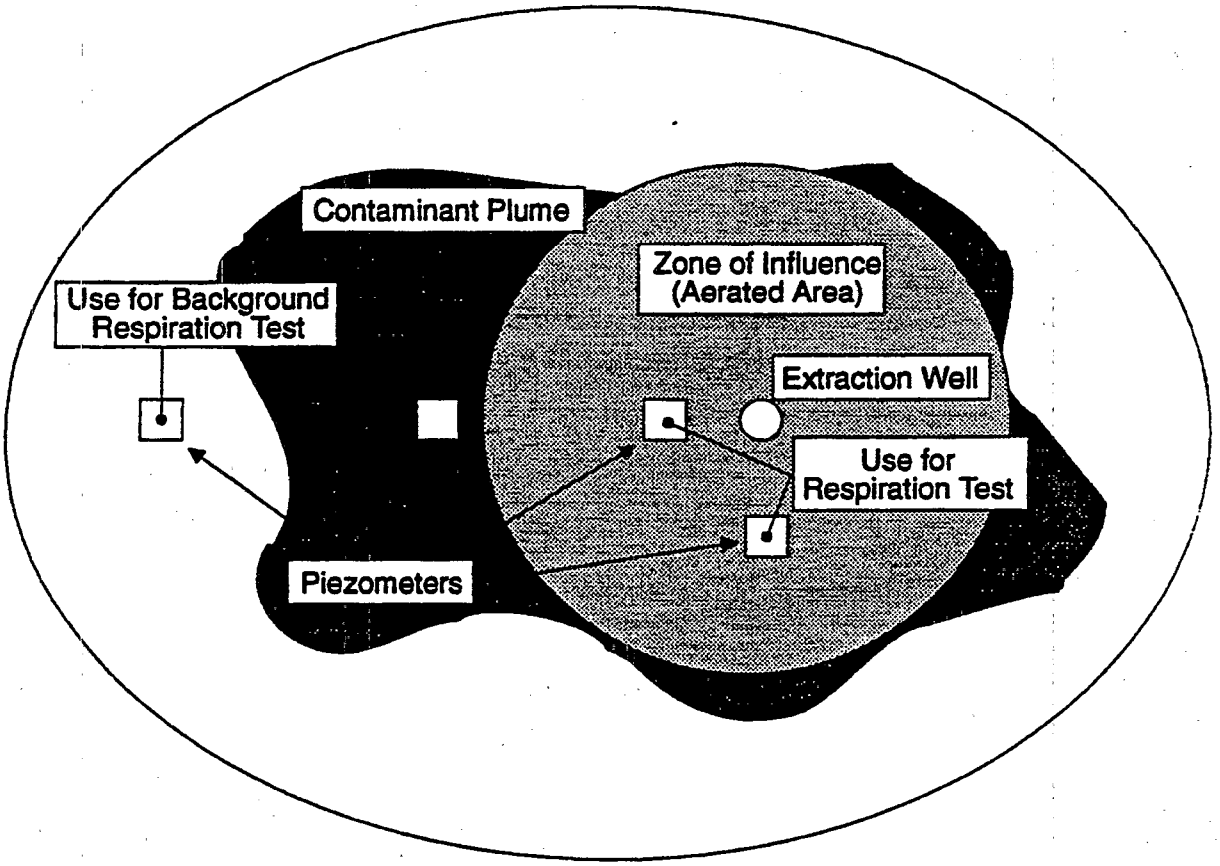


Figure 5-4. Well location for radius of influence and in situ respiration testing.

5.4.3 Soil Gas Composition

Soil gas composition can be used as the principal indicator of the performance of a bioventing system. Under conditions suitable for bioventing, the oxygen and carbon dioxide content of the soil gas in the impacted soil will be very different from atmospheric conditions. Air contains about 20.9 percent oxygen and 0.032 to 0.036 percent carbon dioxide; however, soil gas collected from contaminated soil has been frequently observed to contain less than 10 percent oxygen and more than 5 percent carbon dioxide (Kent and Graves, 1992). These conditions strongly suggest that aerobic biological activity has affected the soil gas composition because aerobic bacteria consume oxygen and produce carbon dioxide during respiration. The oxygen partial pressure of soil gas can be reduced by the presence of VOC; however, the increase in carbon dioxide cannot be correlated to partial pressure changes resulting from the VOC content of the soil gas.

Methane is also commonly detected in soil gas from sites impacted with petroleum products. The presence of methane indicates that anaerobic conditions exist in the subsurface, resulting in methanogenesis. This interpretation must be accepted only after regional geology has been considered because some areas have natural gas seeps.

The goal of a bioventing system is to move air through contaminated soil to increase oxygen content, reduce carbon dioxide content, and encourage aerobic biodegradation of contaminants (Hinchee et al., 1992; Dupont, 1993). Optimum oxygen concentrations for bioventing have not been determined; however, an oxygen concentration greater than 5 percent should be maintained to sustain aerobic metabolism. Table 5-1 indicates the relationship between gaseous oxygen and dissolved oxygen. The carbon dioxide content should be maintained at less than 5 percent to avoid toxicity.

Deciding if the contaminated soil is being adequately aerated requires correct placement of the screened interval in the monitoring wells (vapor monitoring points) (Hinchee, et al., 1992). The vapor monitoring point should be screened within the impacted zone only, otherwise soil gas from clean soil will dilute the soil gas collected from the impacted area. The soil gas composition results collected from an improperly screened vapor monitoring point will show a higher oxygen and lower carbon dioxide content. Erroneous results give the impression that the bioventing system is effectively aerating the soil when the impacted area may be anaerobic.

5.4.4 Respiration Measurement

Measuring the respiration rate in the impacted soil provides the best indicator of the potential performance of a bioventing system (Hinchee and Ong, 1992; Hinchee and Arthur, 1991). In general, a respiration test consists of aerating the soil and measuring the consumption of oxygen and the production of carbon dioxide over time. The U.S. Air Force Center for Environmental Excellence (AFCEE) has produced a widely used guidance document describing in situ respiration testing (Hinchee et al., 1992). Based

on the test results, the rate of respiration can be determined and the amount of hydrocarbon consumed per unit of time can be estimated.

Table 5-1. Gaseous Oxygen, Dissolved Oxygen, and Aerobic Biodegradation.

Gaseous Oxygen (Percent)	Gaseous Oxygen (mg/L)	Gaseous Oxygen (Torr)	Dissolved Oxygen (mg/L)
21[a]	300	159.6	8.6
19[a]	271	144.4	7.8
17[a]	243	129.2	7.0
15[a]	214	114	6.1
13[a]	186	98.9	5.3
11[a]	157	83.6	4.5
9[a]	129	68.4	3.7
7[a]	100	53.2	2.9
5[a]	91	38	2.0
3	43	22.8	1.2
1	14	76	0.4
0	0	9	0

[a] Oxygen concentrations that support aerobic biodegradation.

Performing the respiration test in situ gives the most representative results. To conduct an in situ respiration test, a vapor extraction well or piezometer must be installed with the screened interval placed within the impacted area. Good results can be obtained by using a very small vapor monitoring point (0.5-inch diameter). The well or vapor monitoring point is connected to a vacuum pump or blower, and the soil gas is evacuated (or fresh air injected) until the gas composition approaches that of air. This procedure can be done along with radius-of-influence measurements.

After the impacted soil has been aerated, the vapor monitoring point or well is sealed. Periodic gas samples are collected from the well or from nearby vapor monitoring points and they are then analyzed for oxygen and carbon dioxide. The first sample should be collected immediately after shutdown of the pump system. The next sample should be collected one hour after system shutdown. The next samples should be collected after two or three hours. Subsequent sampling times can be projected based on the changes observed in the first three samples. In situ respiration tests typically last for 24 to 96 hours depending on the level of biological activity in the contaminated soil (Hinchee et al., 1992; Hinchee and Ong, 1992). The test should be stopped after the oxygen concentration drops to 5 to 10 percent. When oxygen consumption is plotted

against time, either a linear or semi-logarithmic curve should fit the points. The slope of the curve represents the in situ respiration rate.

An important control for the in situ respiration test is the measurement of background respiration. To determine this parameter, a vapor monitoring point is placed in an uncontaminated area, the soil is aerated, and a respiration test is conducted. The oxygen consumption and carbon dioxide production rates from this area are subtracted from the results obtained from the contaminated area. The difference is the respiration resulting from contaminant biodegradation.

A useful modification to the test is the injection of helium (2 percent final concentration) as an inert tracer (Hinchee et al., 1992; Hinchee and Ong, 1992). The presence of helium in the air samples collected during the test ensures that the soil gas being collected is the same gas that was injected. This modification greatly increases the validity of an in situ respiration test and is very useful if a rigorous defense of test results is required.

The recommended equipment for the in situ respiration test is a blower (1- to 5-horsepower) and small-diameter vapor monitoring points because they require less volume for effective purging (Hinchee et al., 1992). A small pump can be used to withdraw samples from the vapor monitoring point. Soil gas oxygen and carbon dioxide can be conveniently determined using several different field methods. Comparisons of field and laboratory methods for gas analysis show that field measurements are adequate for the in situ respiration test. Laboratory confirmation is recommended only if quality control issues warrant.

Several options are available to measure oxygen and carbon dioxide in the field. Indicator tubes (Drager and Sensidyne) are available for both carbon dioxide and oxygen. Oxygen indicator tubes span a range of 5 to 23 percent. Several ranges are available for carbon dioxide indicator tubes. Low-and high-range carbon dioxide tubes, which usually provide results as parts per million volumetric or volumetric percent, should be available during the test. The Gastechtor Model 32520X (Gastech, Inc.) is an electronic instrument that provides both a direct reading oxygen and carbon dioxide detector in the same instrument. It also has an internal pump that simplifies sample collection. A confined-space-entry oxygen detector with a range of 0 to 23 percent can also be used for field oxygen measurements. A helium leak detector can be used when helium is used as an inert tracer. The precision of all these devices is adequate if a good sample is collected. A good sample is one that is truly representative of the soil gas in the impacted zone soil. Purging the vapor monitoring point is critical. Placement of the well screen within the contaminated area is also essential.

In cases where an in situ respiration test cannot be performed, soil samples can be collected and shipped for laboratory analysis. Because the test is conducted on disturbed soil, the results are less representative of actual site conditions. The laboratory

respiration test, however, has the benefit of allowing a cost-effective evaluation of nutrient delivery.

5.5 System Design and Installation

The design of the bioventing system is determined by the soil type, depth and extent of contamination, radius of influence, depth to groundwater, air permeability, and soil stratigraphy (Hinchee et al, 1992). Although the best design for a site will ultimately be decided by site conditions, two general design options have merit and should be considered during the design of a bioventing system.

5.5.1 Bioventing Wells and Well Spacing

Wells suitable for bioventing are typically very simple, consisting of a well screen section connected to a solid pipe that continues to the surface. At the surface, the solid pipe is manifolded to other wells or the air-moving equipment. The selection of well screen size is usually not critical. A 10- or 20-slot PVC well screen (slot widths of 0.010 or 0.020 inch) is a common choice. The open space in the well screen ranges between 30 and 40 percent. A key consideration in selecting a well screen is to choose a screen size that does not restrict airflow. Although a wire-wrapped well screen can be used, the extra cost is usually not justified by a significant performance increase. The length of the screened section is based on the vertical extent of contamination. In cases where significant changes in air permeability occur over the vertical extent of contamination, multiple screened areas can be installed and independently controlled to encourage air movement through soil strata of differing permeability.

The borehole for the venting well should be drilled by using a technique that does not alter the cut face of the soil. Drilling a 6- to 10-inch borehole with a hollow-stem auger is a favored method. For very deep systems air rotary drilling can be used. Mud-rotary drilling should be avoided because drilling mud alters the permeability of the cut face. Unlike groundwater wells, a bioventing well cannot be developed to improve the permeability of the cut face.

5.5.2 Well Finishing

Well diameter is determined by the volume of air to be delivered or removed and the pressure drop in the pipe. Two- to four-inch Schedule 40 PVC piping is most commonly used. The well screen and solid riser are placed in the boring, and the screened area is sand packed. A 20- to 30-mesh sand is a common choice for the sand pack. The purpose of the sand is to support the walls of the boring, provide a permeable connection between the venting well and the soil, and protect the well screen from clogging by soil fines. The infiltration of fines and clogging of the screen is a minor concern in most bioventing applications. If the water table rises above the bottom of the well screen, however, the bottom slots can become clogged and ineffective when the water table falls.

The well is sand packed over the entire screened interval and for another few feet above the screen. Bentonite or grout is used to seal the boring above the sand pack. The boring can be completely filled with bentonite/grout or back filled with soil to within a few feet of the surface. Normally, the last 4 to 6 feet of the well should be grouted to the surface. The solid piping used to connect the well to the blower can be installed on the surface or in a shallow trench.

5.5.3 Bioventing Trenches

Shallow vadose zone contamination may be best addressed by using venting trenches. Backhoes or trenchers are adequate for digging bioventing trenches. The depth of the trench is determined by the depth of contamination. After digging is completed, trenches are partially filled with gravel. Slotted pipe or corrugated, perforated, flexible drainage tubing is placed in the trench and covered with gravel. The piping is positioned in about the center of the gravel layer. The top of the gravel layer is then covered with plastic sheeting to prevent air from short-circuiting to the atmosphere. Finally, the trench is back filled with soil to the surface. The top of the gravel layer should be at least one foot below the surface. Depending on local weather and the depth to ground-water, a sump to remove water from the trench may be a useful addition to the design. The slotted/perforated piping is connected to the blower with solid PVC pipe at one or several locations in the trench. If the trench network contains multiple branches, valves to control air flow to each branch can prove useful.

5.5.4 Well Spacing and Airflow Modeling

Wells and trenches are spaced to provide adequate soil aeration. Wells also should be positioned to provide full coverage of the treatment area.

Several computer models are available that model airflow under user-defined soil permeability and injection or extraction pressures. A very useful application of these models is the estimation of airflow patterns by establishing "no flow" areas within the treatment zone. For example, the airflow pattern around a foundation, underneath a paved area, or around an abandoned underground storage tank can be modeled. Additional wells or trenches can be added to the model to achieve the desired coverage. Some models also predict the total airflow into or out of a well or trench system. This information is useful for sizing a blower or vacuum system.

5.5.5 Air Movement Equipment

Blower or vacuum system size depends on the amount of air that must be moved to replace a pore volume of soil gas in the contaminated area. A pore volume replacement rate of once every 1 to 5 days is adequate for most bioventing systems. An adequate pore volume replacement rate is indicated by the in situ respiration test. If the test indicates that most of the soil gas oxygen is consumed within 24 hours, a 1-day pore volume replacement rate should be achieved. The manufacturer's pressure and airflow tables for various blowers, compressors, and vacuum pumps are compared with

the desired flow rate to identify equipment that meets the air movement requirements of the system.

For example, on a site with 250 cubic yards of contaminated soil and a porosity of 30 percent (0.3), the soil pore space within the treatment area is 2,025 cubic feet. The pore volume divided by the replacement time will yield an approximation of the air movement rate required of the blower. Assuming a 1-day pore volume replacement rate, 2,025 cubic feet divided by 1,440 minutes per day indicates that the blower must remove or inject only 1.4 cubic feet of air per minute to effect a pore volume exchange everyday.

5.6 Bioventing Operation and Monitoring

Bioventing is usually a low-maintenance technology. The critical operating parameters include confirming that the aeration equipment (blower) is working, that air emissions meet discharge standards, and that the impacted soil is aerated. Monitoring can be extensive or very limited. A list of common monitoring parameters is shown in Table 5-2 (Sims et al., 1993; Mark-Brown, 1994; Hinchee et al., 1992). Some combination of these parameters is usually adopted to monitor the performance of a bioventing system.

The minimum monitoring protocol involves quarterly to semiannual measurements of in situ soil respiration. If the respiration test results indicate respiration above background, bioventing should continue. Typical rates range from 1 to 20 mg of hydrocarbon consumed per kg of soil per day (Hinchee and Ong, 1992). When a significant decline in respiration is observed, soil samples can be collected and analyzed to quantify the performance of the system. Samples should also be analyzed for soil moisture, pH, microbial population density, and residual nutrients.

Depending on the contaminant, 3 to 3.5 parts of oxygen are required to bio-oxidize 1 part of hydrocarbon. Using this stoichiometry, an estimate of contaminant biodegradation can be made. The biodegradation rate for hydrocarbons (based on hexane with units of mg of hydrocarbon per kg of soil per day) is estimated by using the following equation (Hinchee et al., 1992):

$$K_B = -K_0 A D_0 C/100$$

where:

K_B = hydrocarbon biodegradation rate (mg/kg per day)
K_0 = oxygen utilization rate (percent/day)
A = volume of air/kg of soil (L/kg)
D_0 = density of oxygen gas (mg/L)
C = mass ratio of hydrocarbon to oxygen required for mineralization.

Table 5-2. Suggested Groundwater Monitoring Parameters for Bioventing

Parameter	Method
Contaminant	Varies with contaminant
Oxygen (soil gas)	Field analysis with a direct-reading instrument or colorimetric indicator
Carbon Dioxide (soil gas)	Field analysis with a direct-reading instrument or colorimetric indicator
Methane (soil gas)	Field analysis with a direct-reading instrument or SW-846 Method 8020
Soil Moisture	Gravimetry
pH	Field analysis with pH electrode or SW-846 Method 150.1
Ammonia	SW-846 Method 350.1 or 350.2; Standard Method 4500-NH_3
Phosphate	SW-846 Method 365.1, 365.2, or 365.3
Total Kjeldahl Nitrogen	SW-846 Method 351.1
Microbial Density	Spread Plate or Most Probable Numbers (MPN) Methods (usually modified for environmental samples)
In Situ Respiration Rate	Field Testing and Analysis in Changes of 0_2 and $C0_2$ Concentrations Over Time

"K_0" is determined directly from the in situ respiration test. "A" is calculated assuming a soil porosity of 0.3 and a soil bulk density of 1,440 kg/m^3, yielding 0.3 L of air/kg of soil/1.440 kg/L or 0.21 liter of air per L of soil. "D_0" is typically assumed to be 1,330 mg/L, although this value varies with temperature, barometric pressure, and altitude.

"C" assumes the following chemical stoichiometry for the biological oxidation of hydrocarbon. Hexane is routinely used as a typical hydrocarbon in these calculations.

$$C_6H_{14} + 9.5\ O_2 \rightarrow 6CO_2 + 7\ H_2O$$

Given that oxygen (O_2) has a molecular weight of 32 and hexane has a molecular weight of 86, the mass of oxygen required to oxidize one mole of hexane is given by:

$$C = (\text{Molecular Weight of Hexane})/[(\text{Molecular Weight of } O_2)\ 9.5]$$

$$C = 86/304$$
$$C = 0.28$$

The mass of hydrocarbon biodegraded within the treatment area is calculated by the following equation:

$$B = K_B M/10^6 \text{mg/kg}$$

Where:

- B = kilograms of hydrocarbon degraded per day
- K_B = average hydrocarbon consumption (biodegradation) rate in mg/kg per day
- M = kilograms of soil within the treatment area.

Most practitioners recognize that bioventing is a slow process. The U.S. Air Force predicts that up to 10 years will be required to remediate most of its petroleum-impacted sites using bioventing. The most hazardous constituents (benzene, toluene, ethyl benzene, and xylenes [a.k.a. BTEX]) are also the most biodegradable, however, and they should remediate much faster.

5.7 Bioventing Conclusions

Bioventing is an emerging technology that combines features of SVE and in situ bioremediation. The technology permits the in situ treatment of vadose zone soil impacted with any biodegradable contaminant. Bioventing has the potential to meet several important needs in waste management and remediation. Bioventing should be considered the primary or supplemental treatment technology for contaminated vadose zone soil that cannot be excavated.

5.8 Intrinsic Bioremediation: Process Overview

Intrinsic bioremediation is the preferred term to describe the natural biological processes that lead to contaminant biodegradation. Intrinsic bioremediation can occur in any environment that supports microbiological activity. The rate of biodegradation may be slow, however, because of the lack of a suitable respiratory substrate (such as oxygen) or inorganic nutrients (such as fixed nitrogen), an extreme pH, low soil moisture, or limited contaminant bioavailability. Elimination of the contaminant source is essential for the successful application of intrinsic remediation. Accurate delineation of contamination, an understanding of subsurface conditions and characteristics, as well as an understanding of contaminant migration rates and direction are critical for evaluating the success of intrinsic remediation and for establishing regulatory support

for its use at a site (Davis, Klier, and Carpenter, 1994; Davis et al., 1994; Wisconsin Department of Natural Resources, 1993).

Several criteria should be considered before choosing intrinsic bioremediation as the principal remedial technology (Wisconsin Department of Natural Resources, 1993). These include:

- Risk of further environmental damage
- Risk of human endangerment
- Detrimental consequences to local flora and fauna
- Technical feasibility, practicality, and effectiveness of other technologies
- Site-specific evidence for successful application of intrinsic bioremediation
- Cost of intrinsic bioremediation compared to other options.

When these issues can be addressed in favor of intrinsic bioremediation, the technology is a cost-effective and practical remedial alternative for soil and groundwater.

5.8.1 Intrinsic Bioremediation in the Vadose Zone

Intrinsic bioremediation has been shown to be effective in the vadose zone. The frequent observation of low oxygen and high carbon dioxide and methane in the soil gas within a hydro-carbon plume is indicative of intrinsic microbial activity.

Without an engineered process to supply oxygen, hydrocarbon plumes become anaerobic and the biodegradation rate drops dramatically. Under natural conditions, reaeration of the soil is dependent on diffusion, barometric pressure changes, and oxygenated rainwater infiltration. In areas where the water table is influenced by tides, the daily rise and fall of the water table may act as a pump to displace oxygen-depleted soil gas.

Lacking oxygen, biodegradation can be supported by nitrate and sulfate; however, this is probably not common in the vadose zone because nitrate and sulfate are very soluble and leach into the groundwater. Methanogenic biodegradation is a common anaerobic process in contaminated vadose soil.

The principal difficulty in applying intrinsic bioremediation in the vadose zone is proving that remediation is occurring. Two factors work together to make definitive proof of remediation challenging. First, intrinsic bioremediation is a slow process. Second, variability in soil samples makes analytical proof of reduction in contaminant concentration difficult until large concentration changes have occurred. This may take several years and be further complicated by plume dispersion, diffusion, and migration.

Parameters that indicate the occurrence and effectiveness of intrinsic bioremediation in the vadose zone are ill-defined. The following suggestions, however, highlight some of the more useful approaches for quantitating intrinsic vadose zone bioremediation.

5.8.2 Monitoring Parameters for Intrinsic Vadose Zone Bioremediation

The chemical constituency of the original petroleum product and the chemical profile of contaminants in the soil evaluated over time can indicate the occurrence and magnitude of intrinsic bioremediation. In the case of a gasoline spill, the original product will contain an identifiable mix of chemicals. Over time, the chemical profile will change. The earliest and most obvious changes will occur in the volatile organic compounds, especially benzene, toluene, ethyl benzene, and xylenes (BTEX). In addition to changes in concentration, the relative ratio of the BTEX constituents will also change. This preferential loss of chemicals may indicate biodegradation. For example, toluene and xylene tend to biodegrade faster under anaerobic conditions than do benzene and ethyl benzene. The hydrocarbon "fingerprint" will also be shifted toward a higher ratio of heavy hydrocarbons because high-molecular-weight hydrocarbons tend to biodegrade at a slower rate than the low-molecular-weight compounds. The fingerprint of most hydrocarbon fuels will change with time. Physical and biological processes contribute to the "weathering" process (Wilson, 1993).

The soil gas composition can also indicate intrinsic biodegradation. The occurrence of methane in subsurface soil is uncommon in most areas; however, methane is often associated with soil gas within petroleum-contaminated vadose zone soil. Similarly, the oxygen concentration is frequently very low and the carbon dioxide concentration is high. Biological activity is responsible for these changes. Additionally, the total petroleum hydrocarbon (TPH) and VOC content of the soil gas should eventually decrease as intrinsic biodegradation proceeds. The long-term rate of petroleum biodegradation cannot be determined from simple measurements of soil gas composition. Biodegradation rates can be estimated, however, by determining the rate at which changes in soil gas composition occur (Hinchee et al, 1992; Hinchee and Ong, 1992).

Restricted plume migration and, especially, demonstration of reduced plume dimensions are also indicative of intrinsic biodegradation. Such observations support intrinsic biodegradation as a viable approach for limiting plume migration and treating the contaminant. The process will be very time consuming, and periodic soil and soil gas samples should be collected to determine current conditions and contaminant concentration in soil and soil gas. As long as intrinsic biodegradation is preventing further damage to the environment and monitoring supports contaminant reduction, intrinsic bioremediation can be a cost-effective and practical way to treat a site. The principal cost element during intrinsic bioremediation is monitoring to ensure that biodegradation is occurring and that further environmental degradation is not occurring.

5.8.3 Intrinsic Bioremediation in the Saturated Zone

In contrast to the vadose zone, a growing body of published literature and field experience is available to guide the application of intrinsic bioremediation in the saturated zone (Wisconsin Department of Natural Resources, 1993). Several approaches are available to demonstrate the effectiveness of intrinsic aquifer bioremediation. Because these approaches provide indirect or circumstantial evidence, a set of results

highlighting multiple indicators of intrinsic aquifer bioremediation is usually required to construct a convincing demonstration.

Site hydrogeology is extremely important in evaluating intrinsic bioremediation in groundwater. Groundwater flow rate, recharge rate, vertical and horizontal location of the contaminant within the aquifer, and the geological characteristics of the aquifer influence the interpretation of data collected to evaluate intrinsic bioremediation.

5.8.3.1 Contaminant Monitoring

A decrease in contaminant concentration is an important indicator of intrinsic bioremediation; however, physical losses must be accounted for before biodegradation can be accepted. Contaminant diffusion, dispersion, and adsorption to soil can be estimated by identifying a conserved constituent in petroleum fuel spills. Trimethyl benzenes and 2,3-dimethyl pentane have been used as conservative indicator compounds for jet fuel and gasoline plumes.

Key characteristics of a useful conserved indicator compounds are poor anaerobic biodegradability and chemical properties similar to target contaminants. Because dissolved hydrocarbon plumes undergoing intrinsic bioremediation are anaerobic, compounds that are not susceptible to anaerobic biodegradation persist and are influenced primarily by physical processes. The change in concentration observed as the dissolved contaminant plume moves through the aquifer is used to estimate physical losses likely to also occur with compounds more susceptible to anaerobic biodegradation. The difference between the expected physical reduction in concentration and that observed is attributed to biodegradation.

Another useful comparative analysis involves examining the ratio of one target contaminant to another. This approach is commonly applied when BTEX are the principal contaminants. Toluene and xylenes biodegrade under anaerobic conditions at a greater rate than do benzene and ethyl benzene. Toluene-to-benzene ratios at points down-gradient from the source of contamination typically show a change from a large toluene-to-benzene ratio (more toluene than benzene) to a smaller ratio (more benzene than toluene). Fresh gasoline may have up to 10 times as much toluene as benzene, and groundwater exposed to gasoline may have several times more dissolved toluene as benzene. Down-gradient portions of a dissolved-phase gasoline plume usually have more benzene than toluene. This change in the toluene-to-benzene ratio is due to the more rapid biodegradation of toluene under anaerobic conditions. Benzene biodegradation can also be established by comparing benzene concentrations with compounds whose anaerobic biodegradation rate is less than benzene, such as 2,3-dimethyl pentane or trimethyl benzenes.

Intermediate biodegradation products can be used to evaluate intrinsic biodegradation in some cases. Trichloroethylene and other halogenated solvents are anaerobically

biodegraded through dehalogenation reactions that yield identifiable intermediates. Intermediates observed during anaerobic reduction of trichloroethylene (TCE) include dichloroethylene, vinyl chloride, and ethene (ethylene).

Unfortunately, the chlorinated intermediates associated with the intrinsic biodegradation of polychlorinated aliphatic hydrocarbons are typically less susceptible to further anaerobic degradation than is the parent compound. Demonstrating that a poly-chlorinated aliphatic compound such as TCE is being converted to dichloroethylene (DCE) does not imply that complete bioremediation will follow. Anaerobic removal of chlorine atoms from a hydrocarbon usually leads to greater aerobic biodegradability; however, aerobic biodegradation is impeded by the lack of oxygen in proximity to the newly formed intermediate.

5.8.3.2 Microbially Induced Changes in Groundwater Chemistry

Actively respiring microorganisms alter their environment. Changes may go unnoticed if the local environment is dynamic enough to compensate for microbially induced changes. In many cases, the rate of microbial-induced change within a dissolved contaminant plume exceeds the capacity of the local environment to compensate; the result is that the dissolved contaminant plume has chemical characteristics different from surrounding groundwater (Wisconsin Department of Natural Resources, 1993).

5.8.3.3 Respiratory Substrate Concentrations

Microbes can use several inorganic compounds as the terminal electron acceptor for their respiratory pathways. Frequently encountered terminal electron acceptors or respiratory substrates include oxygen, nitrate, sulfate, and carbonate. Iron and manganese can also serve as respiratory substrates; however, their contribution to intrinsic bioremediation is ill-defined. Respiratory substrates are used preferentially in the following order:

$$O_2 > NO_3^- > Mn^{+4} > Fe^{+3} > SO_4^{-2} > CO_2$$

Differences between respiratory substrate concentration in contaminated groundwater and nearby clean groundwater can be used as an indirect indicator of intrinsic bioremediation. Much lower dissolved oxygen in the contaminated portion of the aquifer suggests that microbial activity has depleted the oxygen in the groundwater. This interpretation is valid if the aquifer does not have a high chemical oxygen demand because of contamination. Lower nitrate content in the contaminated area indicates anaerobic nitrate-reducing activity. Microbes are known to biodegrade hydrocarbons under nitrate reducing conditions. Sulfate-based respiration is often detected by measuring sulfide, the product of respiration. Similarly, carbonate-based respiration results in the production of methane. Correlation of changes in the groundwater content of any of these parameters and the location of a contaminant plume can be indicative of intrinsic bioremediation.

5.8.3.4 Redox Potential, pH, and Other Water Quality Parameters
Table 5-3 lists groundwater parameters that may identify microbiologically mediated changes within the contaminated plume (Wisconsin Department of Natural Resources, 1993). These parameters are not always helpful; however, until the intrinsic bioremediation process is better understood, collection of a variety of data is recommended. As intrinsic bioremediation proceeds and key monitoring elements are identified, less-useful parameters can be eliminated from site-specific monitoring plans.

5.8.4 Intrinsic Bioremediation Rate Estimates

The rate of intrinsic bioremediation can be estimated from the down-gradient change in contaminant concentration when physical loss can be approximated (Wiedemeier et al., 1994). For example, if wells are placed within the dissolved contaminant plume in a line that follows the down-gradient flow path and are spaced to give a 1-year travel time between each well, the intrinsic biodegradation rate can be calculated. Monitoring data from the wells provides contaminant concentration change over time. By correcting for physical losses, the biodegradation rate and contaminant half-life can be calculated by using a first-order decay equation of the form:

$$C_t = C_o e^{-kt}$$

Where:

C_t = concentration after time (concentration in down-gradient well corrected for physical losses)
C_o = starting concentration (concentration in up-gradient well)
t = time (time required for contaminant to travel from the "C_o" well to the "C_t" well)
k = biodegradation rate constant.

Contaminant half-life is given by:

$$t_{1/2} = (\ln 2)/k$$

5.9 Computer Modeling of Intrinsic Bioremediation

The most widely used model for intrinsic bioremediation is BIOPLUME II, developed at Rice University and available from the U.S. EPA. BIOPLUME II can provide accurate two-dimensional simulations of biodegradation if extensive field data are available to calibrate the model. Unfortunately, one of the most significant uses of computer modeling for intrinsic bioremediation is to project a relatively accurate long-term model of biodegradation under natural conditions with limited data.

BIOPLUME II models groundwater and contaminant movement by using aquifer characteristics, and it separately models the distribution and movement of oxygen within the aquifer. The oxygen and contaminant plume models are computationally superimposed, and the contaminant and oxygen are instantaneously consumed in

Table 5-3. Suggested Groundwater Monitoring Parameters for Intrinsic Bioremediation

Parameter	Method
Contaminant	Varies with contaminant
Total Organic Carbon	SW-846 Method 415.1 or 415.2
Methane	SW-846 Method 8020
Dissolved Oxygen	Field analysis with dissolved oxygen meter
Oxidation/Reduction Potential	Field analysis with Oxidation/Reduction (Redox) Potential (ORP) electrode
pH	Field analysis with pH electrode
Temperature	Field analysis with thermometer
Conductivity	Field analysis with conductivity meter; SW-846 Method 120.1
Ammonia	SW-846 Method 350.1 or 350.2; Standard Method 4500-NH_3
Phosphate	SW-846 Method 365.1, 365.2, or 365.3
Total Kjeldahl Nitrogen	SW-846 Method 351.1
Nitrate	SW-846 Method 352.0 or 352.2
Nitrite	SW-846 Method 354.1
Sulfate	SW-846 Method 375.2 or 375.4
Sulfide	SW-846 Method 376.1
Alkalinity	SW-846 Method 310.1
Chloride	SW-846 Method 325.3; Standard Method 4500-Cl^-
Iron (II)	Standard Method 4500-Fe
Microbial Density	Spread Plate or Most Probable Numbers (MPN) Methods (usually modified for environmental samples)

stoichiometric proportions of three parts oxygen per part contaminant. Oxygen can be added to the aquifer model from the vadose zone by advective transport from oxygenated groundwater and by direct injection via wells. Anaerobic biodegradation is modeled by a single anaerobic decay constant that does not accurately reflect the complex processes occurring in a multicomponent hydrocarbon plume. Additionally, the dissolution of contaminants into the groundwater is not easily incorporated into the model. Computer simulations specifically designed to estimate and model intrinsic bioremediation are being developed but are not currently available.

A one-dimensional numerical computer model occasionally used to model intrinsic bioremediation is BIO1D (GeoTrans, Inc.). Computer models are presently not available for vadose zone intrinsic bioremediation.

5.10 Combined Treatment Strategies

An attractive treatment strategy for contaminated vadose zone soil and groundwater involves bioventing and intrinsic bioremediation. Vadose zone contamination is frequently the source of groundwater contamination. Bioventing in source areas can be an affective approach to eliminate the dissolution, diffusion, and leaching of contaminants into the groundwater. Without a constant recharge of contaminants, intrinsic bioremediation in the groundwater can limit plume migration and ultimately reduce contaminant levels to acceptable or even nondetectable levels.

A combined treatment strategy has the potential to be expedient and cost-effective. In some cases, it may be the only feasible alternative. Approaches applying cost-effective, minimum-action technologies deserve full consideration during development of site remediation plans. In the end, they may be just as effective as more expensive and complex technologies.

Chapter 6
In Situ Air Sparging

6.1 Introduction

Soil vacuum extraction is a cost-effective method for removing volatile contaminants from the unsaturated zone. Much of the residual product remaining in the subsurface following completion of free product removal, however, is located within the liquid saturated zone. Several options are available to remove residual product in the saturated zone, including:

- Pump-and-Treat, which involves long-term pumping of contaminated water to gradually remove soluble components as they become dissolved in groundwater.

- Enhanced Bioremediation, where oxygen and nutrients are added to the subsurface to stimulate microbial activity in conjunction with pump-and-treat.

- SVE/Pump-and-Treat, which involves pumping water primarily to draw down the water table and is used concurrently with SVE to remove exposed residual product.

- SVE/In Situ Air Sparging, which involves injecting air below the water table in conjunction with the use of SVE to remove volatile contaminants.

The major limitation of the pump-and-treat technology for remediating groundwater containing residual hydrocarbon is that removal rates are limited by the low solubility of some hydrocarbon components. This constraint results in lengthy remediation programs.

Biodegradation can be used to enhance the pump-and-treat system by remediating residual hydrocarbons that are not removed during its use. The occurrence of bio-degradation in natural groundwater varies depending on the dissolved oxygen content of the aquifer and the presence of other factors affecting microbial population (e.g., oxygen level, pH, nutrients, temperature).

The design and operation of SVE/pump-and-treat systems is identical to that for normal SVE systems, except that water pumping is employed to maximize the air-permeated zone.

In situ air sparging is a recently introduced technology that utilizes in situ volatilization to remove volatile components from residual NAPL or dissolved-phase contaminants present below the water table. Because of the large variation in the systems being applied and general lack of understanding of the effectiveness of these systems, the discussion will be limited to the principles of operation of these methods and their potential advantages and limitations.

As with SVE, air sparging has broad appeal because it is simple to implement and capital costs are moderate. Air sparging technology is still in its infancy, however. In addition, air sparging has not been employed on a routine basis, nor has it been subjected to adequate research or rigorous field investigations. A limited number of air sparging operations and pilot tests have been evaluated; some of these were effective, while several were not (Marley, et al., 1992, 1994; University of Wisconsin, 1992; Hazmat World, 1994).

In situ air sparging involves injecting clean air through wells or horizontal pipes that have been installed in saturated porous media (i.e., below the water table). As shown in Figure 6-1, the injected air streams upward from the well screen through contaminated groundwater and saturated contaminated soil, displacing groundwater as it moves upward. Volatile organic compounds (VOCs) in close proximity to the air stream partition into the vapor phase. The organic vapors are transferred to the vadose zone where they can be recovered by an SVE system. The volatilization and transfer of organics from below the water table to the vadose zone is intended primarily for organic compounds with high vapor pressures. The oxygen introduced to the groundwater system causes a secondary benefit--the enhancement of aerobic microbial degradation of organic compounds, including compounds other than VOCs.

A typical air sparging system using a vertical well configuration is shown in Figure 6-1. The system consists of an oil-free compressor manifolded to one or more air sparging wells and an SVE system. The following should be considered in selecting system components:

- Oil-free reciprocating compressors may be used, but are often rated for intermittent service.

- Continuous-duty oil-free reciprocating compressors are substantially more costly.

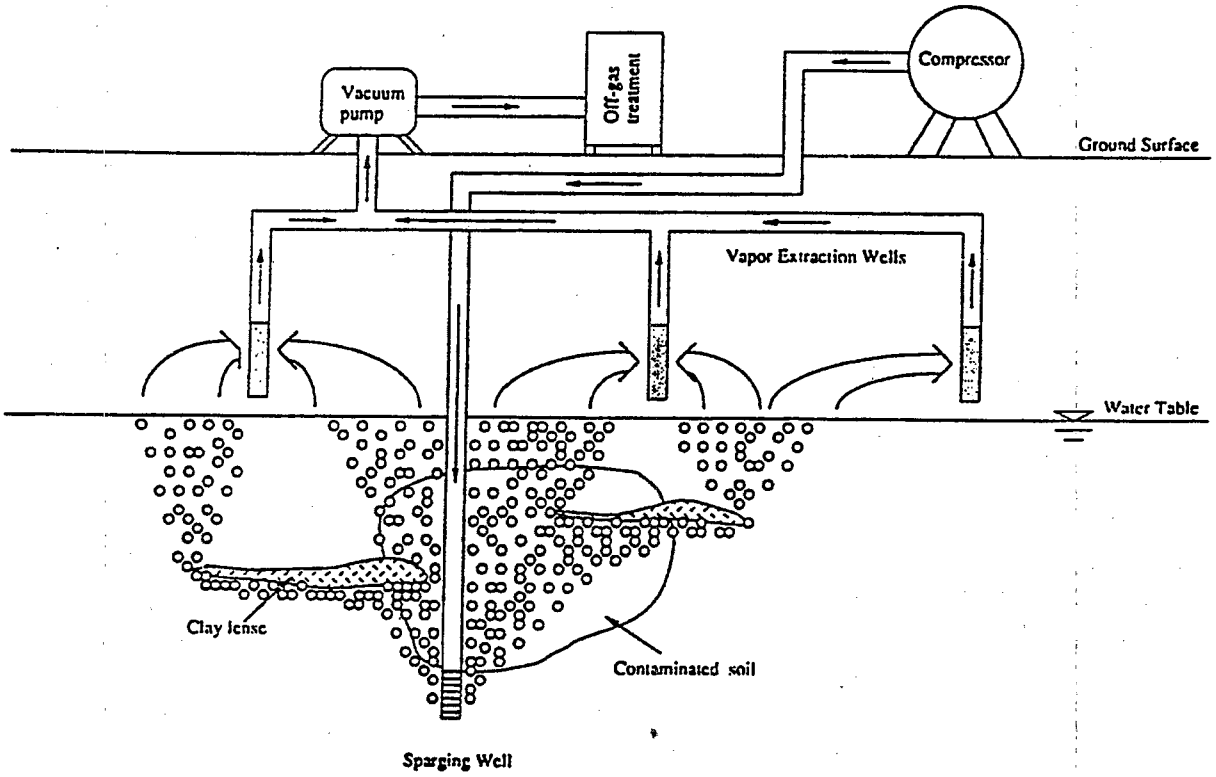


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Figure 6-1. Typical in situ air sparging - soil vapor extraction system (Ground Water, 1993).

- Continuous-duty rotary screw compressors may be used; however, filtration systems must be employed because these compressors are not oil-free.

- Distribution manifolds should be gauged and regulated at each air sparging well to control air pressure and airflow individually.

- Check valves are needed between the regulator and the sparging well to ensure that water will not be forced into the manifold by back pressure in the formation when manifold pressure is decreased.

- The sparging well point may consist of a well screen or air diffuser in a sand filter pack.

- The sparging well casing should be grouted in with bentonite or non-shrinking cement to prevent possible short circuiting of air along the well casing.

The aboveground equipment necessary for an air sparging system includes an air compressor, a main header pipe for the compressed air, pressure regulators, and valves to control the rate of airflow into each air sparging well. The number, design, and spatial arrangement of wells for an air sparging system depend on the type and concentration of contaminants, spatial heterogeneities of the geologic media, air permeability characteristics of the geologic media, and cleanup requirements desired for the groundwater and saturated geological media. These topics will be discussed further in this Section.

Air sparging wells can be placed below the water table by use of vertical, horizontal, or angle drilling techniques. Horizontal pipes can also be placed in trenches dug below the water table, which are backfilled with coarse sand or gravel. As long as the screen interval is below the water table and the annulus around the casing above the screen is sealed properly, air can be forced down the casing, through the screen, and into the adjacent formation. Well placement/configuration depends on site conditions and remediation goals and will be somewhat unique for each application. In general, air is injected into the saturated media about 5 feet vertically below the zone(s) of greatest contamination. This placement allows the injected air to spread laterally away from the well and to contact contaminated media as it rises.

In vertical wells, air displaces water down the inside of the casing and then exits the well near the top of the well screen; a similar arrangement occurs for a well placed at an angle. The buoyancy of the air will not allow it to displace water much below the top of the screen before it flows laterally through the screen and migrates upward. Thus, only short well screens (e.g., 1 to 3 feet in length) are needed for air sparging purposes. In a horizontal well or a horizontal pipe placed in a trench, a long horizontal screen is

placed below the water table and air can be introduced to the formation over a long lateral distance (Figure 6-2).

In the selection and design of in situ air sparging systems, the following factors are critical to an effective application of this technology: air injection pressure, airflow features, soil heterogeneity and mass transfer, and vertical and horizontal placement of sparging well points.

6.1.1 Air Injection Pressure

In order for air to enter soil from the sparging well point, a minimum air pressure, P_{min}, must be maintained. This pressure is described by:

$$P_{min} = g\ \rho_{\omega}\ D + P_d^s + P_d^{\omega} \tag{6-1}$$

where:

g	=	gravitational acceleration
ρ_{ω}	=	density of water
D	=	depth below the static water table where the sparging well is placed
P_d^s	=	air entry pressure for the soil
P_d^{ω}	=	air entry pressure of the sparging point (measured at injection well).

Installation of sparging wells more than a few meters below the water table becomes increasingly prohibitive because of the high pressure required to overcome the hydrostatic head. (Note that one atmosphere of pressure corresponds to 10.2 meters or 34 feet of water head.)

The sparging air entry pressure is a function of the pore size of the diffuser unit and the sand pack pore size through which air (or gas) is introduced into the formation. Diffuser/sand pack pore size controls the bubble size of air injected into the soil. Theoretically, smaller air bubbles should provide greater mass transfer efficiency between contaminated soil and air. If bubbles coalesce (i.e., create an air mass) in the soil or in the sand pack between the sparging well and the soil, however, mass transfer efficiency will be significantly decreased. For this reason, very fine-grained sand should be used for the sand pack to maximize bubble dispersion.

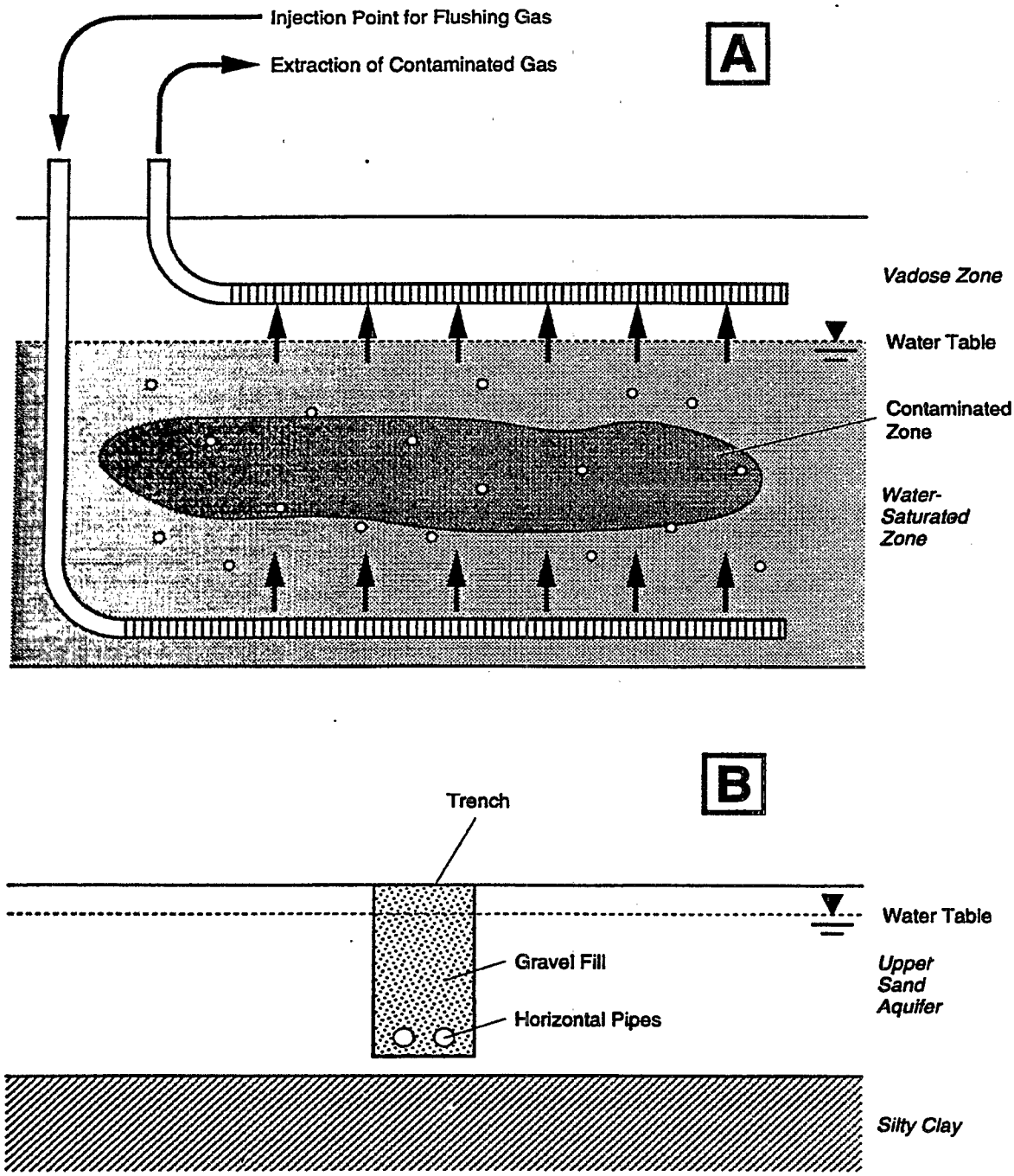

Figure 6-2 Air sparging systems using horizontal wells (A) or pipes placed in trenches (B).

If capillary characteristics of the soil can be described by the Brooks-Corey capillary pressure model, the soil air entry pressure is defined by:

$$P_d^s = g\,\rho_\omega\,h_d \tag{6-2}$$

where h_d is the air entry head.

Typical values of the air entry head can range from a few centimeters for sandy soils to over 1 meter for clayey soils. This technology is not suited for use in fine-grained soils (e.g., silts and clay) because of the high pressures required to initiate airflow and the low flow rates that can be achieved. If the soil matrix is layered (e.g., sandy soils with interlayers of clays), the relevant soil air entry pressure will be that of the finest soil layer between the sparging well and the unsaturated zone (i.e., the upper limit of the natural capillary fringe).

It is imperative that the seal between the sparging well casing and the soil above the diffuser unit have an air entry pressure higher than the applied pressure. Excessive air pressures may cause the seal to fail, resulting in short-circuiting of air along the well bore. Excess pressure may also cause secondary permeability channels to develop.

6.1.2 Airflow Rate

Once the minimum air pressure, P_{min}, is achieved, the minimum sustainable airflow rate, Q_{min} (measured at the injection well), will be obtained. Nonturbulent airflow is described by Darcy's law. For vertical well air sparging systems, the contaminant removal rate is directly related to airflow rate, air injector pressure, and the mass transfer rate of contaminant from soil. The airflow rate will generally increase nonlinearly with increasing pressure, and the rate of contaminant removal will be equal to the product of airflow rate and gas phase concentration.

As air pressure is increased, air pressure gradient and air permeability also increase. The change in air pressure gradient can be described by the regulated air pressure minus diffuser pressure drop divided by distance below water table. The increase in air permeability is due to an increase in air-water capillary pressure.

As the airflow rate increases, the rate of contaminant removal increases. Because the rate of mass transfer from the soil to the air is generally diffusionally limited, however, the concentration of contaminants in the air will commonly decrease as airflow rate increases. For diffusion-limited sites, as the rate of removal increases, the removal efficiency (i.e., mass contaminant removed per volume of gas injected) diminishes with flow rate.

Pulsed airflow is sometimes used to overcome mass transfer limitations and provide greater removal efficiency. It should be recognized that the price of higher efficiency

will be a lower mass removal rate because the total flow is lower for pulsed systems than for continuous flow systems.

6.1.3 Heterogeneity And Mass Transfer Considerations

Because air has a much lower viscosity than water and a much higher relative permeability, except at very low gas saturations, air mobility is much greater than water in soils. Because of this large contrast in mobility, coupled with the high gradient imposed on the gas phase, the following phenomena occur:

- *Unstable flow* during water displacement
- Channeling of the unstable fluid through the soil in fingers
- No uniform movement of air as a front of constant saturation.

Unstable flow results when the displacing fluid (air) encounters differences in soil pore size and moves rapidly through pores that offer a path of least resistance. Even small heterogeneities that occur in the most uniform soil will induce such instabilities (see Figure 6-3). Larger scale heterogeneity, such as lenses of different texture, can exacerbate the instability and lead to yet more random flow patterns (see Figure 6-4).

The nonuniformity of gas flow patterns has important implications to the efficiency of contaminant removal during air sparging. Because air velocity in flow channels (fingers) is quite high and the spacing between fingers may be great, equilibrium will not be achieved between the contaminant in the flowing gas and that in the stagnant regions between fingers. Following an initial flush of high concentration as contaminants are removed within the flow channels, mass transfer to the flowing gas will be limited by the rate of aqueous diffusion and convection in the water, to the extent the latter occurs. The phenomenon of diffusion-limited mass transfer has certain implications compared with SVE. The processes are identical for air sparging, but the main factor controlling the mass transfer rate now is the average size and spacing between fingers (Figure 6-5).

Remediation time is reduced with an increase in the following:

- Airflow rate
- Air channel diameter and frequency
- Diffusion gradient.

However, the gain in mass transfer rate will generally be less than proportional to the increase in flow rate, so that the net efficiency (in terms of mass removed per volume of gas) will be lower.

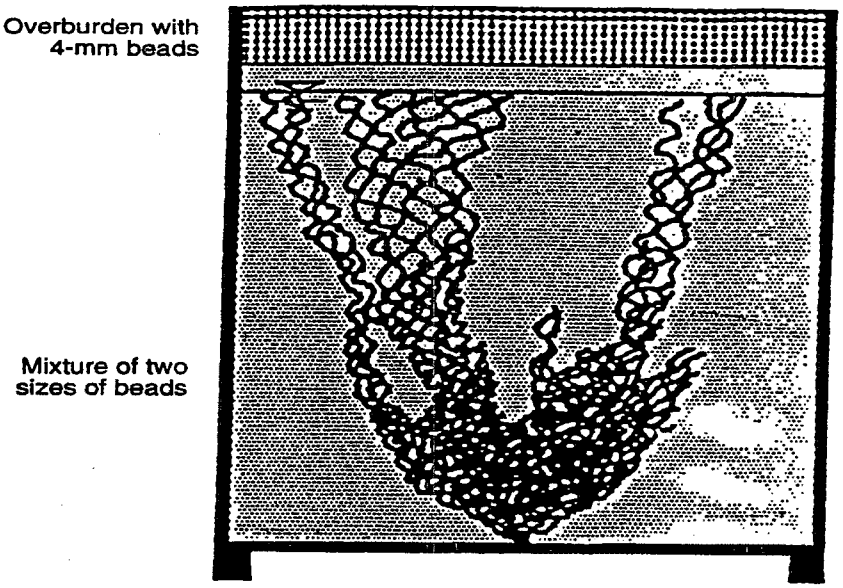

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Figure 6-3. Observed air channel pattern in uniform mixture of 0.75- and 0.3-mm glass beads (Ground Water, 1993).

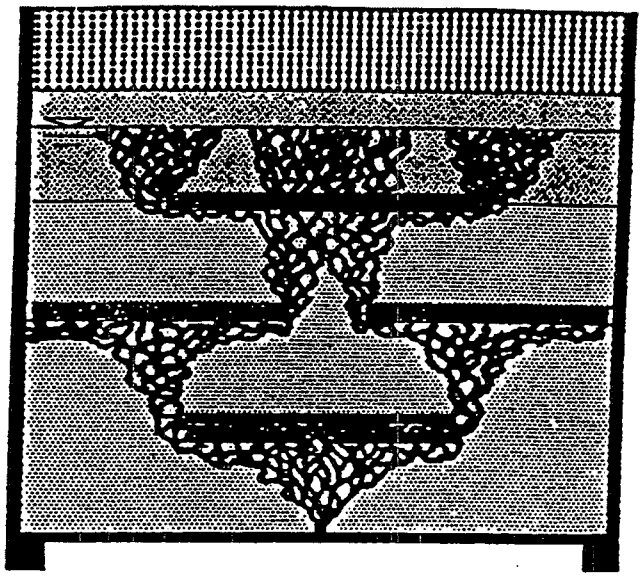

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Figure 6-4. Observed air channel pattern in stratified medium (Ground Water, 1993).

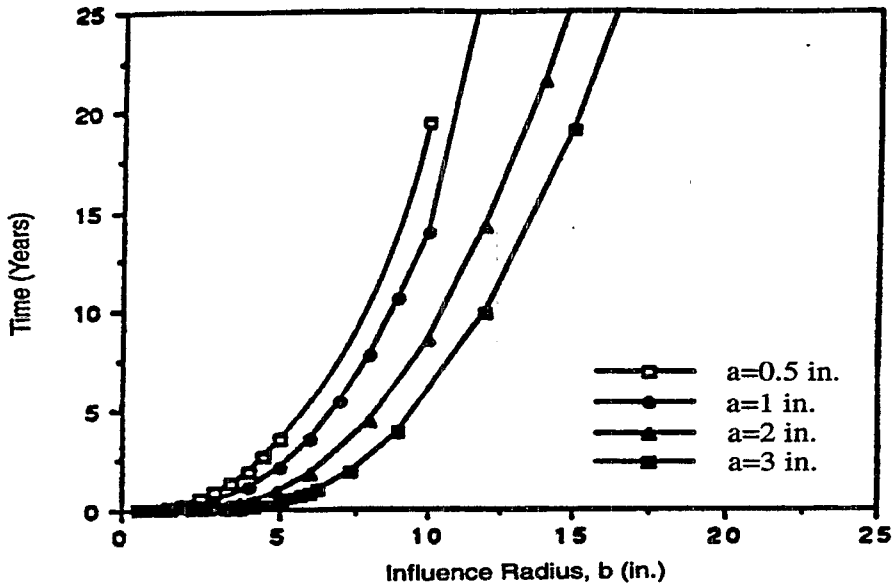

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Figure 6-5. Theoretical dependence of remediation time on air channel radius "a" and average spacing between channels (b) at a constant flow rate (Ground Water, 1996).

6.1.4 Contaminant Type

In general, constituents that are easily removed from contaminated groundwater through traditional air stripping processes are considered to be well suited to removal by *in situ* air sparging systems. Interactions (e.g., soil absorption and retention effects) within the subsurface may limit the effectiveness of this process. Lighter petroleum constituents are most amenable to air sparging (C_3-C_{10}) (Marley et al., 1992).

Enhanced air sparging techniques are being investigated that may influence less-volatile constituents. Examples of these enhanced techniques include combinations of air, ozone, and/or hydrogen peroxide as injected gas to provide increased oxidation or biodegradation potential for semivolatile constituents.

6.1.5 Vertical and Horizontal Placement of Sparging Well Points

The screened interval of sparging wells is usually no greater than 1 to 3 feet in length because nearly all of the airflow will occur very close to the top of the screened interval where the hydrostatic water pressure is lowest. The depth selected for placement of sparging points below the water table will depend on several factors. In particular, sparging points should be placed beneath residual product and at the greatest depth that contamination is found (as determined by soil analysis). In addition, the radius of

influence of a sparging well generally increases with height above the sparging point; thus, the greater the depth of placement below the contaminated zone, the greater the areal sweep of the well and the fewer wells that need to be installed.

In fairly uniform soils, the zone of influence is roughly parabolic in shape. As a general rule, the diameter of the zone of influence will be about 0.5 to 1.5 times the distance above the sparging point. Intermittent layers and other heterogeneities can greatly affect the pattern of airflow, however, thus making an evaluation of the effective diameter one of the most difficult issues in system design.

The factor that must be considered in deciding placement depth is the pressure required to overcome the hydrostatic head of water. For every foot below the water table that the system is placed, the gas pressure must be increased by 0.43 psi.

6.1.6 Other Factors

In addition to uncertainties concerning the effects of soil heterogeneity and flow channeling on remediation effectiveness, the following little-known factors may also affect recovery:

- Enhanced biodegradation from increased aeration via air sparging
- Potential for remobilizing residual NAPL in groundwater
- The further enhancement of biodegradation by the "airlift pump effect."

Air sparging will cause an increase in water pressure at the sparging point. This increase could have various effects. First, it should produce a circulation field in the groundwater near the sparging well. It also could distribute oxygen and bring dissolved contamination to the sparge point where volatiles may be stripped. Finally, the effect could result in migration of volatile contaminants beyond the zone of influence of the sparging wells. The importance of these effects has not been demonstrated, however, and is not well understood.

Another possible effect of sparging is the potential for remobilizing residual NAPL present in the saturated zone because of the change in capillary pressures induced by elevated gas pressures. Pulsed sparging may induce additional dynamic effects that could cause NAPL movement. Remobilization of NAPL could have the beneficial effect of enhancing mass transfer processes by increasing the interfacial surface area between NAPL and water. NAPL mobilization, however, could also result in movement to previously uncontaminated areas. Field studies by Ground Water (1996), for example, have found increased concentrations of dissolved contaminants downgradient of air sparging wells.

6.1.7 Applicability

An air sparging system, if properly designed, installed, and operated, can reduce contaminant concentrations in groundwater and saturated soils. Air sparging is most

applicable if the contaminants are VOCs and the extent of contamination is limited to the upper 5 to 30 feet of a shallow, water-table aquifer. Air sparging technology is more successful and controllable if the aquifer is relatively homogeneous and free of low-permeability layers of silt, clay, or other geologic materials. The volatilization of organics is most effective if the VOCs have a high vapor pressure and volatilize easily.

In many cases, indigenous microbes may be stimulated by the introduction of oxygen during air sparging and cause a significant reduction of hydrocarbons in the groundwater and on the saturated soils. This result is particularly likely for fuel-related hydrocarbons.

6.1.8 Potential Limitations and Disadvantages

Air sparging is a technology primarily intended for easily volatilized organic compounds. It also is appropriate for organic compounds that are biodegraded quickly when oxygen is supplied. For many nonvolatile organic compounds, such as polynuclear aromatic hydrocarbons (PAH) and some chlorinated hydrocarbons, air sparging would probably not be appropriate or effective for remediation.

Because an air sparging well typically has a zone of influence smaller than a pumping well capture zone, more air sparging wells are needed to cover equal areas. As the depth to groundwater increases and the thickness of the aquifer decreases, air sparging becomes less cost-effective relative to a pump-and-treat system. Thus, air sparging is more attractive for use with shallow water-table aquifers.

Air sparging is normally only operated in the region of 0 to 30 feet below the water table. Each foot of water in a well casing requires 0.433 pound per square inch (psi) of air pressure to displace. Therefore, 13.0 psi are required at a minimum to displace 30 feet of water from a casing before air can reach the aquifer. Additional air pressure is needed to overcome friction losses in the airlines and capillary pressures (i.e., air entry pressure) at the well/formation interface. Therefore, equipment and operating costs increase as the depth below water table increases. An increase in the air pressure needed for air sparging is accompanied by an increase in concerns regarding safety and the integrity of pipes and the outer well seals. Thus, air sparging would not be an appropriate technology for use on contaminated zones far below the water table (e.g., greater than 30 feet below the water table).

Moving air into a geologic media is easier if the material is a coarse, high-permeability sand or gravel. The pressure necessary to force air into these materials is much lower than that required for fine-grained materials. In fine-grained clayey sand, silt, or clay, the permeability of the materials essentially precludes the use of air sparging as a remediation technology.

The effectiveness of air sparging is sensitive to the lithologic and stratigraphic heterogeneities of a remediation site. In highly stratified materials, air may travel far from the

well along zones of more permeable strata (i.e., on the underneath side of clay and silt layers) before reaching the vadose zone (Figure 6-4). This course could have one or more negative impacts:

- Airstreams/channels may not fully contact the target contaminated zone.
- Mounding of the groundwater table would result in a lateral flow of groundwater and the contaminant plume.
- Injected air could potentially migrate along low-permeability zones.

Therefore, additional care must be taken during the design and operation of an air sparging system in stratified materials to ensure that contaminants are contained and removed from the ground.

6.1.9 System Design and Operation

A typical air sparging system consists of an oil-free air compressor manifolded to several air sparging wells. A compressor rated for continuous duty at the maximum expected flow rate and pressure provides the greatest flexibility during full-scale system operation. Although oil-free reciprocating compressors are readily available, they are usually intended for intermittent use only. Continuous-duty reciprocating compressors are available, but cost nearly twice as much (Marley, et al., 1992).

Pressurized air is supplied to the sparging wells by a header-type pipe distribution system. Metal pipe or rubber hose rated for pressure may be needed for air distribution, depending on site-specific conditions and the anticipated pressures. The use of rigid plastic pipe (e.g., polyvinyl chloride [PVC]) as header pipes should be avoided because the heat generated during air compression can damage the pipe.

A pressure gauge and regulator should be provided at each sparging well as a means of measuring and controlling airflow at each injection point. In addition, check valves should be placed at the entrance to each sparge well. Once the formation is pressurized, air and water might flow back up the well if the air sparging system is turned off. The check valve prevents the back flow from reaching the pressure regulator, manifold line, or compressor (Marley, et al., 1992).

As stated previously, air sparging wells can be installed vertically, at an angle, or horizontally (by use of directional drilling). In addition, slotted pipe can be placed in the bottom of dug trenches, which are subsequently backfilled with coarse sand or gravel. The well casing and screens can be constructed of PVC or metal. Care should be taken when constructing the annular seal for each well. The grout used to seal the wells should be nonshrinking because any cracks or bridging in the seal will allow short circuiting of air along the outside of the well casing and greatly reduce the effectiveness of the sparging well. A screen length of 1 to 3 feet is usually sufficient for vertical and

angle wells. For horizontal wells, small-diameter pipes of different lengths can be inserted within the horizontal well to ensure that compressed air is distributed along the entire length of the well.

Air pressure supplied to sparging wells typically ranges from <5 to 40 psi. Air pressure as high as 60 psi has been used during one pilot-scale test because air was being injected into fine sandy silt, i.e., low-permeability material (Marley, et al., 1992).

Airflow rates commonly range from 2 to 15 standard cubic feet per minute (scfm) per sparge well (Marley, et al., 1992; Johnson, et al., 1993). A high flow rate (170 to 270 scfm) was reportedly introduced to a horizontal air-sparge well because of the longer available screen length (Kaback, et al., 1991). This is one of the advantages of using horizontal wells or horizontal pipes in trenches.

Air sparging systems can be operated in the following modes:

- Continuous injection of air into all air-sparging wells
- Alternate injection into the wells (e.g., half the wells are used while half are inactive at any one time)
- Pulse flow into all wells (i.e., on/off), thus allowing the compressor to run intermittently.

The advantage of operating under the pulse-flow mode is that the flow into each well is stopped and started in cycles. This causes air channels to collapse during the off period and new ones to reform when airflow is resumed. Presumably, the new air channels will not always coincide with the old channels, thus increasing the potential contact between air and contaminated water/sediment. In other words, channels reform in random locations, thus increasing the chances that more pore spaces will eventually be aerated. The advantage to operating under alternate injection is that air is injected to only half the wells at a time, so the compressor can be sized at roughly half the capacity than what would otherwise be required.

If an SVE system is used to capture VOCs from the unsaturated zone, then the system should be designed for a negative pressure in an area larger than the zone where sparging is occurring, and the extraction flow rate should be greater than the injection flow rate.

6.1.10 Performance Monitoring

Performance monitoring methods for use with air sparging systems are difficult to determine and are still being developed. The zone of influence of individual sparging wells and the overall effects and efficiency of a sparging system can be difficult to measure.

In coarser, homogeneous soils in which channel distribution is more regular, the zone of influence is somewhat symmetrical around the well and the effective radius is dependent on the air injection pressure and flow rate. In heterogeneous, stratified materials, sparge air can traverse laterally over fairly long distances in one or more directions.

Although specific parameters for monitoring system performance have not been fully determined, Table 6-1 presents recommended parameters for monitoring system operation and in situ response. These parameters can be used in determining the following:

- Influence of the sparging system based on dissolved oxygen concentrations.
- Changes in contaminant concentrations in groundwater during system operation.
- Mass removed by the air sparging-soil vapor evaporation (AS-SVE) system from SVE off-gas concentrations.
- Distribution of contamination and SVE performance based on soil data.
- Airflow in the subsurface based on vacuum/pressure distribution and airflow measurements.

As mentioned in Chapter 4, a series of tracer tests (e.g., SF_6, He) and in situ aerobic respiration tests can be performed in addition to tests on those parameters that are important to successful performance monitoring of AS-SVE systems (e.g., dissolved oxygen, hydrocarbon concentrations, flow rates, and pressure). At many sites, it may be difficult to determine and interpret these performance monitoring data because of the high degree of temporal variability. Therefore, tracer tests can be used to gain a better understanding of the contributing factors leading to the variability. The tracer tests can be used to assess airflow in the unsaturated zone and to determine the extent to which hydrocarbon vapors are migrating off site. The tracer tests can also complement aerobic respiration tests that are used to determine oxygen utilization as an indicator of biodegradation.

Table 6-1. Recommended Monitoring Requirements

Parameter	Measurement Method
System Operation	
Extraction well flow rate	Flowmeter measurement methods (pitot tube, orifice plate, etc.)
Injection well flow rate	Flowmeter (rotameter, orifice plate, thermal anemometer, etc.)
Extraction well vacuum	Vacuum gauge or manometer
Injection well pressure	Pressure gauge
Extraction gas concentration	Flame ionization detector (FID)
Extraction well composition[a]	Gas chromatography with FID
O_2 and CO_2	Electrochemical cell (oxygen) Infrared detector (carbon dioxide)
In Situ Response	
Contaminant distribution levels in vadose zone and saturated zone soil	Analysis of soil sample by accepted method
Soil gas concentrations	FID
Soil gas composition[a]	Analysis by accepted method
O_2 and CO_2	Electrochemical cell (oxygen) Infrared detector (carbon dioxide)
Soil gas pressure/vacuum	Pressure/vacuum gauge manometer,[b] or inclined manometer
Groundwater elevation	Electronic water level indicator or tape in monitoring well
Contaminant levels and distribution in groundwater	Analysis of groundwater sample by accepted method
Dissolved oxygen levels	Analysis of groundwater sample
In situ airflow rate	Flowmeter[b]

[a] Includes compositional analyses of hydrocarbon (boiling point fractionation or individual species).

[b] Requires vadose monitoring installations or soil gas probes.

Source: Modified from Johnson et al., 1993

Section 7
Cost Estimates

7.1 SVE Systems

The cost of procuring, installing, and maintaining a soil vapor extraction (SVE) system can be divided into three general categories, as described in detail in the "Soil Vapor Extraction Technology Reference Handbook" (EPA, 1991a):

- Site assessment costs, including a site history and detailed site characterization.
- Capital costs, including design and installation of system components, permitting, and contingencies.
- Operation and Monitoring (O&M) costs associated with continued operation of the system.

Table 7-1 briefly describes each type of cost along with a summary of example unit costs. Table 7-2 presents an example cost estimate for a hypothetical SVE system. These costs are modified from estimates provided in the SVE Handbook.

7.1.1 Site Investigation Costs

A complete site investigation includes a review of site history, on-site field screening, and, if necessary, geological and geophysical investigations and environmental sampling. The site historical review, including interviews and file searches, is designed to minimize the effort necessary on later tasks. On-site field screening often includes soil gas and groundwater sampling, and should be designed to better define the nature and extent of any contamination present. Sites with more complex geology, or more extensive contamination, may require more detailed site characterization, including geophysical surveys, more detailed soil gas surveys, and detailed geologic sampling and evaluation.

The costs for all of the above tasks can vary dramatically, depending on site history (surface structures, land use), geological characteristics (depth to groundwater, soil properties, and homogeneity), and nature of contamination (one or more constituents or product types, single or multiple events). At the low end, for a site with a known history,

Table 7-1. Example Unit Costs for SVE Systems

Item	Type	Size	Cost ($)
Site Investigation			
Soil sampling	hand auger drilling rig	1- to 2-inch ID 4-inch auger	$10-40/sample $20-50/ft
Soil gas analysis	KV system		$100-3000/day
Surface geophysics	EM GPR Seismic		$1500/day $2000/day $3000/day
Analytical	VOC ABN TPH		$200/sample $500/sample $100/sample
Capital Costs			
Extraction well construction	PVC	8-inch auger	$20-50/foot
Casing	PVC	4-inch	$3-5/foot
Screen	PVC	4-inch	$5-7/foot
Piping	PVC	4-inch	$3/foot
Valves	PVC	4-inch	$300 ea.
Joints	PVC	4-inch	$16 ea.
Surface seals	Bentonite for annular seal, concrete at surface	6-inch	$3/sq. yd.
Blower	Intrinsically safe	1 hp	$1700 ea.
Air/water separator	Knockout pots	130 gal.	$2400 ea.
Magnehelic gauge	Vacuum		$50-75 ea.
Flow meter			
Sampling port	Brass T		$20-30 ea.
Soil gas probe	Aluminum	0.5-inch ID	$30-50 ea.
Diffuser stacks	Carbon steel Stainless steel	4-inch 4-inch	$8/foot $30/foot
Activated carbon canisters	G-series	100-200 cfm	$700-1000 ea.
Operation and Monitoring Costs			
Power (continuous operation)	Electricity at 10¢/kWh	1-hp blower	$18/day
Vapor treatment	Carbon adsorption		$20/pound gasoline removal
	Thermal incineration	Supplemental fuel	$1/gallon

Table 7-1 (continued)

Item	Type	Size	Cost ($)
	Catalytic oxidation	200 scfm	$800/month
	Internal combustion engines	Propane Natural gas	$1/gallon $0.75/gallon
Monitoring and analysis	Soil or groundwater	TPH TCLP VOC BTEX ABN	$75-125 ea. $1100-1600 ea. $200-250 ea. $100 ea. $450-550 ea.

1993 dollars

Table 7-2. Hypothetical SVE System Cost Estimate

Cost Component	Description	Cost ($)
Site investigation	Soil gas survey	$4,000
	Soil sampling and well installation	11,000
	Soil analysis	4,000
	Data evaluation and interpretation	9,000
	Total Site Investigation Costs	$28,000
Capital costs	Recovery well installation	$18,000
	Piping system	15,000
	Blower system	30,000
	Carbon adsorption system	10,000
	License, permit, legal fees	2,000
	Project management, engineering design	18,000
	Total Capital Costs	$73,000
Operation and monitoring (5 years planned)	Power requirements	10,000
	Maintenance	10,000
	Water disposal from knockout tank	20,000
	Monthly monitoring and analysis	60,000
	Additional carbon	30,000
	Total O&M	130,000
Total Cost		$251,000

1993 dollars

a well-documented recent release of a known contaminant, and a relatively simple geologic environment, complete site assessment costs could be as low as $2,000 assuming no intrusive field work is necessary to define the problem.

A more typical situation would involve an investigation of site history (including interviews with employees and adjacent property owners). In addition, a preliminary soil gas survey and use of surface geophysical methods may help define the extent of plume contamination. Confirmatory soil borings and an analysis of soil and groundwater could bring the cost of this type of site assessment to between $10,000 and $50,000.

For the more complex site, with perhaps multiple industrial users, multiple historical contamination events, and a heterogeneous hydrogeologic environment, more detailed historical review and site characterization would probably be required. Including a more detailed soil gas survey, additional soil borings and laboratory analyses and perhaps complementary geophysical techniques, a detailed site assessment on such a site could range between $20,000 and $75,000.

7.1.2 Capital Costs

Capital costs include engineering design, procurement and installation of the SVE system, permitting, piping, and instrumentation. The primary cost groups include:

- Vapor capture - primarily well installation, surface seals, and groundwater level control. The typical system consists of PVC wells and a piping system to connect injection wells and extraction wells to the removal system. A typical 30-foot-deep extraction well installation may range in cost from $2,000 to $4,000, depending on the method of construction, type of geologic conditions encountered, and diameter of piping. Of this cost, up to one-half may be for well materials. Depending on the extent of contamination and the properties of the aquifer, the number of wells needed for remediation could range from as few as 3 to more than 50.

- Vapor removal - consisting of pumps, blowers, valves, monitoring devices, and other equipment used to remove vapors from the ground and transport them to the vapor treatment system. Typically, a vacuum pump or positive displacement blower provides the power for an SVE system. Spark and explosion-proof blowers range in price from $1,700 (1-hp) to $6,000 (30-hp), depending on fan size and flow rating. Monitoring equipment, which measures vacuum airflow and vapor characteristics, includes a magnehelic gauge at each well ($50-$75) to measure vacuum, in-line airflow meters ($300), and quick-coupling sampling ports ($25) used in conjunction with a portable organic vapor analyzer (OVA) or similar device to measure hydrocarbon concentrations ($6,000 to $25,000).

- Vapor treatment - including vapor pretreatment, side-stream treatment, and a vapor treatment device. Pretreatment involves an air-water separator (often with a demister) ranging from a simple drum to complex level controls. Typical size ranges from 20 to 130 gallons, with cost in the $1,000 to $2,500 range. A variety of methods are available to treat accumulated liquids and vapors, ranging from carbon adsorption (canisters range in cost between $600 and $11,000), catalytic oxidation ($3,000 to $200,000), and thermal incineration ($12,000 to $40,000). In general, costs are proportional to the flow rate to be treated and influent concentrations. Supplemental fuel may be required to maintain temperatures for adequate removal at some influent streams.

For a typical site, the range of expected capital costs is between $10,000 and $50,000. As with site-assessment costs, site and contaminant characteristics can dramatically affect total capital costs.

7.1.3 Operation and Monitoring Costs

Costs for system operation and monitoring (O&M) include blower and piping system power requirements, handling and disposal of recovered liquids, and off-gas treatment. O&M costs for small systems are low, ranging up to $50/month. Off-gas treatment, if necessary, can be expensive, ranging up to $2,000/month.

O&M costs primarily include power requirements for blowers and condensers (if necessary), fuel costs for incineration, monitoring and analyses to measure progress, and labor costs (if operated manually). The cost for power is calculated using the formula:

Cost = 0.75 (fan horsepower) (electricity cost, per kWh) (hours of operation)

Vapor treatment costs are a function of the treatment method, contaminant concentration, and flow rate. Carbon adsorption costs generally increase with concentration; incineration and oxidation costs generally decrease with concentration, with sustaining fuel costs dominating the total cost. Example unit costs are shown in Table 7-1.

7.1.4 Hypothetical Cost Estimate Case

The total cost of a site remediation using SVE can be estimated as:

$$C_R = C_S + C_C + (C_{MO} + C_{MM})\ T$$

where:

C_R = cost of remediation
C_S = cost of site assessment

C_C = capital cost
C_{MO} = average monthly operation cost
C_{MM} = average monthly maintenance cost
T = time of remediation in months.

Total cost C_R is the sum of the site assessment and capital costs plus the O&M unit costs multiplied by the estimated time necessary to achieve site remediation. The time estimate involves selection of target constituents, initial groundwater concentrations, and ultimate cleanup concentrations.

Overall system costs have been estimated to range from $35 to $100 per cubic yard of contaminated soil. This range of costs should cover the small- to average-size site experiencing controlled site and waste conditions. Site assessment and capital costs are site specific as described above.

The hypothetical site is a service station that reports a 1000-gallon spill of unleaded gasoline. After the leak is detected, 400 gallons of product are recovered from the silty sand aquifer underlying the site. The water table is 20 feet below grade, and the response of the field investigation is able to limit the extent of contamination to an area above the water table and about 50 feet by 150 feet in extent underlying the site. Six recovery wells are installed in the vadose zone and an SVE system initiated. The cost estimate on Table 7-2 presents the hypothetical costing for this site remediation.

7.2 SVE/Air Sparging Systems

The cost for SVE/air sparging systems is similar to that for SVE-based systems, including the division into the same three general categories--site assessment costs, capital costs, and operating and monitoring costs.

Table 7-3 briefly describes each type of cost in a summary of example unit costs presented in similar fashion to that shown for SVE systems (see Table 7-1). This table also presents an example of a hypothetical SVE/air sparging system cost estimate.

7.2.1 Site Investigation Costs

As with SVE systems, site investigations involving SVE/air sparging can include a wide variety of site conditions and data requirements. The investigation could range from a low of about $2000 (no extensive field work) to upwards of $60,000 for a complex site in a heterogenous hydrogeologic environment. The most typical situations will include limited field screening and analyses, with costs ranging between $10,000 and $25,000.

7.2.2 Capital Costs

As with SVE-based systems, capital costs include engineering design, procurement and installation of the SVE/air sparging system, permitting, piping, and instrumentation. The primary cost groups include vapor capture, vapor removal, and vapor treatment.

Table 7-3. Hypothetical SVE/Air Sparging System Cost Estimate

Cost Component	Description	Cost ($)
Site Investigation	Soil gas survey	$4,000
	Soil sampling and well installation	15,000
	Soil analysis	8,000
	Data evaluation and interpretation	12,000
	Total Site Investigation	39,000
Capital Costs	Injection wells	
	Recovery well installation	18,000
	Piping system	25,000
	Blower system	60,000
	License, permit, legal fee,	3,000
	project management, engineering design	25,000
	Total capital costs	131,000
Operation and Monitoring (2 years)	Power requirements	$16,000
	Off-gas emissions control	240,000
	Maintenance	10,000
	Bimonthly monitoring	68,000
	Labor	30,000
	Total O&M	364,000
	Contingency	20,000
Total Cost		$554,000

Vapor capture typically includes installation of PVC wells and piping in various diameters (2 to 12 inch). As described under SVE system costs, a typical 30-foot-deep extraction well may range in cost between $2000 and $4000, depending on the method of construction, type of geologic conditions encountered, and pipe diameter. Of this cost, about one-half may be for well materials (casing, screen, plugs, filter pack, bentonite, and grout). Costs can be reduced by early implementation of an effective well configuration. For example, the use of nested wells, including both sparging and extraction wells in the same hole, can reduce the total number of borings required. The use of horizontal wells, although more expensive, may increase the VOC extraction efficiency and thus the cost-effectiveness of the system. System piping can be placed aboveground or buried in trenches. Aboveground piping is obviously more economical if the site is inactive and the piping is secure. Aboveground piping may also require heat tracing and insulation to prevent freezing.

A vapor removal system consists of pumps, blowers, and other equipment used to remove vapors from the ground. An air sparging system introduces air into the saturated zone using mechanical compression equipment. The type of equipment used depends upon the flow rate and pressure required, which is partially governed by the static water pressure above the sparge point and the air-entry pressure of the soil. The injected air must be oil-free. Vacuum pumps or positive-displacement blowers extract the sparged air in addition to the airflow induced through the vadose zone. Example costs are described under SVE-based systems costs.

Vapor treatment includes pretreatment, side-stream treatment, and treatment devices identical to an SVE-based system. If pretreatment is required, options include carbon adsorption (55-gallon drums and skid-mounted systems), catalytic oxidation (requires additional treatment of hydrochloric acid generated during the process), and thermal incineration (may require supplemental fuel to maintain required temperatures). If pretreatment is not required, diffuser stacks may be designed to direct vapors into the atmosphere.

In addition to the above costs, engineering and design fees, permit acquisition, and other miscellaneous costs are often included as capital costs. Because these costs are highly site-specific, the figures estimated here are arbitrary. A general guideline is that engineering and design fees should comprise about 10 to 15 percent of total system cost. For a typical site, the range of expected capital costs is between $20,000 and $75,000. Site variability and contaminant characteristics are the major factors in determining the construction requirements of the system.

7.2.3 Operation and Monitoring Costs

Costs required for system operation and monitoring (O&M) include blower and piping system power requirements, handling and disposal of recovered liquids, and other ongoing costs such as labor. Table 7-1 presents example unit costs needed for operating a system. The successful operation of an SVE/air sparging system requires

monitoring of the extracted vapor stream (VOCs, O_2/CO_2), groundwater (BTEX, TPH, dissolved oxygen), and soil (VOCs, biological assay tests) to ensure appropriate contaminant removal during degradation. Air sparging systems are expected to add 20 to 25 percent to the cost of conventional SVE systems.

7.2.4 Hypothetical Cost Estimate Case

Overall system costs are expected to range from $35 to $75 per cubic yard in the unsaturated/saturated zones of petroleum-related cleanup sites. These costs are estimated to be approximately 50 percent of those for conventional SVE systems designed primarily to accelerate cleanup times using air sparging technology.

As an example cost estimate, consider a leaking UST site remediation where air sparging is used to deal with gasoline contamination in both the unsaturated and saturated zones. At this hypothetical site, the depth to water is 60 feet, and up to 10,000 cubic yards of soil are believed to be contaminated.

Capital costs at this site include those for two vapor extraction wells, one air injection well, and four groundwater monitoring wells. The system includes a 25-hp vacuum pump, a 15-hp air injection compressor, two air/water separators, and piping. An off-gas emissions control system, consisting of granular-activated carbon, is required to capture BTEX compounds. Because carbon regeneration will occur off site, costs are included under O&M. O&M costs assume bimonthly analysis of extraction well effluent concentrations with a portable GC and a total cleanup period of two years.

Appendix A
Chemical Data

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Table A-1. Unweathered Composition of Three Common Hydrocarbon Products (from USEPA, 1990d).

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (% w/w)		
		1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
n-Alkanes		10.8 - 29.6		
C4	n-Butane	4.8 - 7.0		0.12
C5	n-Pentane	1.9 - 4.5		1.06
C6	n-Hexane	2.0 - 12.9		2.21
C7	n-Heptane	0.2 - 2.3		3.67
C8	n-Octane	1.3		3.80
C9	n-Nonane	0.4 - 0.8		2.25
C10 - C14	n-Decane	0.2 - 0.8		8.73
Branched Alkanes		18.18 - 59.5		
C4	Isobutane	0.7 - 2.2		0.66
C5	Isopentane	8.6 - 17.3		
C6	2-Methylpentane	4.6 - 9.7		2.27
C7	2-Methylhexane	1.4 - 8.3		5.48
C8	2,4-Dimethylhexane	1.8 - 16.7		8.82
C9	2,2,4-Trimethylhexane	1.2 - 2.7		3.36
C10 - C14	2,2,5,5-Tetramethyl-hexane	0.5 - 2.6		1.35

Table A-1. Unweathered Composition of Three Common Hydrocarbon Products (continued).

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (% w/w) 1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
Cycloalkanes		3.2 - 13.7		
C6		0.2		
C7	Cyclohexane	1.0 - 3.9		2.40
C8	Methylcyclohexane	0.2 - 1.4		3.77
C9	1,2,4-Trimethylcyclo-pentane	0.2 - 0.7		1.35
Others	1,1,3-Trimethylcyclo-hexane	1.6 - 7.5		3.21
Olefins		5.5-13.5		
C4	1-Butene	0.9		
C5	1-Pentene	1.3 - 3.3		
C6	1-Hexene	0.8 - 1.8		
Others		2.5 - 7.5		
Mono-aromatics		19.3 - 40.9		
Benzene	Benzene	0.9 - 4.4		0.50
Toluene	Toluene	4.0 - 6.5		1.33
Xylenes	m-Xylene	5.6 - 8.8	0.07	2.32
Ethyl benzene	Ethyl benzene	1.2 - 1.4	0.03	0.37
C3-benzenes	1,3,5-Trimethylbenzene	3.2 - 11.3	0.67	3.59

Table A-1. Unweathered Composition of Three Common Hydrocarbon Products (continued).

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (% w/w) 1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
Mono-aromatics (continued)				
C4-benzenes	1,4-Diethylbenzene	2.1 - 2.6	0.88	3.98
Other		1.6 - 5.2		
Phenols				
Phenol	Phenol		0.001	
C1-phenols	o-Cresol		0.01	
C2-phenols	2,4-Dimethylphenol		0.02	
C3-phenols	2,4,6-Trimethylphenol		0.02	
C4-phenols	m-Ethylphenol		0.01	
Indanol	Indanol		0.001	
Poly-aromatics	Fluorene		0.57	
Nitro-aromatics				
C1-anilines			0.003	
C2-anilines			0.004	
Complex anilines	Quinoline		0.002	
Di-aromatics	Naphthalene	0.7	3.43	1.59

Table A-1. Unweathered Composition of Three Common Hydrocarbon Products (continued).

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (% w/w)		
		1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
Saturated hydrocarbons				
C8	n-Octane		0.05	
C9	n-Nonane		0.20	
C10	n-Decane		0.58	
C11	n-Undecane		0.98	
C12	n-Dodecane		1.14	
C13	n-Tridecane		1.20	
C14	n-Tetradecane		1.31	
C15	n-Pentadecane		1.42	
C16	n-Hexadecane		1.53	
C17	n-Heptadecane		1.51	
C18	n-Octadecane		1.31	
C19	n-Nonadecane		1.16	
C20	n-Eicosane		0.99	
C21	n-Heneicosane		0.51	
C22	n-Docosane		0.29	
C23	n-Tricosane		0.15	
C24	n-Tetracosane		0.05	
Pristane			0.52	
Phytane			0.46	

Table A-1. Unweathered Composition of Three Common Hydrocarbon Products (continued).

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (% w/w)		
		1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
Unknowns		6.6 - 13.8		

NOTE: Blanks indicate the unavailability of data and do not indicate the absence of a particular compound from the hydrocarbon product.

Table A-2. Range of Abundance of Some of the Constituents Typically Found in Virgin Mixtures of Gasoline. Values are in Percent by Weight.[a] (From Stelljes and Watkin, 1993).

Component	Maximum Abundance	Minimum Abundance
Aromatics		
Benzene	3.5	0.12
Toluene	21.8	2.73
Ethylbenzene	2.86	0.36
Xylenes (total)	8.31	3.22
Naphthalene	0.49	0.09
2-Methylnaphthalene	3.85	2.91
Benzo(a)pyrene	2.8×10^{-6}	1.9×10^{-7}
Branched Alkanes		
Isopentane	10.17	6.07
n-Alkanes		
n-Butane	4.70	3.93
n-Pentane	10.92	5.75
n-Hexane	3.5	0.24
Additives		
Ethylene dibromide	1.77×10^{-4}	7×10^{-7}

[a] Percent by weight values can be converted to parts per million (milligrams per kilogram) by multiplying the values shown above by 10^6.

Table A-3. Range of Abundance of Some Aromatic Chemicals Typically Found in Virgin Mixtures of Diesel Fuel. Values are in Parts Per Million (mg/l) by Weight[a] (From Stelljes and Watkin, 1993).

Component	Maximum Abundance	Minimum Abundance
Benzene	82	6
Toluene	800	100
Ethylbenzene	800	100
Xylenes (total)	800	100
Naphthalene	2,730[b]	2,730[b]
2-Methylnaphthalene	6,700[b]	6,700[b]
Benzo(a)pyrene	0.6	0.006
Benz(a)anthracene	1.2	0.001
Chrysene	2.2[b]	2.2[b]
Fluoranthene	37	ND[c]
Phenanthrene	1,500[b]	1,500[b]
Pyrene	41[b]	41[b]
Triphenylene	2.2[b]	2.2[b]
Cresol	54.3[b]	54.3[b]
Phenol	6.8[b]	6.8[b]
Quinoline	9.2[b]	9.2[b]

[a] Parts per million can be converted to percent by weight by dividing the concentrations shown above by 10^6.

[b] Only one concentration was reported for this chemical.

[c] ND = Not detected.

Table A-4. Major Components of JP-4 (From Smith et al., 1989).

Fuel Component	Kovats Index	Percent by Weight
n-Butane	400.0	0.12
Isobutane	466.3	0.66
N-Pentane	500.0	1.06
2,2-Dimethylbutane	527.7	0.10
2-Methylpentane	562.4	1.28
3-Methylpentane	578.7	0.89
N-Hexane	600.0	2.21
Methylcyclopentane	622.0	1.16
2,2-Dimethylpentane	629.1	0.25
Benzene	644.5	0.50
Cyclohexane	653.6	1.24
2-Methylhexane	669.5	2.35
3-Methylhexane	677.3	1.97
trans-1,2-Dimethylcyclopentane	679.6	0.36
cis-1,3-Dimethylcyclopentane	681.9	0.34
cis-1,2-Dimethylcyclopentane	684.4	0.54
n-Heptane	700.0	3.67
Methylcyclohexane	715.1	2.27
2,2,3,3-Tetramethylbutane	720.5	0.24
Ethylcyclopentane	729.8	0.26
2,5-Dimethylhexane	737.3	0.37
2,4-Dimethylhexane	738.4	0.58
1,2,4-Trimethylcyclopentane	740.8	0.25
3,3-Dimethylhexane	743.3	0.26

Table A-4. Major Components of JP-4 (continued).

Fuel Component	Kovats Index	Percent by Weight
1,2,3-Trimethylcyclopentane	748.1	0.25
Toluene	753.0	1.33
2,2-Dimethylhexane	764.2	0.71
2-Methylheptane	772.0	2.70
4-Methylheptane	772.7	0.92
cis-1,3-Dimethylcyclohexane	775.3	0.42
3-Methylheptane	778.0	3.04
1-Methyl-3-ethylcyclohexane	784.1	0.17
1-Methyl-2-ethylcyclohexane	786.7	0.39
Dimethylcyclohexane	788.8	0.43
n-Octane	800.0	3.80
1,3,5-Trimethylcyclohexane	825.3	0.99
1,1,3-Trimethylcyclohexane	831.0	0.48
2,5-Dimethylheptane	833.6	0.52
Unidentified	839.9	0.98
Ethylbenzene	844.9	0.37
m-Xylene	853.9	0.96
p-Xylene	854.8	0.35
3,4-Dimethylheptane	859.8	0.43
4-Ethylheptane	865.0	0.18
4-Methyloctane	868.5	0.86
2-Methyloctane	869.6	0.88
3-Methyloctane	873.9	0.79
o-Xylene	875.3	1.01

Table A-4. Major Components of JP-4 (continued).

Fuel Component	Kovats Index	Percent by Weight
1-Methyl-4-ethylcyclohexane	881.3	0.48
n-Nonane	900.0	2.25
Isopropylbenzene	905.1	0.30
n-Propylbenzene	937.2	0.71
1-Methyl-3-ethylbenzene	944.9	0.49
1-Methyl-4-ethylbenzene	946.8	0.43
1,3,5-Trimethylbenzene	952.8	0.42
1-Methyl-3-ethylbenzene	961.0	0.23
1,2,4-Trimethylbenzene	975.6	1.01
n-Decane	1000.0	2.16
n-Butylcyclohexane	1025.6	0.70
1,3-Diethylbenzene	1031.4	0.46
1-Methyl-4-propylbenzene	1034.7	0.40
1,3-Dimethyl-5-ethylbenzene	1041.6	0.61
1-Methyl-2-i-propylbenzene	1049.1	0.29
1,4-Dimethyl-2-ethylbenzene	1060.2	0.70
1,2-Dimethyl-4-ethylbenzene	1067.1	0.77
n-Undecane	1100.0	2032
1,2,3,4-Tetramethylbenzene	1128.8	0.75
Naphthalene	1156.5	0.50
2-Methylundecane	1166.0	0.64
n-Dodecane	1200.0	2.00
2,6-Dimethylundecane	1216.1	0.71
Unidentified	1262.3	0.68

Table A-4. Major Components of JP-4 (continued).

Fuel Component	Kovats Index	Percent by Weight
2-Methylnaphthalene	1265.7	0.56
1-Methylnapthalene	1276.4	0.78
n-Tridecane	1300.0	1.52
2,6-Dimethylnaphthalene	1379.4	0.25
n-Tetradecane	1400.0	0.73

Table A-5. Average Composition of Gasoline Vapor Exposures (From Halder et al., 1986).

	Compound	Compositional Make-Up[a]			
		Amoco Oil[b] (wt %)	Amoco Oil[c] (wt %)	Shell Oil[d] (vol %)	API[e] (wt %)
	Alkanes:				
C_3	n-Propane	-	-	0.8 (1.1)	
C_4	n-Butane	33.7 (7.8)	21.2 (10.4)	38.1 (5.7)	
	Isobutane	4.1 (0.8)	3.4 (1.6)	5.2 (1.9)	
C_5	n-Pentane	8.1 (2.5)	9.4 (1.5)	7.0 (4.0)	10.9 (4.2)
	Isopentane	21.6 (3.7)	27.2 (6.7)	22.9 (6.1)	
	Cyclopentane	-	-	0.7 (0.7)	
C_6	2,3-Dimethylbutane	1.3 (0.7)	3.3 (1.8)	0.7 (0.5)	
	2-Methylpentane	3.4 (1.3)	4.9 (1.4)	2.1 (1.3)	
	3-Methylpentane	2.0 (0.7)	3.2 (0.9)	1.6 (0.9)	
	Methylcyclopentane	1.1 (0.6)	1.5 (0.4)	1.3 (0.4)	
	3-Methylhexane	0.7 (0.4)	11.03	-	
	n-Hexane	1.8 (0.7)	3.1 (0.7)	1.5 (0.9)	1.7 (0.9)
C_7	2,3-Dimethylpentane	0.6 (0.3)	0.9 (0.8)	0.7 (0.6)	
	2,4-Dimethylpentane	-	0.8 (0.5)	-	
	2-Methylhexane	0.6 (0.3)	1.1 (0.3)	-	
	3-methylhexane	0.7 (0.4)	11.03	-	
	n-Heptane	-	0.7 (0.2)	0	
C_8	2,2,4-Trimethylpentane	0.7 (0.5)	1.8 (1.2)	0.5 (0.5)	
	Alkenes:				
C_4	Isobutylene	-	-	1.1 (1.5)	
	1-Butene	-	1.0 (0.7)	-	
	trans-2 Butene	1.2 (0.5)	-	-	
	cis-2-Butene	0.9 (0.3)	1.2 (0.7)	-	

Table A-5. Average Composition of Gasoline Vapor Exposures (continued).

	Compound	Compositional Make-Up[a]			
		Amoco Oil[b] (wt %)	Amoco Oil[c] (wt %)	Shell Oil[d] (vol %)	API[e] (wt %)
C_5	2-Methyl-1-butene	0.9 (0.4)	-	1.6 (2.1)	
	2-Methyl-2-butene	-	1.5 (0.7)	1.7 (1.8)	
	1-Pentene	-	0.7 (0.4)	-	
	trans-2-Pentene	0.8 (0.6)	-	-	
	cis-2-Pentene	-	-	1.2 (1.7)	
	Aromatics:				
C_6	Benzene	2.2 (1.0)	0.6 (0.3)	0.7 (0.4)	2.2 (1.1)
C_7	Toluene	3.1 (1.6)[b]	4.0 (1.8)[b]	1.8 (1.3)	2.2 (1.8)
C_8	Xylene (p, m, o)	0.9 (0.7)	1.5 (0.7)	0.5 (0.6)	1.1 (1.5)
	Total Percent	89.7	94.1	91.7	

[a] Components listed comprise at least 0.5% by wt. or vol. Composition less than 0.5% denoted by "-", Composition presented as arithmetic mean (± standard deviation).

[b] N = 12. Bulk terminal exposures.

[c] N = 11. Marine loading exposures.

[d] N = 95.

[e] N = 152.

[f] Toluene coeluted with 2,3,3-trimethylpentane on the analytical column; however, the major proportion is assumed to be toluene.

Table A-6. Physiochemical Properties of Five Common Hydrocarbon Mixtures (From USEPA, 1990a).

Product	Liquid Density (g/cm^3)	Liquid Viscosity (cPoise)	Water Solubility (mg/l)	Vapor Pressure (mmHg)
Automotive Gasoline	(0.73) 0.72-0.76 [15.6]	(0.45) 0.36-0.49 [15.6]	(158) 131-185 [13-25]	(469) 263-675 [38]
#2 Fuel Oil	(0.91) 0.87-0.95	(1.56) 1.15-1.97 [21]	3 - 10 [20-23]	(14.3) 2.12-26.4 [21]
#6 Fuel Oil	(0.91) 0.87-0.95	(254) 14.5-493.5 [38]	-5	(14.3) 2.12-26.4 [21]
Jet Fuel (JP-4)	0.75	0.829 [21]	10 - 20	91
Mineral Base Crankcase Oil	0.84-0.96 [15]	275 [38]	insoluble	N/A
Air	-	-	-	760
Saturated Aqueous Vapor	1	1	-	17.5

N/A = Not Available.

Notes: All values for 20°C unless noted in brackets [ ].
Values in parentheses are typical of the parameter ( ).
Values for air and saturated aqueous vapor are included, where applicable, as a means of comparison.

Appendix B
Recommended Specifications

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Appendix B.1
Well Construction and Specifications

Introduction

This Appendix provides guidance on the specification of proper well/trench construction for multiphase fluid extraction, soil vapor extraction (SVE), and system monitoring. This guidance is not comprehensive and must be adapted as necessary for site-specific conditions and objectives. Guide specifications for well construction are available through the Corps of Engineers' Guide Specification (CEGS) system, including CEGS 02671 Wells for Monitoring Groundwater and CEGS 02670 Water Wells. These can be modified for typical SVE system or multiphase fluid recovery applications. Guidance for selecting well location and screen placement is not provided here; refer to the main text.

Applicable Standards

In the specification, reference is made by title and number of all American Society for Testing and Materials (ASTM) or other standards for materials and testing procedures identified within the specification. For example, standards exist for plastic well casing (ASTM F 480, D 1785, D 2241), cement (C 150), and soil classification (D 2487 and D 2488). The Environmental Protection Agency (EPA), ASTM, American Water Works Association (AWWA), American National Standards Institute (ANSI), and National Sanitation Foundation (NSF) also have applicable standards for materials (e.g., NSF Standard 14) or well construction (e.g., EPA 570/9-75/001, AWWA A100, ANSI/ASAE EP400.1, ASTM D 5092) that may be appropriate to reference. Standard texts on well construction, such as Driscoll (1986), may also be appropriate to reference.

Quality Control/Assurance

Several testing procedures can be performed to ensure that the installation of the wells or trenches has been successful. Specifications require appropriate quality verification.

Well/Trench Performance Testing

Multiphase Fluid Recovery Well Performance

The performance of the well should be verified. This includes requiring a measurement of the draw down in the well at various flow rates (specific capacity), measuring free product recovery rates, and/or performing a pump test in the well. The measurement of specific capacity or product recovery rates after completion allows a comparison with the design yield and provides a baseline against which later performance can be

compared as a guide for well maintenance. The performance of a pump test, using nearby observation or monitoring wells, provides data on aquifer transmissivity and storativity that can be useful in operational modeling of the extraction system. Perhaps more important, a pump test can provide an estimate of well efficiency to be developed. This estimate can be used to evaluate the adequacy of the installation. The specification should describe the testing procedures and duration(s) and the methods of data analysis. Driscoll or other text on well hydraulics can be used to obtain information on applicable methods.

SVE Well Performance and Leak Testing
Preliminary testing of the airflow rate and vacuum levels at the well head can indicate if the well has been adequately installed. Drastically lower-than-expected airflow rates or much-higher-than-expected vacuum levels, compared to design values, at a well may suggest damage or improper placement. Either the main blower system or a skid-mounted blower and treatment system can be used for the test. If the SVE extraction or vapor monitoring well is not properly sealed, air may "short circuit" from the surface along to the casing. Monitoring of nearby wells during the performance testing of extraction may indicate a drastically smaller-than-expected radius of influence for the well and suggest a leak. Cement-bond geophysical logging may be appropriate if a poor bond between the casing and grout or voids behind the casing are suspected. The well can also be pressurized and if air is found leaking around the well head, poor installation should be suspected.

Recovery Trench Performance Testing
The performance of the trench should be assessed in a manner similar to a vertical extraction well. The response of vacuum monitoring points or piezometers installed within and outside the trench backfill should be measured to verify the response along the trench.

Alignment Verification

Vertical Well Alignment and Survey
For deep (greater than 75 to 100 feet) installations, some wells may significantly deviate from the vertical. In these relatively rare instances, an alignment test, typically run by a geophysical firm, may be necessary to verify the actual screen location and attitude. Specification of maximum deviation from vertical or the target coordinates may be appropriate.

Plumbness and Pump Placement
Wells in which pumps are to be placed should be tested for plumbness and alignment to assure that the pumps can be placed in the wells. Usually a well survey will determine the actual deviation of the well from the vertical. A dummy pipe of a diameter ¼- to ½-inch larger than the pump can be used to verify easy passage in the well. The dummy must be decontaminated and disinfected before each use.

Trench Alignment
A survey may be required of the alignment of the casing and screen to verify its grade, placement, and condition. Downhole (i.e., crawler-type) cameras can be used to verify the condition of the pipe and identify breaks or crimping in large-diameter pipe. Various methods are used for surveying horizontal wells to verify location. These surveys are strongly recommended because the directional control is highly variable, especially on long (more than 100 feet) runs.

Trench Backfill Compaction Density Testing
Soil density of the trench backfill is tested to verify adequate compaction for excavated trenches. Many methods are used to determine soil density, including Esteems D 2922, Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Method; D 2167, Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method; and D 1556, Test Method for Density of Soil in Place by the Sand-Cone Method. These tests should be specified at intervals along the trench or at the discretion of the field representative.

Contractor Qualifications
Competent professionals, drillers, and installers are required for successful installation of wells and trenches. Minimum criteria for these personnel must be identified in the specification.

Well Installation
Specify the level of experience of the contractor's well driller and hydrogeologist (or engineer) directing the well installation. Also specify state registration or certification where required.

Horizontal Well/Trench Installer Qualifications
Special requirements may be established for the operators of the trenching machine or horizontal drilling rig, such as a minimum number of months or years of experience. A registered or licensed driller may also be necessary.

Submittals
The contractor must submit various items to allow evaluation of contractor designs, to verify contractor performance, and to record installations. The level of approval for the submittal depends on the needs of the project. Items that are critical to project success should require approval before the contractor moves forward with the work. Others are only provided for information and do not need approval.

Work Plan
The contractor must submit a general plan of action, including materials, locations, drilling and installation procedures, and schedules. This requirement is particularly important if much of the design was left to the contractor to meet a performance goal. This submittal normally requires approval. For efficiency, this plan should include all

drilling activities, including those required for installation of multiphase fluid extraction wells, vapor monitoring points, and groundwater monitoring points. This plan may be part of a comprehensive contractor work plan governing all cleanup activities.

Permits and Other Documentation
Copies of the permits and clearances should be submitted, including disposal records pertaining to drill cutting and other waste. Documentation of the contractor's qualifications is often required as a submittal.

Catalog Data
Catalog information on the materials used or to be used should be submitted.

Boring Logs and As-Built Diagrams
The contractor must submit a log of materials encountered in drilling and a detailed as-built drawing of each well.

Test Results
The results of testing conducted for quality assurance purposes, such as the survey/ alignment, performance, leak, compaction density or alignment tests, should be submitted if performed by the contractor. In addition, results of any chemical or physical testing of soils or other materials should be submitted.

Development Records
In specifications for multiphase fluid extraction wells, the contractor must submit a record of the actions taken to develop the well. This requirement includes quantitative observations of turbidity and sand production, calculations of the total fluid volume removed, and a description of the development tools used.

Multiphase Fluid Recovery Wells
Multiphase fluid recovery wells are intended to capture any combination of groundwater, free product, and vapors. This action provides a checklist of topics to be covered in a specification for such wells. Typical requirements are discussed under each topic. Measurement and payment, chemical quality management, safety, site preparation and cleanup, and other topics are not included here but would normally be addressed in the specifications.

Materials
The materials used for multiphase fluid recovery wells will generally depend on site conditions and project objectives. Composition of the materials depends on the subsurface geochemistry uncloaking the natural constituents and contaminants.

Casing
For many applications, Schedule 40 PVC well casing is adequate. The recommended specification is ASTM D 1785, Standard Specification for Polyvinyl Chloride (PVC)

Plastic Pipe, Schedule 40, 80, 120 or ASTM F 480, Standard Specification for Thermoplastic Water Well Casing Pipe and Couplings Made in Standard Dimension Ratio (SDR). If high levels of liquid organics are to be encountered by the casing, the compatibility of the casing material with the fluids must be considered. Stainless steel (generally Schedule 5S or 10S, type 304) is required if PVC will be degraded by the product. The recommended specification is ASTM A 312, Standard Specification for Seamless and Welded Austenitic Stainless Steel pipe.

Alternatively, PVC may be preferred in an environment that is highly corrosive to metals. The well can be a "hybrid" of PVC casing and stainless steel screen. PVC casing exposed to sunlight should be protected or treated to withstand ultraviolet radiation without becoming brittle. Casing diameter generally depends on pump space requirements. Dual-phase pumps usually require a minimum of 6 inches inside diameter; larger diameters allow easier pump installation. If only groundwater and vapors are to be removed, groundwater pumps as small as 2 inches in diameter capable of pumping 10 gallons per minute are available. Generally, 6-inch-diameter or larger wells are recommended. The specifications should require casing with flush-threaded joints and O-ring seals.

Screen

Well screen is usually PVC, but as noted above, other materials may be more appropriate. The use of continuous-wrap "V-wire" screen is strongly recommended. Screen slot size is designed based on the formation material gradation established in the methods outlined in Driscoll (1986) or another similar reference. Different slot sizes can be used in different portions of the screened interval if the producing formation varies in soil gradation. If the gradations of the producing formation have not been determined during design, the contractor should obtain samples during drilling. The contractor must run gradations according to an appropriate method (e.g., ASTM D 422 Standard Method for Particle-C Size Analysis of Soils) and then size the screen slot (and filter pack, discussed below) accordingly. Screening with flush-threaded joints and O-ring seals is preferred.

Filter Pack

The filter pack requirements for this application are generally more critical than for SVE wells because the filter pack plays a more significant role in reducing entrainment of fine sands, silts, and clays in the fluid produced. As described above, the filter pack gradation should be chosen based on the gradation of the producing formation. Design should follow methods outlined in Driscoll (1986) or another similar reference. If only groundwater and vapors are to be recovered, the chosen filter pack must have a uniformity coefficient of 2.5 or less. A less uniform filter pack may be appropriate if nonwetting fluids, such as hydrocarbons, are to be recovered. Rounded to subrounded siliceous particles, free from organic matter and calcareous or elongated particles, are required. If free product recovery is of primary concern, a special filter pack that includes hydrophobic materials, such as ground plastic or PTFE, may improve the early

rates of product recovery (Hampton and others, 1993). In certain (relatively rare) circumstances, a well can be designed that does not initially include a filter pack, but rather develops a natural filter pack. Thorough well development can selectively remove fines from the native formation material and leave coarser native sands and gravel around the well as a natural pack.

Seal and Grout

A well seal is necessary to prevent entry of grout into the filter pack and well screen. Unamended sodium bentonite, as pellets, granules, or a high-solids bentonite grout, is normally specified for the seal material. Because most applications will involve the extraction of groundwater and either floating product or soil vapors, the well seal will be above the water table and pellets or granules must be hydrated with water added to the annulus. A cement grout is normally required above the bentonite well seal. The mixture of the grout, which should be specified, is normally one 94-pound bag of cement (with up to 5 pounds of bentonite powder added to further resist cracking) and less than 8 gallons of clean water. The recommended specification is ASTM standard C 150, Standard Specification for Portland Cement. In the event that the seal will be placed below the water table, the use of bentonite pellets placed by tremie pipe is preferred.

End Caps and Centralizers

Flush-threaded end caps, consistent with the casing and screen in size and material, should be specified. Centralizers center the well in the borehole and must be the size appropriate for the casing and borehole. Centralizers must be made of material that will not lead to galvanic corrosion of the casing. Stainless steel centralizers are recommended with PVC or stainless steel casing.

Installation

Acceptable practices for installing the wells should be described in this portion of the specification.

Test Holes

Careful design of the filter pack, screen slot size, and screen location is based on site-specific conditions. The contractor may need to drill test holes at the proposed well locations to obtain boring logs and samples. The number, locations, and depths of test holes should be specified.

Drilling Methods

There are many methods for drilling. Drilling methods can be proposed by the contractor or specified. Mud-based drilling fluids should be avoided if possible because of the difficulty in developing the zone containing floating product. The use of water-based fluids can also impede product recovery because the water can displace the hydrocarbon near the well and disrupt continuous hydrocarbon flow pathways. Auger, air-rotary, dual-wall air-casing-hammer, or cable tool drilling may be acceptable,

depending on site conditions. All equipment must be decontaminated and disinfected before drilling is begun at each location.

Soil Sampling and Logging

Sampling of soils encountered during drilling can lead to an increase understanding of the subsurface and can allow a better decision to be made about well construction including screen placement. Soils must be sampled at regular intervals, at least every 5 feet; sometimes, continuous sampling is appropriate. Samples should be obtained by an appropriate method such as a split spoon sampler or thin-walled tube, as specified in ASTM D-1586, Standard Method for Penetration test and Split-Barrel Sampling of Soils, or D-1587, Thin-Walled Tube Sampling of Soils, respectively. Sample volume requirements should be considered when specifying the sampling method. Sampling for chemical and physical analyses must be done according to an approved sampling and analysis plan. It is strongly recommended that a drilling log be prepared by a geologist or geotechnical engineer. Materials encountered should be described according to a standard such as ASTM D 2488, Standard Practice for Description and Identification of Soil (Visual-Manual Procedure). Geophysical logging may be appropriate for borings that extend into the water table. Electrical and gamma ray logs can help identify coarser materials for screen placement and can supplement or reduce the amount of soil sampling. This can reduce the time needed to drill and sample the hole.

Borehole Diameter and Depth

The dimensions of the borehole for well installation should be specified. Normally, the diameter is at least 4 inches greater than the diameter of the casing and screen to allow placement of the filter pack. The depth of the borehole should be based on the screen depth. The borehole should only extend to 1 foot below the projected bottom of the screen.

Screen and Casing Placement

The casing and screen should be cleaned or decontaminated before placement. The screen and casing should be joined by flush-threaded joints and suspended in the center of the borehole. To maintain plumbness and alignment, the string should not be allowed to rest on the bottom of the hole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds some minimum value such as 20 feet.

Filter Pack Placement

The specification should require the filter pack to be placed by using a decontaminated tremie pipe. Because much, if not most, of the filter pack is placed below the water table, the tremie pipe should be kept within 2 to 5 feet of the surface of the placed filter pack. This prevents the pack material from bridging or segregating by size while falling through the water column. The level of the pack material should be measured following placement. Approximately 1 foot of filter pack should be placed in the borehole below

the bottom of the screen to act as a cushion for the screen and casing. Filter pack material should extend 2 to 5 feet above the top of the screen to allow for settlement so that native material will not collapse around the screen. Gentle agitation of the water within the well during or after filter pack placement can help in ensuring full settlement before grouting. The pack material should be stored and handled carefully to avoid contamination from undesirable materials.

Seal and Grout Placement

The grouting of the well is critical to prevent short circuiting resulting from air leakage from the ground surface when a vacuum is applied. Normally 3 to 5 feet of a bentonite well seal is placed above the filter pack. If the well seal is to be placed above the water table, the specification should include a requirement for hydrating the bentonite before placement of the grout. The specification should require the addition of a volume of distilled or potable water for every 6-inch lift of bentonite pellets or granules. The bentonite should hydrate for at least 1 to 2 hours prior to placement of the grout. This can be avoided by specifying the use of a bentonite high-solids grout as the seal. The high-solids bentonite grout should be placed by tremie pipe. A cement grout should also be pumped into annular space via a side-discharge tremie pipe, and the pipe should be kept submerged in the grout during grout placement. If the grout is to be placed to a depth of less than 15 feet, the grout may be poured into place directly from the surface. If the well seal is to be placed below the water table, the bentonite pellets must be allowed to hydrate in place for 2 to 4 hours before the well is grouted. Fine sand can be placed above the bentonite pellets to further prevent grout intrusion.

Surface Completion

A suitable well head is required to extract multiple phases from a single well. The well head specifications may require multiple discharge pipes, electrical leads, compressed-air or vacuum lines, control device leads, and sampling ports. These requirements are project-specific. If finished above grade, the well may require suitable protection, such as bollards, to avoid damage to the well from traffic, etc. A well vault may also be required. Separate specifications may be required for the construction of the vault itself and for other aspects of the instrumentation, as appropriate. The use of pittless adapters, etc., should be described, and reference should be made to appropriate drawing details.

Well Development

Well development is critical to the ultimate performance of the well. A careful specification of the acceptable development methods and development criteria is strongly recommended. The well must be developed by surging and bailing. In addition, a suitable size surge block or jetting must be used at appropriate water velocities. Note that jetting can affect product recovery by disrupting floating hydrocarbon flow pathways. The development should continue until the well is producing clear water with less than 2 to 5 ppm by weight sand and/or other suspended solids. A turbidity criterion defined as less than 5 nephelometric turbidity units (NTU) determined by a

nephelometric turbidity measure merit method can be used. Sometimes, the use of dispersing agents such as phosphates can help develop wells by breaking down clay smears on the borehole walls. The regulatory authorities may need to approve dispersing agents or other additives such as acids. The well is developed after placement of the filter pack and before or after the well is grouted. Development prior to the grouting of the well will ensure that the filter pack is fully settled before grout placement, thus assuring no voids would be created; however, the potential exists for cross contamination while the well annulus is open above the pack. Normally, the well should be developed after grouting.

Disinfection
In some cases, biological encrustation has caused severe degradation of the performance of the extraction wells. Contaminated sites often provide ample food for microorganisms that can plug well screens. Disinfection of the drilling tools and the well itself can help prevent or slow these problems. Disinfection can be accomplished by various means (Driscoll, 1986), including creating a specified concentration of a strong oxidizing agent, such as sodium hypochlorite, in the well. The chemical ramifications of any additives should be considered.

Surveys
A survey should be done to establish the horizontal coordinates of the well. The elevation of the top of the casing should be surveyed to provide accurate groundwater elevations. The accuracy of the surveys depends on the project needs, but generally they are accurate to the nearest foot for the horizontal coordinates and the nearest 0.01 foot for elevation.

Permits
The contractor may be required to obtain utility clearances and certain permits from the regulatory agencies and/or the land owner. In addition, the contractor should comply with local water well installation, abandonment, and reporting requirements for SVE/EV/ air sparging wells.

Well Acceptance
The contractor must provide a well that functions properly, to the extent that site conditions permit. If the contractor, due to its negligence or error, installs a nonfunctional well, the specification must require the contractor to repair or replace the well at its expense. If the well cannot be repaired, the contractor must be required to properly decommission the well (see Section on "Well Decommissioning").

Soil Vapor Extraction Wells
Many topics covered in the section on multiphase fluid recovery wells are relevant for SVE wells. This section outlines differences between the checklist topics described for multiphase fluid recovery wells and topics appropriate for SVE well construction specifications. Other topics covered for multiphase fluid recovery wells but not

mentioned here are directly applicable to soil vapor extraction wells with the exception of well development and disinfection. Wells used for passive or active air injection generally can also be installed according to these requirements.

Materials

The composition, properties, and sizes of materials should be specified as discussed below.

Casing

New polyvinyl chloride (PVC) pipe, 4 to 6 inches in diameter, is normally used for SVE well casing. Larger diameters are preferred to increase flow capacity, but require larger boreholes. Schedule 40 PVC well casing is adequate for most SVE applications because the casing will generally not be in contact with liquids. Other materials may be specified if contaminants, at expected vapor/condensate concentrations, are likely to be damaging to PVC. PVC casing exposed to sunlight should be protected or treated to withstand ultraviolet radiation without becoming brittle. The casing must be strong enough to resist collapse at the expected vacuum levels and grout pressures.

Screen

Well screen is usually PVC with slotted or continuous wrap openings. Continuous-wrap screen is strongly preferred because the increased open area reduces the pressure drop across the screen and therefore reduces energy costs for the blower. Slot size is generally 0.020 inch, but should be as large as possible to reduce the pressure vacuum drop across the screen. Slot sizes of 0.040 inch or larger may be used. Larger slots sizes may, in a few cases, lead to increased entrainment of abrasive particles in the airflow.

Filter Pack

Pack material should be a commercially available highly uniform gradation of siliceous sand or gravel with no contaminants (chemical or physical). A uniformity coefficient of 2.5 or less should be specified. The actual gradation should generally be based on the formation grain size and the screen slot size. Coarser material may be used; however, coarser gradations may, in a few cases, lead to increased entrainment of abrasive particles in the airflow.

Seal and Grout

In essentially all cases, the well seal in SVE wells will be placed above the water table. Guidance on specifying materials in seals or above the water table in multiphase fluid extraction wells will apply here. A cement/bentonite grout is preferred to fill the annulus above the seal to the ground surface because it resists desiccation cracking.

Installation

The installation of the SVE well is similar to the installation of multiphase fluid extraction wells. This section notes the differences.

Drilling Methods
Some drilling methods, particularly those using drilling mud, are to be avoided because of the potential to plug the unsaturated soils. Hollow-stem auger drilling is most common and is preferred where appropriate.

Filter Pack Placement
Filter pack should be placed around the screen to some level above the top of the screen, normally 2 to 3 feet. Filter pack is normally placed dry by being poured down a tremie pipe.

Surface Completion
The completion of the well head will depend on the other features of the design, such as the piping and instrumentation requirements. Project drawings should be referenced as appropriate. An appropriate "tee" may be placed below or at grade to establish a connection with buried or aboveground piping, respectively. A vertical extension from the tee to a specified level will allow attachment of appropriate instrumentation. If a surface cover is used, it may be appropriate to describe the means by which the cover is sealed around the well. This can also be described in a specification for the placement of the cover. Refer to CEGS 02271, Geomembrane Barrier, for further guidance.

Surveys
A survey is used to establish the horizontal coordinates of the well. The elevation of the top of the casing should be surveyed. If the SVE well intercepts groundwater, the water elevation would be of interest. Caruso requirements are similar to those for multiphase fluid extraction wells.

Vapor Extraction Trench
This section provides a checklist of topics to be covered in a specification for vapor (or liquid) extraction trenches. Such trenches are often used at sites with shallow groundwater or near-surface contamination; thus, the depth of excavation is often modest. A horizontal recovery system can be placed by several methods including normal excavation, trenching machines (which excavate and place pipe and filter pack in one pass), and horizontal well drilling. Where possible, typical requirements are discussed under each topic. Many specification topics are very site specific. Additional topics, such as measurement and payment, chemical quality management, safety, site preparation and cleanup, are not included here but would normally be addressed in the specifications. A Corps of Engineers Guide Specification, 02222 Excavation and Backfilling for Utilities Systems, can be modified for application to vapor extraction trenches excavated by normal means.

Materials
Materials specified for extraction trench construction are often similar to those specified for vertical wells. Different materials may be needed if specialized trenching (or

drilling/jacking) methods or machines are used. Differences between horizontal and vertical applications are discussed below.

Casing

Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain excavation methods such as trenching machines. The pipe must resist the crushing pressures of the backfill and compaction equipment. Reference should be made to appropriate ASTM standards for PVC pipe or ASTM D 3350, Standard Specification for Polyethylene Plastics Pipe and Fittings Materials. The specification should allow casing to be joined by threaded coupling or thermowelds, as appropriate for the material. Pipe sizes of 4 to 8 inches are often used. Larger pipe sizes allow easier access for surveys and maintenance.

Screen

Given the generally longer screened intervals in horizontal applications, air-entry velocities are generally lower and well efficiency is less of a concern. Thus, the screen open area can be somewhat lower than is needed in vertical wells. Although continuous-wrap screen is still preferred, successful systems have also used slotted pipe. If slotted pipe is specified or allowed, the specification should require a minimum open area perfect. Drain pipe wrapped with geotextile must not be used because of the potential for fine material to plug the geotextile. Slot size can be quite large, 0.040 inch or larger, because the lower air velocities reduce the potential for entrainment of small particles. The screen can be joined by threaded couplings or it can be thermowelded. For some horizontal well applications, a prepacked well screen is appropriate. Prepacked screens are really two screens enclosing preselected filter pack material. The use of prepacked screen can overcome the difficulties of installing filter pack within a horizontal well.

Bedding Material/ Filter Pack

Generally, the guidance for specifying filter pack in SVE wells applies for trenches, but somewhat coarser material may be needed for a secure bedding for the pipe and screen. A reference to ASTM D 2321, Standard Practice for Underground Installation of Flexible Thermoplastic Sewer Pipe may be appropriate. Filter material placed above the water table generally need not be sized for the formation, and can be quite coarse. A reference to ASTM C 136, Standard Method for Sieve Analysis of Fine and Coarse Aggregate, may be appropriate for verifying the gradation.

Cover and Seal Material

Native material may occasionally be used as backfill above the filter pack in an excavated trench. Given that vapor extraction trenches are typically used at sites with shallow groundwater, low permeability material is preferable to enhance the lateral vacuum influence of the trench. The use of clay or a geomembrane is required, if appropriate. Refer to the CEGS 02271, Geomembrane Barrier for Landfill over for

guidance on specifications for geomembranes, or CEGS 2443, Low Permeability Clay Layer, for specification of clay backfill.

Geotextile
A geotextile may be needed to separate the filter pack from native material or clay backfill in an excavated trench. Refer to CEGS 02272, Separation/Filtration Geotextile, for guidance in specifying the geotextile.

Marking Tape and Locator Strips
A locator strip is needed specifically manufactured for marking underground utilities. This tape is made of colored polyethylene that is backed with foil or contains embedded wire to allow others to locate the trench at later dates. This would not be applicable for horizontal well installations.

Installation
Installation methods vary significantly depending on excavation method.

Excavation Methods
Methods used to install trenches or other horizontal installations include standard earth excavating equipment (e.g., backhoe), trenching machines, horizontal drilling techniques, and pipe jacking/microtunneling. Given this wide variety, it may be desirable to only specify the pipe, screen, pack materials, and an ultimate pipe alignment and depth. This would allow the contractor the option to propose what might be the most cost-effective method; however, the trenching technique used by the contractor must provide an adequate filter placement around the collector pipe. Note that horizontal drilling, pipe jacking, etc., reduces the amount of disturbed material and minimizes both the potential for worker exposure and disruption to surface features. Most horizontal drilling techniques require drilling fluids that may not be appropriate for vapor extraction techniques.

Soil Sampling and Logging
If open excavation techniques are used, a graphical log of the materials encountered in the trench should be prepared, including the description of the materials according to ASTM D 2488. Other excavation methods will require some log of the materials encountered at different stations, and would usually be based on cutting returns from the trenching machine or drilling. Other sampling should be done as needed according to an approved sampling and analysis plan.

Trench Dimensions
The trench dimension should be wide enough to allow preparation of the bottom of the trench and placement of the pipe. Normally, the trench width is limited to the pipe diameter plus 24 inches. If the material to be trenched is contaminated, a smaller trench reduces the volume of material to be disposed of or treated as waste. Compliance with appropriate OSHA regulations is required for workers who need to enter a

trench for installation. If a horizontal drilling method is used, some annular space between the borehole and the screen should be required in a manner similar to that used for vertical wells. The use of a prepacked well screen may require less annular space.

Trench Bottom Preparation and Pipe Placement

The bottoms of the excavated trenches must be prepared prior to placement of pipe and screen. The trench must be leveled to the required grade to provide uniform bearing for the pipe. A bedding layer of filter pack material 4 to 8 inches thick should be placed and compacted prior to pipe and screen placement. All rocks or angular debris greater than 3 inches in diameter must be removed from the trench bottom to avoid damage to the pipe. Unstable materials should also be removed. The pipe and screen should be placed in a way that prevents entrapment of filter pack or native material inside the pipe. The section of the pipe and screen must be joined in a manner consistent with the material used and the manufacturer's recommendations. A clean-out or access port for the pipe should be provided to allow for later surveys and maintenance of the screen and casing. This should be shown on the drawings. The contractor must prevent the run-in of surface water into the trench. If the trench is to be installed to below groundwater, dewatering may be necessary. Separate dewatering and water treatment spell suffocations may be required.

Soil Stockpiles

The specification should describe what should be done to manage the excavated material. This is highly site-specific. For example, the soil may be used for backfill or it may need treatment. Adequate measures to protect the material from being contaminated or from spreading contamination should be required.

Filter Pack Placement

Filter pack placement is relatively simple in open trenches, but much more difficult in drilling or jacking operations. The filter pack material should not be compacted with 6 inches to 1-foot of the pipe and screen. Some trenching machines place the pipe and filter pack material as it progresses. In these cases, it is important to verify that the machine is placing adequate filter pack around the screen. For horizontal drilling applications, various methods exist for placing the filter pack; the most common and probably most desirable of these methods is the use of the prepacked screen. In this method, the native material is allowed to collapse back upon the prepacked screen.

Backfilling and Compaction

The remainder of an excavated trench should be backfilled with the specified material to the grades shown on the drawings. Placement of a geotextile between the filter pack and backfill may be appropriate if there is a significant difference in grain size between the two materials. Refer to CEGS 2272 Separation/Filtration Geotextile for guidance on specifying placement of the geotextile. Backfill should be placed in 6- to 8-inch lifts and compacted to approximately 90 percent optimum standard density, determined by

ASTM D 69, Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort, if cohesive materials are used. The specification can identify the acceptable compaction method. The locator strip should be placed within 18 inches of the surface.

Surface Cover and Seal Placement
The specification should identify the means to place the surface cover, if one is used. Refer to the CEGS 02271 Geomembrane Liner for guidance on specifying handling, seaming, penetration, and other practices if a geomembrane is required. Generally, a minimum of 6 inches of soil cover is placed over a geomembrane to protect it. Sometimes concrete or asphalt paving is used instead of a geomembrane, and a reference to separate specifications on base course and pavement construction would be appropriate. As with the vertical wells, an appropriate surface completion will be required, such as a well vault or below-grade connection.

Repair of Casing or Screen or Removal of Trench
The contractor should be required to repair or replace, at its expense, any segment of the casing or screen that was damaged because of inadequate installation or materials. In the event the entire installation fails to function or is no longer needed at the end of the project, the casing and screen can be pressure grouted or excavated for salvage. Excavated trenches should be backfilled and compacted according to the appropriate part of the specification.

Soil, Vapor, and Water Sampling

Extraction Well Sampling
The specifications should require a baseline sample of the groundwater, soil vapor, and/or product constituents prior to system operation. This can assist in treatment design and monitoring of overall system performance upon startup. Sampling should be done according to the approved sampling and analysis plan.

Soil Sampling for Chemical Analysis
In addition to sampling for logging and physical testing purposes, soil samples for chemical analyses are often required. This information is used to further characterize the extent of contamination and to establish a baseline against which soil remediation by vapor extraction is judged. Sampling should be done according to an approved sampling and analysis plan.

Monitoring Point Sampling
The specification should require an initial sampling of the soil gas and/or groundwater contaminant concentrations from each monitoring point. This should be done according to the approved site sampling and analysis plan.

Soil Gas/Vacuum Monitoring Points

This section outlines differences between the check lists for multiphase fluid recovery/SVE wells and the topics appropriate for monitoring point construction specifications. Other topics covered for extraction wells are also generally applicable to soil gas/vacuum monitoring points. The applicability of the topics should be evaluated on a site-specific basis. Again, this appendix does not address the location or depth selection for these features.

Materials

Generally, the same materials can be used for the monitoring points as are used for the soil vapor extraction wells; however, there will be obvious differences in size.

Casing

Generally, 3/4- to 2-inch-diameter PVC pipe is used. Flush-threaded pipe is preferred, but for smaller diameters, couplings may be needed. For some shallow applications, flexible Teflon or polyethylene tubing can be used.

Screen

Either slotted or continuous-wrap screen can be specified. Slotted pipe is adequate for monitoring ports. Continuous-wrap screen is not commonly available at the smaller diameters (less than normal 2-inch-diameter), but can be ordered. Slot sizes smaller than those typically used for extraction wells may be appropriate for monitoring points (i.e., 0.010- to 0.020-inch slots). Other "screen" types can be used. Options include slotted drive points, porous points or, for short-term use, even open-ended pipe.

Filter Pack

Filter pack material should be appropriately sized for the screen slot width. The pack simply provides support for the screen and is not critical to monitoring point function. In some cases, no filter pack will be necessary (see Section on "Drilling Methods").

Installation

Drilling Methods

Although the use of a hollow-stem auger is still the primary means of installing monitoring points, direct-push methods can also be used to place slotted-drive points or other vacuum/soil gas probes at specific depths. Again, mud- or fluid-based drilling methods are not appropriate for this work.

Soil Sampling and Logging

As with SVE wells, it is appropriate to adequately sample the materials encountered for logging purposes and physical and chemical testing. Samples must be obtained at least every 5 feet from holes drilled for monitoring points. If the monitoring point is located in close proximity (less than 5 to 10 feet away) to another well that has been logged and sampled, a separate log is usually not required.

Borehole Diameter and Depth
The borehole diameter should be approximately 4 inches larger than the screen/casing to allow placement of the filter pack. This obviously would not apply to points placed by direct push methods. Multiple wells/tubes can be placed in a single borehole, and these are typically referred to as multiport completions. Adequate room must be allowed for proper installation if multiport monitoring systems are to be used. Multiport monitoring systems are difficult to place, and it may be more time-efficient to drill separate holes for the points at different depths in a cluster. Monitoring point depth selection is entirely site dependent, but monitoring of multiple depths within the vadose zone is recommended. It may be appropriate to extend the monitoring point into the water table to monitor water table fluctuations resulting from seasonal change or in response to the SVE system or other remedial actions.

Screen and Casing Placement
Casing and screen are normally placed by methods seemlier to those used to install SVE extraction wells; however, direct-push techniques are rapid alternatives for placing monitoring points to the desired depths. Actual means of placement is dependent on the system, materials used, and site geology.

Seal and Grout Placement
The procedures for sealing the well would generally be the same as those used for the SVE wells. Points placed by direct-push methods may depend on a tight seal with native soil to prevent leaks. Multiport monitoring systems require careful placement of seals between the monitored intervals to prevent leakage of vapors between the various target intervals.

Surface Completion
The monitoring points can be completed with a suitable barbed/valved sampling port attached by threaded connection to an appropriate end cap. The cap is attached to the top of the casing by an air-tight connection. The points can be set above grade with suitable protection or below grade, typically in a flush-mount valve box. Refer as appropriate to a drawing detail showing the desired surface completion.

Surveys
Horizontal coordinates are necessary for each point, and vertical coordinates to the nearest 0.01 foot are necessary if water levels are monitored.

Groundwater Monitoring Well Construction
Consult CEGS 02671 for specification language and design guidance. ASTM D 5092, Recommended Practice for Design and Installation of Groundwater Monitoring Wells in Aquifers, is also an excellent reference for specifying monitoring well installation.

Drill Cuttings Disposal
The specifications should address the means for disposing of the drill cuttings and other potentially contaminated waste. This depends on the project, but actual disposal can be left to the contractor.

Well Decommissioning
The specification should describe acceptable methods for sealing wells that are either no longer needed near the end of the project or do not meet the specification. Individual states may have specific requirements for well decommissioning. These must be followed. Normally, wells are sealed to prevent preferential migration of contaminants via the well. Wells also can be physically removed (by drilling them out if made of plastic, or by over excavation and pulling the casing and screen) and the hole grouted. Alternatively, the wells can be pressure grouted from bottom to top. If the well is to be decommissioned because of a questionable grout seal, pressure grouting may not be effective in preventing preferential contaminant migration. If the decommissioning is required because of poor contractor performance, the decommissioning and replacement of the well should be at the contractor's expense. The contractor must submit an alert describing the decommissioning activities.

Appendix B.2
Collection System Design Guidance

Introduction
This Appendix provides guidance on the specification, layout, and construction of the manifold collection system piping and associated appurtenances. This guidance is not comprehensive and must be adapted as necessary for site-specific conditions and objectives.

Layout and Plans
A manifold system interconnects the injection or extraction wells into a single-flow network prior to being connected to the remainder of the SVE/BV system. A manifold system generally includes a series of flow-control valves, pressure and airflow meters (liquid flow meters for liquid phase), and VOC sampling ports at each well head; these devices may be grouped in one central location for convenience. A typical manifold system is constructed of PVC, high-density polyethylene (HDPE), or stainless steel.

Diameter (SVE and BV)
Manifolds are generally constructed with 4-inch pipe. Although manifolds as large as 24 inches have been installed, these large system have centrifugal blowers that require a low manifold vacuum. The designer should evaluate pipe friction in the system to ascertain that the manifold will conduct the desired airflow rate under either of the following conditions:

- If a 2-inch manifold pipe is used, the airflow rate is over 50 scfm, and any piping run is longer than 50 feet.

- If a 4-inch manifold pipe is used, the airflow rate is over 300 scfm, and any piping run is longer than 50 feet.

If the air velocity is lower than a few thousand feet per minute, the manifold may accumulate condensation. Condensation buildup may be avoided by sloping the manifold toward the air-extraction wells where it can drain. A second method with buried manifolds is to use a relatively small-diameter vertical pipe where the direction changes from horizontal to vertical, allowing the airstream to carry condensation toward a condensate trap. See Section on Motors and Gages. A third alternative, but less

satisfactory, is to use a smaller diameter pipe in order to maintain a high air velocity on the entire manifold. This alternative is less satisfactory because pipe friction may be excessive, resulting in added requirements for blower capacity and excessive electrical costs.

Condensate Traps

A condensate trap is also called a water trap, separator tank, or demister. For SVE/BV systems, condensate controls are often necessary to prevent unwanted liquids from accumulating in piping, blowers, or air emission control devices. These controls remove moisture and store the liquid prior to disposal. In general, a condensate trap should be included in the design if the up-hole air velocity in the air-extraction wells is greater than 1,000 feet per minute or if a rotary lobe blower is used.

Condensate trap configuration includes the following:

- A vertical pipe, cap, and tee in a manifold that is capable of holding less than 5 gallons
- A large tank in line with the manifold
- An engineered trap that uses a cyclone action to separate water droplets from the air system.

Water that accumulates within these traps needs to be addressed. If a groundwater extraction system is also used at the site, the condensate water can be added to the pumped groundwater that is to be treated and/or disposed of. If no groundwater extraction system is used at the site, the water must be properly disposed of.

Motors and Gages

Flow Meter (SVE/BV)

Regular or averaging pitot tubes are generally used to measure flow. Averaging pitot tubes are designed to only require a single reading. In general, manufacturers recommend installing these tubes ten or more straight unobstructed pipe diameters upstream and five or more diameters downstream.

Flow Meter (Free Product Recovery)

A flow meter should be installed on the system to measure the amount of pumping from each well. It should be a totalizing-flow meter that indicates the total fluid pumped.

Vacuum (SVE/BV)
Vacuums should be measured with a manometer, a magnehelic gauge, or a vacuum gauge. Most SVE systems operate at a low enough vacuum that the measurements are read in inches of water column.

Temperature
Temperature is usually read with a bimetal dial-type thermometer that is installed through a hole in the manifold pipe.

Relative Humidity or Dew Point
Relative humidity or dew point measurements are not required, but may be beneficial to evaluate moisture content of biodegradation or carbon filters. A wet bulb thermometer or digital meter is used to measure relative humidity or dew point.

Sample Taps
The sample tap design is specific to the sample container and the field procedure used for collecting samples. It may have a septa fitting for direct syringe insertion, or it may be as simple as a hose barb for a piece of plastic tubing. The sample ports may have to be fabricated for the specific sampling device. For aboveground systems, the sample ports and instrumentation for each well may be located near the well itself. On buried manifold systems, the sample ports and instrumentation may be located near the blower system where the manifold pipe exits from the ground.

Configuration
The designer should configure the manifold and place valves in such a way to allow control and sample collection at each well. The option that places the instrumentation nearest the well generally provides the best vacuum and temperature information for the well, but is more likely to freeze up in winter on low-flow systems and systems with a shallow water table.

Piping and Valves

Materials of Construction
Proper selection and specification of materials plays an important role in the success of SVE/BV remediation and free product recovery.

Piping (SVE/BV)
Piping for SVE/BV systems generally includes vacuum lines, pressure lines, sampling lines, and condensate lines. Off-gas treatment, such as catalytic or thermal oxidizers, may also require fuel supply lines. The design of a piping system must consider the following major issues: pressure limitations, temperature limitations, insulation, mechanical considerations, pneumatics and hydraulics, and chemical compatibility.

Pressure Limitations The design pressure must not exceed the maximum allowable limits for the piping system minus a factor of safety (e.g., 50 percent). Per ANSI B31.3, Section 301.2, pressure relief valves should be included where required. It should be noted that PVC pipe is not appropriate for uses involving high pressures (many atmospheres) because it cannot safely withstand the stresses that are imposed. It should be noted that vacuums and pressures exerted during SVE/BV operations are usually less than one atmosphere, however, and therefore fall well within the safe range of operation under the provision of appropriate pressure/vacuum relief. When flexible hoses are used on the vacuum side of the system, vacuum limits may be far less than pressure limits.

Temperature Limitations Plastic piping, such as PVC, chlorinated polyvinyl chloride (CPVC), polypropylene (PPE), or polyvinylidene fluoride (PVDF), is commonly used for SVE/BV systems. Temperature limitations of the material also must not be exceeded. Plastic piping should never be used on the blower discharge because if the blower overheats, the piping may melt.

Winter Operations In cases where the project must operate all year, the manifold system should be winterized. Self-regulating heat tape and/or pipe insulation should be used for aboveground manifolds. Because these aboveground systems are not easily winterized, they are usually insulated or installed near or below frost level. If heat tape is to be used for winterizing, CPVC pipe should be used instead of PVC in order to provide higher strength at high temperatures.

Mechanical Stress Supports for all piping should be designed and spaced in accordance with ANSI/MSS SP-58, 69, 89, and 90. Supports shall have a nominal diameter of at least 2 inches.

Pneumatics and Hydraulics The piping system must be sized to be compatible with the overall pneumatic scheme. Friction losses and settling velocities should be considered. Velocities greater than 3 feet per second are recommended for pumped condensate lines.

Chemical Compatibility A list of acceptable materials is provided in Table 126.1 of ANSI B31.1. Specifically, chlorinated solvents may degrade plastic piping. Piping that will be exposed to sunlight must be UV resistant or contain a UV protective coating.

Piping Manifold (Liquid Phase)

The manifold consists of the piping system used to move the pumped liquids to the storage tanks and/or treatment system. It may be above ground, but in most cases it is buried. These piping systems must be constructed of a material compatible with the contaminants that are being pumped. The piping must also be capable of withstanding the pressure and volume of the pumping system under worst-case scenarios. If the designer utilizes a pneumatic-pumping system, the lines must be capable of holding the

pressure of the regulated compressed air source. If the designer utilizes a submersible pump, the lines should be able to hold the pump pressure if the flow is blocked at the treatment location. Designers should use the working pressure rating, and not the burst pressure rating, when assessing the pressure capability for manifold lines. Steel or other materials should be used in lieu of PVC if heat tape is used.

Metallic Piping

Unlined steel is not recommended because of the potential for condensation and the possibility of acid formation. The presence of entrained solids and ambient temperature fluctuations may limit the use of metallic pipe with its sophisticated lining system. Although copper is a suitable material for most installations, it is prohibitively expensive in diameters above 250 mm (1 inch). Stainless steel may be a suitable material for some installations. Stainless is available in a variety of grades, which are not equally resistant to corrosion and other physical damage, and has a wide price range.

Double-Walled Pipe

In general, single-walled pipe is preferable to double-walled pipe. The performance of single-walled pipe, joints, and coupling is superior to the performance of double-walled pipe under a wide range of conditions. Regulations may require the use of double-walled pipe.

Fittings

The manifold for plastic piping should be constructed with glued fittings because slip fit joints may fail with time. A steel wire or similar material should be installed in the trench along with buried manifolds containing plastic pipe so that a metal detector can detect its location at a later date.

Valves and Meters

Most of the above considerations that apply to piping also apply to valves. Valves are used in SVE/BV systems to regulate flow rate and on/off control. A typical SVE/BV system will be equipped with a flow control valve on each extraction or injection line. The valves must be chemically compatible with the liquid or air stream; they must operate safely in the temperature and pressure range of the system; they must not create excessive frictional loss when fully opened; and in some situations, they must be insulated and/or heated to prevent condensation. In addition, the operating range of a control valve must match the flow control requirements of the application. All control valves must be sized properly. If a valve is sized too large, the valve will operate mostly in the near-closed position, and will give poor sensitivity and control action. If a valve is sized too small, the upper range of the valve will limit flow. Formulas and sizing procedures vary with valve manufacturer. During the layout of the system, the designer should ensure that the valves are accessible. Valves should be numbered and tagged. Several valves commonly used for SVE/BV are described below.

Plug Valve A plug valve is primarily used for on-off service and throttling applications. Flow is controlled by a plug with a hole in the center that rotates to align with the flow path.

Ball Valve A ball valve is also used primarily for on-off control and throttling applications. Flow is controlled by a plug with a hole in the center that rotates to align with the flow path.

Butterfly Valve Used for on-off and throttling applications, the butterfly valve controls flow with a rotating disk or vane. This valve has relatively low friction loss in the fully-open position.

Diaphragm Valve This multiturn valve is used to control flow in both clean and dirty services. The diagram valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

Needle Valve This multiturn valve is used for precise flow control applications in clean services, typically on small-diameter piping. Needle valves have high frictional losses in the fully-open position.

Globe Valve A glove valve is used for on-off control and throttling applications. This valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through.

Dilution or Bleed Valve This valve is needed on the manifold immediately before air enters the air filter or blower (if no filter is used). The dilution valve allows atmospheric air into the blower, when opened, and relieves vacuum to reduce overall air-extraction rates from the wells. These valves should not be installed between the wells and the sample ports because the sample results would not represent extracted air concentrations. A dilution valve is more efficient than a throttle valve. In addition to a dilution valve, an automatic pressure relief valve should be installed if the blower has the potential to overheat under a blocked flow condition.

General Installation Requirements

Abrasion

It is important to protect against abrasion that weakens the pipe in spots and may interfere with joint construction. Flexible materials withstand internal abrasion better than rigid materials.

Bending

It is also important to avoid bending in excess of the deflection recommended for the pipe material.

Pressure and Leakage Tests
Pressure and leakage tests should be performed after joints have cured and before pipe is buried where possible.

Casings
Casings should be avoided where possible. Entrances and exits from casings are potential shear points where the shear stresses may exceed the stress allowable for the pipe.

Aboveground Piping

Support
Minimum support dimensions required for the pipe material and diameter shall be met. Support shall be provided for valves and other heavy equipment independently of the pipe.

Restraints
Guides, anchors, and restraints shall be provided within the allowances for the pipe design. Provision shall be made for longitudinal expansion and contraction.

Protection
Protection from mechanical damage shall be provided.

Insulation
See section on "Winter Operations."

UV Protection
UV protection should be provided for any PVC pipe used.

Below Grade Piping

Loading Conditions
Loading conditions must be designed to avoid excessive point loads. Pipe passing under or through walls is particularly susceptible.

Burial Depth
Adequate cover for freeze prevention shall be provided in severe climates and for mechanical protection, in mild climates.

Surge and Thrust
Surge and thrust effects shall be evaluated and pipe restraints provided where necessary.

Specification Sources

ASTM D2447 Polyethylene (PE) Plastic Pipe, Schedules 40 and 80 Based on Outside Diameter.

ASTM D2513 Thermoplastic Gas Pressure Pipe, Tubing, and Fittings.

ASTM D2517 Reinforced Epoxy Resin Gas Pressure Pipe and Fittings.

ASTM D3035 Polyethylene (PE) Plastic Pipe (SDR-PR) based on Controlled Outside Diameter.

ASTM D2241 Poly (Vinyl Chloride) (PVC) Plastic Pipe and Fittings (SDR-PR).

ASTM D2740 Poly (Vinyl Chloride) (PVC) Plastic Tubing.

Soil Vapor Extraction and Bioventing Engineer Manual, EM 1110-1-4001. In Press.

Guidance for Design, Installation and Operation of Soil Venting Systems, Wisconsin Department of Natural Resources, July 1993, PUBL-SW 185-93

Guidance for Design, Installation and Operation of Groundwater Extraction and Product Recovery Systems, Wisconsin.

Department of Natural Resources. August 1993, PUBL-SW 183-93.

Appendix B.3
Equipment Specifications

A. Blower/Vacuum Pumps

Introduction
Blower/vacuum pumps should be provided and installed as complete and totally functional systems, along with all necessary ancillary equipment including a motor, filtration system, silencers, controls, protective devices, instrumentation, and lubrication system. Blower/vacuum pumps commonly used in SVE/BV systems include regenerative blowers, rotary lobe blowers, liquid ring vacuum pumps, rotary vane blowers, and centrifugal blowers. Although many blower/vacuum pumps could be used in SVE/BV systems, the types listed are frequently encountered.

Regenerative Blower
Regenerative blowers consist of a multistage impeller that rotates in a stationary housing. The multistage impeller creates pressure through centrifugal force. A unit of air enters the impeller and fills the space between two of the rotating vanes. The air is thrust outward toward the casing but then is tuned back to another area of the rotating impeller. This process continues regenerating the pressure until the air reaches to the outlet. Regenerative blowers are compact and produce an oil-free airflow.

Rotary Lobe Blower
Rotary lobe blowers consist of a pair of matched impellers rotating in a stationary housing with inlet and outlet ports. The impellers rotate in opposite directions in the housing and trap a volume of air at the inlet port and move it around the perimeter to the outlet port. Rotation of the impellers is synchronized by timing gears keyed into the shaft. Oil seals are required to avoid contaminating the air stream with lubricating oil. These seals must be chemically compatible with site contaminants. When a belt drive is employed, blower speed may be regulated by changing the diameter of one or both sheaves or by using a variable-speed motor pulley.

Liquid Ring Vacuum Pump
A liquid ring vacuum pump transfers both liquid and gas through the pump casing. Centrifugal force acting on the liquid within the pump causes the liquid to form a ring around the inside of the casing. Gas is trapped between rotating blades and compressed by the liquid ring as the gas is forced radially inward toward a central discharge

port. After each revolution, the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be properly disposed of. The waste stream can be reduced by recycling the liquid; however, a cooling system for the liquid stream may be required to avoid overheating the pump.

Rotary Vane Vacuum Pump

A rotary vane vacuum pump consists of multiple vanes in a rotor located on a driven rotating shaft located inside an eccentric housing. The rotor and vanes rotate, and the volume between adjacent vanes decreases (compression) and increases (suction) as the vanes sweep across the eccentric housing. The gas enters when the vanes sweep past the inlet port, is compressed as the volume between the rotor and eccentric housing decreases, and is discharged out the discharge port when the volume between the rotor and eccentric housing is at a minimum. The cycle continues as each vane on the rotor sweeps past the inlet and discharge ports.

Centrifugal Vacuum Producer

A centrifugal vacuum producer, sometimes called a turbocompressor, belongs to a family of turbo machines that includes fans, propellers, and turbines. These machines continuously exchange angular momentum between a rotating mechanical element (impeller) and a steadily flowing fluid. The suction flow enters the impeller in the axial direction and discharges radially at high velocity. The change in diameter through the impeller increases the velocity of the gas flow. The dynamic head is converted into static head, or pressure, through a diffusion process that generally begins within the impeller and ends in a radial diffuser and scroll outboard of the impeller. Centrifugal compressors can be single stage, with only one impeller, or can be multistage, with two or more impellers mounted in the same casing. In multistage compressors, the gas discharged from the first stage is directed to the inlet of the second stage through a return channel. Once the gas reaches the last stage, it discharges to a volute or collector chamber and then passes out through the compressor discharge connection.

Accessories

Blower Particulate Filters and Demisters

Particulate filters are typically installed between the condensate removal system and the blower inlet. Although the condensate removal system will decrease the concentration levels of airborne particulate, the removal efficiency may not be sufficient. High particulate levels may cause operational problems with the blower, downstream piping, or off-gas treatment equipment. Particulate air filters should be employed to remove airborne particles down to the 1- to 10-micron range.

Cartridge air filters are often used in this type of application. Filter elements are manufactured from a variety of elements including pleated paper, felt, or wire mesh.

Paper elements are inexpensive and typically disposable. Felt and wire mesh filters may be washed. The filter is selected based on airflow rate, desired removal efficiency, and pressure drop.

Pressure gauges, or a single deferential pressure gauge, should be installed upstream and downstream of the filter. Filters should be changed at the recommended pressure difference across the filter.

Demisters are often installed downstream of vacuum units to reduce the entrained oil/water mists in the vapor stream.

Blower Silencers and Acoustics
Depending on the size and the location of the SVE/BV system, inlet and outlet silencers may be necessary to reduce blower noise. Blowers present two noise problems: (1) pulsation within the piping system, and (2) noise radiation from the blower itself. Pulsation noise peaks can be severe for large blowers and can result in noise discharges in the high decibel range.

Silencers are selected based on flow capacities and noise attenuation properties. These devices typically contain chambers with noise absorptive elements. Silencer manufacturers should provide the designer with an attenuation curve, which is a plot of noise attenuation (decibels) versus frequency (hertz). The objective is to obtain the greatest noise reduction near the sound frequencies emitted by the blower.

Also, if the SVE/BV system is located within a building, shed, or trailer, the choice of wall material should be selected taking into consideration acoustical properties. Complete tables of absorption coefficients of various building materials vs. frequency may be found in books on architectural acoustics.

Issues concerning hearing protection must be addressed in the site health and safety plan. The 8-hour time weighted-average (TWA) sound level is 85 decibels. The TWA represents an action level requiring that workers be provided with hearing protection.

Specification Sources

Antifriction Bearing Manufacturers Association (AFBMA)
AFBMA 9 (1990) Load Ratings and Fatigue Life for Ball Bearings
AFBMA 11 (1990) Load Ratings and Fatigue Life for Roller Bearings
American Society of Mechanical Engineers (ASME)
ASME B40.1 (1991) Gauges - Pressure Indicating Dial Type - Elastic Element

Submittals
Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining

if a submittal for the item should be required. Submittals should include drawings showing shop and erection details, including catalog cuts, connections, holes, bolts, and welds; manufacturer's certificates attesting that the blower/vacuum pumps meet the specified requirements; and manufacturer's operation and maintenance manuals including startup and shutdown procedures.

Materials and Equipment
Materials and equipment shall conform to their respective reference publications and specification requirements. Specifications for blower/vacuum pumps for SVE/BV projects should address the following requirements.

Performance requirements: cfm and pressure
Air quality: oil free, filtration
Drive type: direct drive, belt drive, adjustability, VFD
Motors: starting requirements, speed control
Controls: automatic, manual
Duty cycle: continuous, intermittent, cycles per hour
Pump type: regenerative, rotary lobe, water ring, rotary vane, centrifugal
Construction details: materials, configuration, coatings
Bearing life: L-10 life as defined by AFBMA 9 or 11; 5 years suggested
Lubrication system: pressure, splash
Installation requirements
Field testing
Equipment painting
O&M manuals
Field training
Accessories: filters, silencers
Pressure gauges: ASME B40.1, locations, range
Thermometers: locations, glass, or deal tepee range
Valve position indicators
Air volume indicator
Protective devices: bearing temperatures surge protection, vibration monitoring.

B. Electric Motors

Introduction
Alternating Current (AC) motors, fractional and integral horsepower, 500-hp and smaller, shall conform to NEMA MG 1 and UL 1004 for motors; NEMA MG 10 for energy management selection of polyphase motors; and UL 674 for use of motors in hazardous (classified) locations. Installation shall be limited in accordance with NFPA 70. The horsepower rating of motors should be limited to no more than 125 percent of the maximum load being served unless a NEMA standard size does not fall within this range; otherwise, the next larger NEMA standard motor size should be used. Motors of 1 hp or more with open, drip-proof or totally-enclosed fan-cooled enclosures should be

high-efficiency type. Equipment and wiring shall conform to the class, division, group, and temperature requirements in NFPA 70.

Specification Sources

National Electrical Manufacturers Association (NEMA)
NEMA MG 1 Motors and generators
NEMA MG 10 Energy Management Guide for Selection and Use of Polyphase Motors
NEMA ICS 1 Industrial Controls and Systems
NEMA ICS 2 Industrial Control Devices, Controllers and Assemblies
NEMA ICS 3 Industrial Systems
NEMA ICS 6 Enclosures for Industrial Control and Systems
National Fire Protection Association (NFPA)
NFPA 70 National Electrical Code
Underwriters Laboratories (UL)
UL 508 Industrial Control Equipment
UL 674 Electric Motors and Generators for Use in Hazardous (Classified) Locations
UL 845 Motor Control Centers
UL 1004 Electric Motors

Submittals
Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required. Submittals should include drawings showing shop and erection details, including catalog cuts, connections, holes, bolts, and welds; manufacturer's certificates attesting that the motors meet the specified requirements; and manufacturer's operation and maintenance manuals including startup and shutdown procedures.

Materials and Equipment
Materials and equipment shall conform to their respective reference publications and specification requirements. Specifications for electric motors for SVE/BV projects should address the following requirements.

Motor requirements: efficiency, voltage, phase frame, duty temperature reference, starting characteristics
Motor control requirements: manual, automatic
Reduced-Voltage controllers: auto transformer, reactor, resistor, wye-delta, part winding
Motor control centers: class, type
Contacts
Safety controls
Motor disconnect means

Equipment connections: flexible conduits, liquid tight conduits
Testing.

C. Generator Sets

Introduction

Engine-generator sets should be provided and installed as complete and totally functional systems, with all necessary ancillary equipment to include air filtration; starting system; generator controls, protection, and isolation; instrumentation; lubrication; fuel system; cooling system; and engine exhaust system.

Specification Sources

American Society for Testing and Materials (ASTM)
ASTM D 975 (1991) Diesel Fuel Oils
National Fire Protection Association (NFPA)
NFPA 30 (1990) Flammable and Combustible Liquids
NFPA 37 (1990) Installation and Use of Stationary Combustion Engines and Gas Turbines

Submittals

Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required. Submittals should include drawings showing shop and erection details, including catalog cuts, connections, holes, bolts, and welds; manufacturer's certificates attesting that the generator sets meet the specified requirements; and manufacturers operation and maintenance manuals including startup and shutdown procedures.

Materials and Equipment

Materials and equipment shall conform to their respective reference publications and specification requirements. Specifications for generator sets for SVE/BV projects should address the following suggested items:

Power application: prime, standby
Engine-Generator application: parallel, stand-alone
Engine cooling type: water, air, remote, integral
Governor type: hydraulic, electric-hydraulic, mechanical, electronic-hydraulic
Governor application: Isochronous, droop
Maximum speed: rpm
Frequency: 59, 60 Hz
Voltage
Phases: 3-phase, WYE - 3-phase, delta - single phase
Phase rotation: ABC, ACB

Service load: VA, kW
Power factor: 0.8 lagging
Nonlinear loads: kVA
Overload capacity: percent of service load for number of consecutive hours
Motor starting kVA
Max step load increase: percent of service load
Transient recovery time: seconds
with step load increase (voltage)
Transient recovery time: seconds
with step load increase (frequency)
Maximum voltage deviation: percent of rated voltage
with step load increase
Maximum frequency deviation: percent of rated frequency
with step load increase
Max step load decrease: percent of service load
Transient recovery time: seconds
Step load decrease (voltage)
Transient recovery time: seconds
Step load decrease (frequency)
Maximum voltage deviation: percent of rated voltage
with step load decrease
Maximum frequency deviation with step load decrease: percent of rated frequency
Max time To start and assume load: seconds
Max summer indoor temp
Min winter indoor temp
Seismic zone: 1,2,3,4
Installation elevation: above sea level
Max summer outdoor temp
Min winter outdoor temp
Engine generator set enclosure
Vibration limitation
Fuel system: filter, day tank, NFPA 30 and 37, No. 2-D diesel - ASTM D 975.
Lubrication: NFPA 30 and 37
Air intake equipment: filters and silencers
Exhaust system
Emissions: local and federal regulations
Starting system: air, battery, starting aids
Safety system: alarms and action logic
Generator: 1 or 2 bearing
Exciter: type
Voltage regulator
Generator control and protection
Generator and synchronizing panels
Factory inspection

Field testing
O&M manuals
Field training.

D. Prime Movers

Introduction

Prime movers should be provided and installed in a complete and totally functional system, with all necessary ancillary equipment including air filtration, starting system, controls, protection, instrumentation, lubrication, fuel system, cooling system, and engine exhaust system.

Specification Sources

American Society for Testing and Materials (ASTM)
ASTM D 975 (1991) Diesel Fuel Oils
National Fire Protection Association
NFPA 30 (1990) Flammable and Combustible Liquids
NFPA 37 (1990) Installation and Use of Stationary Combustion Engines and Gas Turbines

Submittals

Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required. Submittals should include drawings showing shop and erection details, including catalog cuts, connections, holes, bolts, and welds; manufacturer's certificates attesting that the prime movers meet the specified requirements; and manufacturer's operation and maintenance manuals including startup and shutdown procedures.

Materials and Equipment

Materials and equipment shall conform to their respective reference publications and specification requirements. Specifications for prime movers for SVE/BV projects should address the following suggested items:

Application: describe usage
Engine cooling type: water, air, remote, integral
Governor type: hydraulic, electric-hydraulic, mechanical, electronic-hydraulic
Maximum speed: rpm
Power: hp
Torque: Ft-lb at rpm
Overload capacity: percent of power for number of consecutive hours
Max time to start and assume load: seconds
Max summer indoor temp

Min winter indoor temp
Seismic zone: 1,2,3,4
Installation elevation: above sea level
Max summer outdoor temp
Min winter outdoor temp
Engine generator set enclosure
Vibration limitation
Fuel system: filter, day tank, NFPA 30 and 37, No. 2-D diesel - ASTM D 975
Lubrication: NFPA 30 and 37
Air intake equipment: filters and silencers
Exhaust system
Emissions: local and federal regulations
Starting system: air, battery, starting aids
Safety system: alarms and action logic
Factory inspection
Field testing
Equipment painting
O&M manuals
Field training.

Appendix B.4
Instrumentation and Control

Introduction

In the design of an SVE/BV system, a good deal of attention must be paid to the instrumentation and control system. A good instrumentation and control system design will assure that the individual components are coordinated and operate effectively.

Description of Design Elements

An SVE/BV design will include, at a minimum, the following elements:

P&I Diagrams

Process and instrumentation (P&I) diagrams show the interrelationship between process components, piping and process control devices. ISA and ANSI standards (ANSI/ISA-S5.1) govern the preparation of P&I diagrams. These diagrams show all major process components organized according to process flow. The instrumentation symbols are shown in "bubbles."

Elementary Wiring Diagram

This diagram shows the wiring of all physical electrical devices, such as transformers, motors, and lights. If appropriate, the diagram is organized in ladder logic form.

Description of Components

The specifications must include a description of instrumentation and control components including installation and mounting requirements.

Sequence of Control

The sequence of control must be included in the design submittal and the operation and maintenance manual. Control information concerning system start-up, system shut-down, and response to malfunctions must be included.

Control Panel Layout

A control panel layout must be designed. This drawing will show, to scale, all electrical components and associated wiring. Depending on the project, this control item may be submitted as a shop drawing by the instrumentation and control contractor.

Logic Diagram
A logic diagram must be included if the process control logic is not apparent from the P&I Diagram. This diagram shows the logical (and, or, nor, if-then) relationships between control components, but does not show interconnecting process flow. For example, the diagram may show that if Switch No. 2 is placed in the on position and there are no alarm conditions, then the blower will turn on and energize a green indicator light.

Legend
The set of documents must have a legend to explain the symbols used. Despite the existence of the legend, standard symbols must be used wherever applicable.

Degrees of Automation
The degree of automation is generally dependent on the complexity of the treatment system, remoteness of the site, and monitoring and control requirements. Typically, there is a tradeoff between the initial capital cost of the instrumentation and control equipment, and the labor cost savings in system operation.

Generally, there are the following three forms of process control: local control, centralized control, and remote control. In a local control system, all control elements (i.e., indicators, switches, relays, motor starters) are located next to the associated equipment. In a centralized control system, the control elements are mounted in a single location. These systems may include a hard-wired control panel, a programmable logic controller (PLC), or a computer. Remote control can be accomplished several ways, including by means of modems or radio telemetry.

To select the appropriate control scheme, the advantages and disadvantages each control scheme must be considered. A localized control system is less complex, less expensive, and easier to construct. For example, if a level switch in a tank is controlling an adjacent discharge pump, it would obviously be simpler to wire from the tank directly to the adjacent pump rather than to wire from the tank to the centralized control panel and then from the panel back to the pump. As the control system becomes more complex, it quickly becomes advantageous to locate the control components in a central location. Centralized control systems are also easier to operate. Centralized data acquisition and control may include the use of computers or programmable logic controllers (PLC). Automated process control is a complex topic that is beyond the scope of this document; however, several points are worth considering. The greater the number of control inputs, the more worthwhile it is to use a computer or PLC control. For SVE/BV systems, the inputs may include signals from level indicators, pressure switches, or thermocouples. The threshold for using PLCs or computers is generally between five and ten inputs, depending on the type of input and operator background. Often plant operators will be more familiar with traditional hard-wired control logic than with control logic contained in software. Process logic contained in software, however, is easier to change (once you learn the software) than hard wiring.

Hard wiring of the process logic should be avoided if extensive future modifications to the proposed system are anticipated.

Modems and radio telemetry can be used to control these systems remotely. Radio telemetry is typically used over shorter distances when radio transmission is possible. Modems are used with computerized control systems. Systems can also be equipped with auto dials to alert the operator of a malfunction by telephone or pager. Again, considerations such as site location, capital cost, standardization, operator background, and system complexity govern the selection of these devices.

Minimum Acceptable Process Control Components

For SVE/BV systems, the four major operational parameters that require control are:

Liquid Collection

The condensate collection system accumulates liquid that may overflow. Liquid level indicators, switches, and alarms are required.

Pressure/Vacuum

Blowers may require vacuum breaking controls to protect the motor units. The system may also require pressure-relief valves to protect tanks or vessels.

Flow Rate

Flow rate monitoring is essential to judge the progress of the SVE remediation effort, and flow control is required to balance multiwell systems. Flow rate can be determined by orifice plates, flow nozzles, venturi tubes, annular pitot tubes, turbine meters, vortex shedding flow meters, and acoustic flow meters.

Temperature

Temperature control may be necessary to (1) prevent motor overload on the pumps and blower, (2) prevent carbon bed fires, (3) safely operate catalytic or thermal oxidation systems, and (4) protect piping from thermal stresses and melting.

At a minimum, the following process control components are required:

- Pressure and flow indicators for each well
- Blower motor thermal overload protection
- Run time for indicating the total hours of blower/vacuum pump operation
- Vacuum-relief valve and/or vacuum switch to effect blower shutdown
- Sampling ports before and after air treatment and at each well head
- Pressure indicators at blower inlet and outlet
- High-level switch/alarm for condensate collection system
- Explosimeter for sites with recently-measured LEL levels greater than 10 percent
- UL-listed burner controls for catalytic and thermal oxidizers for SVE systems.

Special Instrumentation
Several specific instruments are common to SVE/BV systems. These instruments include piezometers, LEL meters, organic vapor analyzers, and process gas chromatographs.

Piezometers
Vacuum levels should be monitored at individual wells or at the treatment system. Pressure transmitters and data loggers can be used.

Explosimeter
Used on sites where high-VOC levels cause a potential explosion hazard, these meters must be equipped with relays to automatically shut off process component or dilute the air stream with ambient air. Most explosimeter probes use catalytic combustion as part of the detection process.

Organic Vapor Analyzers
Used to monitor vapor-phase discharges, these units are typically equipped with flame ionization (FID), photoionization, thermal conductivity, or infrared detectors. Process units (as opposed to the hand-held units frequently used in environmental work) can be rack- or panel-mounted and equipped with control relays.

Process Gas Chromatography (GC)
SVE/BV systems can use GC-FID for on-site monitoring and control (on-line GC and/or portable field GC). Several vendors manufacture GCs that can be automated for process monitoring and control; however, laboratory facilities (to prepare standards, etc.) and trained chemists are also required for GC monitoring.

Specification Sources

American National Standards Institute (ANSI)
ANSI/ISA-S5.I
Code of Federal Regulations (CFR)
CFR 47 PART 15 Radio Frequency Devices
CFR 47 PART 68 Connection of Terminal Equipment to Telephone Network
National Electrical Manufacturers Association (NEMA)
NEMA ICS 1 Industrial Control and Systems

Submittals
Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required. Submittals should include equipment data, system descriptions, system drawings, commissioning procedures, hardware testing manuals, software manuals, operator's manual; manufacturer's certificates attesting that the instrumentation and controls meet the specified requirements; and

manufacturer's operation and maintenance manuals including startup and shutdown procedures.

Materials and Equipment

Materials and equipment shall conform to their respective reference publications and specification requirements. The instrumentation and control system shall be a complete system suitable for the process. Specifications for instrumentation and control for SVE/BV projects should address the following suggested items:

Power-line surge protection
Power-line conditioners
System reliability
System accuracy
Field hardware
Instrumentation
Control devices (electric solenoid-operated pneumatic control valves)
Electronic devices
Standardization of signals
Temperature limits
Control panel software
Parameter definition
I/O point database definition to include:

- Name
- Device or sensor type (i.e., sensor, control, motors)
- Point identification number
- Area
- Sensor range
- Controller range
- Sensor span
- Controller span
- Engineering units conversion (scale factor)
- High and low reasonableness value (analog)
- High and low alarm limit (analog)
- High and low alarm limit differential (return to normal)
- Analog change differential (for reporting)
- High accumulator limit (pulse)
- Status description (digital inputs)

Wire and cable
Installation criteria
Contractor responsibilities
Control sequences of operation
Factory testing
Site testing
Performance verification testing

Endurance testing
System calibration
Commissioning procedures
O&M manuals
Hardware manual
Software manual
Training
Maintenance and service
Emergency service.

Glossary

adsorption: The attraction and adhesion of ions from an aqueous solution to the surface of solids.

air sparging: The process of injection of air below the water table to strip volatile contaminants from the saturated zone.

anisotropy: The conditions under which one or more of the hydraulic properties of an aquifer vary with direction.

aquifer: A geologic formation, group of formations, or part of a formation that contains saturated permeable material that yields sufficient, economical quantities of groundwater.

aquifer test: A test to determine hydraulic properties of an aquifer, involving the withdrawal or injection of measured quantities of water from or to a well and the measurement of resulting changes in hydraulic head in the aquifer.

aquitard: A semipervious geologic formation that can store water but transmits water at a very low rate compared to the aquifer.

biodegradation: A subset of biotransformation, it is the biologically mediated conversion of a compound to more simple products.

bioventing: A process by which air is injected into the subsurface to stimulate biodegradation by microbes.

bubbling pressure: The pressure at which air enters the saturated zone (also known as air entry value or threshold pressure).

bulk density: The mass of a soil per unit bulk volume of soil; the mass is measured after all water has been extracted, and the volume includes the volume of the soil itself and the pore volume.

capillary forces: Interfacial forces between immiscible fluid phases, resulting in pressure differences between the two phases.

capillary fringe: The zone immediately above the water table within which the water is drawn by capillary forces (fluid is under tension). The capillary fringe is saturated and it is considered to be part of the unsaturated zone.

concentration gradient: The change in concentration with distance across a fluid medium.

cone of depression: A depression in the groundwater table (or potentiometric surface) that has the shape of an inverted cone and develops around a vertical discharge well.

confined aquifer: An aquifer bounded above and below by confining layers of distinctly lower permeability than the aquifer material and the one containing confined groundwater. When a well is installed in a confined aquifer, the water level in the well rises above the top of the aquifer.

conservative solute: A nonreactive constituent that does not undergo chemical reaction during substance migration.

cosolvency: The interaction of one or more organic contaminants that may cause them to behave differently in the subsurface than if they were present alone in their pure form.

Darcy's law: An empirically derived equation for the flow of fluids through porous media. It is based on the assumptions that flow is laminar and inertia can be neglected, and states that the specific discharge, q, is directly proportional to the hydraulic conductivity, K, and the hydraulic gradient, J.

dispersion: The spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

distribution (partitioning) coefficient: Relates the quantity of a solute sorbed per unit weight of the solid phase and the quantity of the solute dissolved in water per unit volume of water.

DNAPL: Dense Nonaqueous Phase Liquid. A liquid consisting of a solution of organic compounds (e.g., chlorinated hydrocarbons) and which is denser than water.

drawdown: A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of groundwater from wells. The vertical distance between the original water level and the new water level.

effective porosity: The interconnected pore space through which fluids can pass, expressed as a percent of bulk volume. Part of the total porosity will be occupied by static fluid being held to mineral surface by surface tension, so effective porosity will be less than total porosity.

effective grain size: The grain size corresponding to the 10% fines by weight on the grain-size distribution curve.

extraction well: A discharge well used to remove groundwater or air.

Fick's law: The mass flux due to the molecular diffusion is proportional to the concentration gradient and the diffusion coefficient.

gravitational water: Water that moves into, through, or out of a soil or rock mass under the influence of gravity.

groundwater: The water contained in interconnected pores below the water table in an unconfined aquifer or in a confined aquifer.

Henry's Law: The relationship between the partial pressure of a compound and its equilibrium concentration in a dilute aqueous solution through a constant of proportionality know as the Henry's Law Constant.

heterogeneity: Characteristic of a medium in which material properties vary from point to point.

homogeneity: Characteristic of a medium in which material properties are identical throughout. Though **heterogeneity** or nonuniformity is the characteristic of most aquifers, assumed homogeneity, with some other additional assumptions, allows use of analytical models as a valuable tool for approximate analyses of groundwater movement.

hydraulic conductivity (K): Proportionality constant relating hydraulic gradient to specific discharge, which for an isotropic medium and homogeneous fluid, equals the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. The rate of flow of water in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature (gpd/ft^2). In the standard International System, the units are m^3/day/m^2 or m/day. A coefficient of proportionality describing the rate at which

water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

hydraulic conductivity, effective: Rate of water flow through a porous medium that contains more than one fluid (such as water and air in the unsaturated zone), which should be specified in terms of the fluid type, content, and the existing pressure.

hydraulic gradient (J): Slope of a water table or potentiometric surface. More specifically, change in the hydraulic head per unit of distance in the direction of the maximum rate of decrease. The difference in hydraulic heads (h_1-h_2), divided by the distance (L) along the flowpath: $J = (h_1-h_2)/L$.

hydraulic head (h): Height above a datum plane (such as mean sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. Equal to the distance between the water level in a well and the datum plane.

ideal gas: A gas whose pressure-volume-temperature (P-V-T) behavior can be described completely by the ideal gas law, $PV = nRT$, where n is the number of moles of gas and R is the universal gas constant.

immiscible: The chemical property where two or more liquids or phases do not readily dissolve in one another, such as soil and water.

intrinsic permeability: Pertaining to the relative ease with which a porous medium can transmit a liquid under a hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field.

isotropy: The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions.

kinematic viscosity: The ratio of dynamic viscosity to mass density. It is obtained by dividing dynamic viscosity by the fluid density. Units of kinematic viscosity are square meters per second (m^2/s).

Klinkenberg effect: Gas slippage along pore walls. Darcy's Law assumes that the velocity of a fluid at the pore wall surface is zero.

laminar flow: Fluid flow in which the head loss is proportional to the first power of the velocity; synonymous with streamline flow and viscous flow. Type of flow in which the fluid particles follow paths that are smooth, straight, and parallel to the

channel walls. In laminar flow, the viscosity of the fluid dampens out turbulent motion.

leaky aquifer: An artesian or water table aquifer that loses or gains water through adjacent semipermeable confining units.

LNAPL: Lighter-than-water nonaqueous phase liquid.

molecular diffusion: Process in which solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases.

NAPL: Nonaqueous phase liquids.

organic carbon content: The amount of the organic carbon present in a soil. Organic chemicals in soil adsorb to soil organic carbon, and the amount of adsorption can be related to the soil organic carbon content.

partitioning: Chemical equilibrium condition where a chemical's concentration is apportioned between two different phases according to the partition coefficient, which is the ratio of a chemical's concentration in one phase to its concentration in the other phase.

perched aquifer: A special case of phreatic aquifer that occurs wherever an impervious (or semipervious) layer of limited areal extent is located between the water table of a phreatic aquifer and the ground surface.

permeability: Ability of a porous medium to transmit fluids under a hydraulic gradient. The capacity of a porous rock, sediment, or soil to transmit a fluid; it is a measure of the relative ease of fluid flow under unequal pressure.

Permeability coefficient: Rate of flow of water through a unit cross-sectional area under a unit hydraulic gradient at the prevailing temperature (field permeability coefficient), or adjusted to 15°C.

permeability, effective: Observed permeability of a porous medium to one fluid phase, under conditions of physical interaction between the phase and other fluid phases present.

permeability, intrinsic: Relative ease with which a porous medium can transmit a fluid under a potential gradient, as a property of the medium itself. Property of a medium expressing the relative ease with which fluids can pass through it.

porosity: Ratio of the total volume of voids to the total volume of a porous medium. The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected. Porosity may be primary (formed during deposition or cementation of the material), or secondary (formed after deposition or cementation), such as fractures.

pressure head: Hydrostatic pressure expressed as the height (above a measurement point) of a column of water that the pressure can support.

pumping test: A test that is conducted to determine aquifer or well characteristics. A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called **aquifer test**.

radial flow: The flow of water in an aquifer toward a vertical well.

radius of influence: The radial distance from the center of a wellbore to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression). The radial distance from an extraction well that has adequate air flow for effective removal of contaminants when a vacuum is applied to the extraction well.

Raoult's Law: A physical law that describes the relationship between the vapor pressure of a component over a solution, the vapor pressure of the same component over pure liquid, and the mole fraction of the component in the solution.

residual saturation: Saturation below which fluid drainage will not occur.

retardation: The movement of a solute through a geologic medium at a velocity less than that of the flowing groundwater due to sorption or other removal of the solute.

saturation: The ratio of the volume of a single fluid in the pores to pore volume expressed as a percentage or a fraction.

saturated zone: Portion of the subsurface environment in which all voids are ideally filled with water under pressure greater than atmospheric. The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

slug test: A test for estimating hydraulic conductivity of an aquifer in which a rapid water-level change is produced in a piezometer or monitoring well, usually by introducing or withdrawing a "slug" of water or a weight. The rise or decline in the water level is monitored.

sorption: Processes that remove solutes from the fluid phase and concentrate them on the solid phase of a medium; used to encompass absorption and adsorption.

specific surface: The amount of surface area of a dispersed system per gram or per unit volume of the dispersed phase.

storativity: A dimensionless term representing the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield.

transmissivity: Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths. The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values are given in gallons per minute through a vertical section of an aquifer one foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one in the English Engineering System; in the Standard International System, transmissivity is given in cubic meters per day through a vertical section of an aquifer one meter wide and extending the full saturated height of an aquifer under a hydraulic gradient of one. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

unconfined: Conditions in which the upper surface of the zone of saturation forms a water table under atmospheric pressure.

unsaturated flow: Movement of water in a porous medium in which the pore spaces are not completely filled with water.

unsaturated zone: The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water, as well as air and other gases at less than atmospheric pressure. Saturated bodies, such as perched groundwater, may exist in the unsaturated zone, and water pressure within these may be greater than atmospheric. Also known as "vadose zone."

viscosity: The internal friction within a fluid that causes it to resist flow. See Kinematic and Dynamic viscosity.

VOC: Volatile organic contaminants, typically with a high vapor pressure and a tendency to evaporate rapidly.

volatilization: The transfer of a chemical from liquid to the gas phase. Solubility, molecular weight, vapor pressure of the liquid, and the nature of the air-liquid interface affect the rate of volatilization.

water content: Ratio of the volume of water to the bulk volume in the unsaturated flow.

water table: Upper surface of a zone of saturation, where that surface is not formed by a confining unit; water pressure in the porous medium is equal to atmospheric pressure. The surface between the vadose zone and the groundwater; that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

References

American Petroleum Institute. 1989. *A guide to the assessment and remediation of underground petroleum releases*, API Publication No. 1628, 2nd ed., 81 pp., Washington, D.C.

American Petroleum Institute. 1993. *A guide to the assessment and remediation of petroleum hydrocarbons in soil*, API Publication No. 1629, Washington, D.C.

American Society for Testing and Materials. 1994. *Emergency standard guide for risk-based corrective action applied at petroleum release sites*, ASTM Designation: ES 38-94, July, Philadelphia, PA.

Angell, K. G. 1992. In Situ Remedial Methods: Air Sparging. *The National Environmental Journal* (January/February), pp. 20-23.

Ayra, L. M. and J. F. Paris. 1981. A physicoempirical model to predict the soil moisture characteristics from particle size distribution and bulk density data. *Soil Sci. Soc. Am. J.* 45:1023-1030.

Baker, O.M., and W. Swerdloff. 1956. Finding surface tension of hydrocarbon liquids. *Oil and Gas Journal*, 125 (January 2).

Bear, J. 1972. *Dynamics of fluids in porous media*, American Elsevier Publishing Company, Inc.

Bear, J. 1979. *Hydraulics of groundwater*, McGraw-Hill.

Benson, D. A., D. Huntley, and P. C. Johnson. 1993. Modeling vapor extraction and general transport in the presence of NAPL mixtures and nonideal conditions, *National Groundwater Association, Dublin, Ohio*, 31 (3).

Buscheck, T. E., and T. R. Peargin. 1991. Summary of a nation-wide vapor extraction system performance study, *Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water,* National Well Association, Houston, Texas, November.

Chevron Research and Technology Company (CRTC). 1991. *Vapor extraction system performance study*. Chevron Research and Technology Company internal document written for Chevron USA marketing department.

Cohen, R. M., and J. W. Mercer. 1993. *DNAPL site evaluation*. CRC Press, Boca Raton, Florida.

The College of Engineering, University of Wisconsin-Madison. 1993. Passive bioremediation; case history. *Underground Tank Technology Update*, 7 (6).

Conner, J. R. 1988. Case study of soil venting. *Pollution Engineering*, July.

Davis, A., et al. 1994. Attenuation and biodegradation of chlorophenols in ground water at a former wood treating facility. *Ground Water*, 32 (2).

Davis, J. W., N. J. Klier, and C. L. Carpenter. 1994. Natural biological attenuation of benzene in ground water beneath a manufacturing facility. *Ground Water*, 32 (2).

Driscoll, F. G. 1986. *Groundwater and wells*. Johnson Filtration Systems, Inc., St. Paul, Minnesota.

Dupont, R. 1993. Fundamentals of bioventing applied to fuel contaminated sites. *Environmental Progress*, 12 (1):45-53.

Environmental Systems and Technologies Software (ES&T), Ltd. 1988-1993. VENTING User's Guide, ES&T, Inc., Blackburg, Virginia.

ES&T, ARMOS - *A Program to Estimate Unsaturated Soil Hydraulic Properties From Particle Size Distribution Data*, Vers. 2.0 User's Guide, Environmental Systems & Technologies, Inc., Blacksburg, Virginia. 1990.

Everett, L. G., L. G., Wilson, and E. W. Hoylamn. 1984. *Vadose zone monitoring for hazardous waste sites*. Noyes Data Corporation, Park Ridge, New Jersey.

Farr, A. M., R. J. Houghtalen, and D. B. McWorter. 1990. Volume estimation of light nonaqueous phase liquids in porous media. *Groundwater* 28:48-56.

Fetter, C. W. 1993. *Contaminant Hydrogeology*. MacMillan Publishing Company, New York.

Fetter, C. W. 1994. *Applied Hydrogeology*. MacMillan Publishing Company, New York.

Graves, D. A., and M. E. Leavitt. 1993. Vapor-phase nutrient delivery system for in situ biorernediation of soil. U.S. Patent No. 5,178,491.

Ground Water, Vol. 28, pp. 244-252. 1990. Kemblowski, M. W. and C. Y. Chiang. Hydrocarbon thickness fluctuations in monitoring wells.

Ground Water, 1996, Ahlfeld, D., A. Dahmani, M. Farrell, and W. Ji. *Detailed Field Measurements of an Air Sparging Pilot Test.* Environmental Research Institute, U. Conn., Draft Manuscript Submitted to Groundwater.

Ground Water Monitoring and Remediation 13 (4):115-126. 1993. Ji, W., A. Dahmani, D. Ahlfeld, J. Lin, and E. Hill. Laboratory study of air sparging: air flow visualization.

Johnson, P. C. 1992a. Soil vapor extraction workshop figures. Shell Development Corp. (personal communication).

Hampton, D. R., T. R. Barrett, H. S. Nayyar, and T. P. O'Connell. 1993. "Hydrophobic gravel packs for product monitoring and recovery wells." In *Proceedings of the Seventh National Outdoor Action Conference*, May 25-27, 1993, National Groundwater Association, pp. 581-595.

Hazmat World. 1994. *Air sparging success* 7 (5):25.

Hinchee, R. E. 1990. "Soil venting techniques." Paper presented at *Annual Chevron USA Inc., Marketing Environmental Engineering Conference*, Denver, CO.

Hinchee, R. E., and M. Arthur. 1991. Bench scale studies of the soil aeration process for bioremediation of petroleum hydrocarbons. *Applied Biochemistry and Biotechnology* 28/29:901-906.

Hinchee, R. E., and S. K. Ong. 1992. A rapid in situ respiration test for measuring aerobic biodegradation rates of hydrocarbons in soil. J. Air Waste Management Assoc. 42:1305-1312.

Hinchee, R. E., et al. 1992. *Test plan and technical protocol for a field treatability test for bioventing.* Air Force Center for Environmental Excellence, Brooks Air Force Base, San Antonio, Texas.

Hoag, G. 1991. The U. Conn/U.S. EPA draft site remediation course: soil vapor extraction (in review).

Johnson, P. C., and R. A. Ettinger. 1991. Heuristic model for predicting the intrusion-rate of contaminant vapors into buildings. *Environ. Sci. Technol.* 25:1445-1447.

Johnson, P. C., M. B. Hertz, and D. L. Byers. 1990c. Estimates for hydrocarbon vapor emissions resulting from service station remediations and buried gasoline-contaminated soils. *Petroleum Contaminated Soils.* 3:295-326.

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart. 1988. "Practical screening models for soil venting application." In *Proceedings of NWWA/API conference on petroleum hydrocarbons and organic chemicals in ground water, Houston, Texas.*

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart. 1990b. Quantitative analysis for the cleanup of hydrocarbon-contaminated soils by in situ soil venting. *Groundwater* 8 (3):413-429.

Johnson, P. C., et al. 1990a. A practical approach to the design, operation, and monitoring of in situ soil-venting systems. *Groundwater Monitoring Review* 10(2):150-178.

Johnson, P. C., et al. 1992b. Vapor extraction-based remedial technologies: soil venting, air sparging, bioventing, and thermally-enhanced vapor extraction (in review).

Johnson, R. L. 1993. "Enhancing biodegradation with in situ air sparging: a conceptual model." In *Proceedings of the Conference on In Situ and On-Site Bioreclamation*, April 6-8, Battelle Memorial Institute, San Diego, California.

Johnson, R. L., et al. 1992. *Experimental examination of integrated soil vapor extraction techniques.* Project Report, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory.

Johnson, R. L., et al. 1993. An overview of in situ air sparging. *Ground Water Monitoring and Remediation* 13 (4):127-135.

Joss, J. C., and A. L. Baehr. 1994. AIR3D: An Adaptation of the Groundwater Flow Code MODFLOW to Simulate Airflow in the Unsaturated Zone. U.S. Geological Survey Open File Report, publication expected 1994.

Kabak, D. S., et al. 1991. Innovative Ground Water and Soil Remediation: In Situ Air Stripping Using Horizontal Wells. Proc., Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, held in Las Vegas, Nevada, May 13-16.

Kent, B., and D. Graves. 1992. Enhanced Biodegradation of Contaminated Soils Using Vent Wells. Contaminated Soils - Diesel Fuel Contamination. Eds. P. T. Kostecki and E. J. Calabrese. Lewis Publishers, Boca Raton. Chapter 6, pp. 81-94.

Lakshmiprasad, T., and R. R. Dupont. 1993. Pilot Scale Study of the Enhanced Biodegradation Potential of JP-4 Jet Fuel Under Simulated Soil Vacuum Extraction Conditions. Poster No. 15. Air and Waste Management Association, Denver, Colorado.

Lenhard, R. J., and J. C. Parker. 1990. Estimation of Free Hydrocarbon Volume From Fluid Levels in Observation Wells. *Groundwater*, 28: 57-67.

Lenhard, R. J., and J. C. Parker. 1987. Measurement and Prediction of Saturation-Pressure Relationships in Three-Phase Porous Media Systems. *J. Contam. Hydrol.* 1: 407-424.

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

Mackay, D. M., and J. A. Cherry. 1989. Groundwater contamination: pump-and-treat remediation, *Environmental Science and Technology* 23, (6): 630-636.

Mark-Brown, N. V. 1994. Aspects of soil venting design, *Hydrocarbon Bioremediation*, R. E. Hinchee, B. C. Alleman, and R. E. Hoeppel, eds. CRC Press, Inc., Boca Raton, pp. 362-367.

Marley, M. C., D. J. Hazelbrouck, and M. T. Walsh. 1992. The application of in situ air sparging as an innovative soil and groundwater remediation technology. *Groundwater Monitoring Review*, 12 (2), 137-145.

Marley, M. C., E. X. Droste, and R. J. Cody. 1994. "Mechanisms that govern the successful application of sparging technologies. Paper 94-WP102.05, presented at *Air and Waste Management Association 87th Annual Meeting*, Cincinnati, Ohio, June 19-24.

McDonald, M. G., and A. W. Harbaugh. 1988. *A modular three dimensional finite difference ground water flow model*, U.S. Geological Society Book 6.

Miller, R. N., et al. 1990. "A field scale investigation of enhanced petroleum hydrocarbon biodegradation in the vadose-zone at tyndall AFB, Florida." In *Petroleum Hydrocarbons and Organic Chemicals in Ground Water Prevention, Detection, and Restoration*, NWWA Conference, Houston, Texas.

Millington, R. J., and J. M. Quirk. 1961. Permeability of porous solids. *Trans. Faraday Soc.* 57:1200-1207.

Mishra, S. J., C. Parker, and N. Singhal. 1988. Estimation of soil hydraulic properties and their uncertainty from particle size distribution data. *J. Hydrol.* 108:1-18.

Morris, D. A. and A. I. Johnson, 1967. "Summary of hydrologic and physical properties of rock and soil materials." *USGS Water-Supply Paper 1839-D.*

Sabadell, G. P., et al. 1988. CSUGAS: Flowfield Model for In Situ Volatilization of Organic Compounds in Soils. Argonne National Laboratory, Argonne, Illinois.

Sabadell, G. P. Eisenbecs, and J. J. Sunada. 1988. "The 3-D model CSUGAS: a management tool for the design and operation of soil venting systems." *Proceedings of the 9th National Superfund Conference* (November).

Shan, C., R. W. Falta, and I. Javandel. 1992. Analytical solutions for steady state gas flow to a soil vapor extraction well. Water Resources Research 28 (4):1105-1120.

Sims, J. L., et al. 1993. In situ bioremediation of contaminated unsaturated subsurface soils. *EPA Engineering Issue*, EPA 540/S-93/501.

Travis, C. C., and J. M. MacInnis. 1992. Vapor extraction of organics from subsurface soils: Is it effective? *Environmental Science and Technology* 26(10):1885-1887.

University of Wisconsin. 1992. Underground tank technology update. University of Wisconsin-Madison, College of Engineering. 6(3).

U.S. Environmental Protection Agency. 1990a. *Field measurements: Dependable data when you need it*, EPA/530/UST-90-003, pp. 61-74.

U.S. Environmental Protection Agency. 1990b. *Assessing UST corrective action technologies: Early screening of cleanup technologies for the saturated zone*, EPA/600/2-90-027.

U.S. Environmental Protection Agency. 1990c. *Assessing UST corrective action technologies: Site assessment and selection of unsaturated zone treatment technologies*, EPA/600/2-90-011.

U.S. Environmental Protection Agency. 1991a. *Soil vapor extraction technology reference handbook*, EPA-540/2-91/011.

U.S. Environmental Protection Agency. 1991b. *Site characterization for subsurface remediation*. EPA/625-4-91/026.

U.S. Environmental Protection Agency. 1991c. Assessing UST Corrective Action Technology, A Scientific Evaluation of the Mobility and Degradability of Organic Contaminants in Subsurface Environments. EPA/600/2-91/053.

U.S. Environmental Protection Agency. 1992. *Underground storage tank research program*, Vol. 1 - Draft Report.

U.S. Environmental Protection Agency. 1993a. *Free product recovery and residual hydrocarbon removal.* UST Corrective Action Workshop (January).

U.S. Environmental Protection Agency. 1993b. *Subsurface characterization and monitoring techniques. Volume I: Solids and ground water*, EPA/625/R-93/003a.

U.S. Environmental Protection Agency. 1993c. *Subsurface characterization and monitoring techniques. Volume II: The vadose zone, field screening and analytical methods.* EPA/625/R-93/0036.

U.S. Environmental Protection Agency. 1993d. *Remediation technologies screening matric and reference guide.* A joint project of the U.S. Environmental Protection Agency and the U.S. Air Force.

U.S. Environmental Protection Agency. 1994. Soil Vapor Extraction Technology: *Evaluation of Mathematical Models for Remediation of VOC-Contaminated Sites.* Geotrans, Inc. Prepared for Risk Reduction Engineering Laboratory, Office of Research and Development.

Valsacaj, K. T., and L. J. Thibodeaux. 1988. Equilibrium adsorption of chemical vapors on surface soils, landfills, and landfarms--A review. *J. Hazard Materials* 19:79-99.

Waterloo Hydrogeologic Software. 1993. *Airflow user's guide.* Waterloo, Ontario, Canada.

Weis, G. (Ed). 1990. *Hazardous Chemicals Data Book*, Noyes Data Corp., Park, Ridge, New Jersey, p. 485.

Wilson, J. T. 1993. *Testing bioremediation in the field. In situ bioremediation when does it work?* Natural Academy Press, Washington, D.C.

Wisconsin Department of Natural Resources. 1993. ERRP issue guidance on natural biodegradation. *Release News* 3(1).